PROGRESS REPORT OF A RESEARCH PROGRAM
IN EXPERIMENTAL HIGH ENERGY PHYSICS

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Progress Report
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Anatole M. Shapiro and Robert E. Lanou, Jr.

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Brown University
Providence, Rhode Island

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ABSTRACT

An experimental program in strong interaction physics is being carried out using a bubble chamber - hybrid system and counter-spark chamber techniques. The experiments have been and are being performed utilizing the accelerators of the National Laboratories at Argonne, Brookhaven and Batavia.

The bubble chamber - hybrid system group is primarily engaged in several experiments at the Fermilab. Extensive analysis of multiparticle production in π^-p interactions at 147 GeV/c has been carried out, with particular emphasis on the production of strange particles and on inclusive production of various particles and resonances. Measurements are in progress for a larger investigation of π^+p , K^+p , pp , and π^-p interactions, which will yield results on the particle production mechanisms of the four different projectile particles under identical experimental conditions. An expanded detector for forward-going gammas and an ISIS downstream particle identifier have been designed and constructed, and are being added to the hybrid system for new experiments to be started in the fall of 1978.

The experiments of the electronic detector-spark chamber group include the following: 1) a search at BNL for high mass boson resonances and determination of quantum numbers in antiproton-proton systems; 2) a hadron-deuteron elastic and quasi-elastic scattering experiment at FNAL at the highest energies; 3) also at FNAL, a study of inclusive scattering up to high values of $p_{\perp}$, with associated multiplicity and pseudo-rapidity distributions, for hadrons on protons to hadrons at incident energies up to 175 GeV; 4) an experiment to study the A-dependence of hadronic inclusive scattering at Fermilab; 5) a search for charged, long-lived, massive particles up to the kinematic limit at Fermilab; 6) a study of hadronic final states and weak-electromagnetic interference effects produced by 15 GeV-15 GeV e^+e^- collisions at PEP.

Progress Report of a Research Program
in Experimental High Energy Physics

The Department of Physics of Brown University presents herein a report of the progress made in the experimental program during the present contract period (1 September 1976 - 31 December 1977). This work has been supported by the U.S. Energy Research and Development Administration under Contract EY-76-C-02-3130.A001 (Task B-Experimental).

This report is divided as follows:

A. Bubble Chamber-Proportional Hybrid System Program

- I. Data Analysis in Progress
- II. Experimental Runs in Progress and in Preparation
- III. Associated Matters
- IV. Scientific Personnel

B. Electronic Detector-Spark Chamber Program

- I. Data Analysis in Progress
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C. Papers Published During the Preceding Year and Papers in Press

A. Bubble Chamber - Proportional Hybrid System Program.

I. Analysis in Progress.

a) The Proportional Hybrid System (PHS) Study of π^-p Interactions at 147 GeV/c (FNAL Experiment 154).

The data of this experiment were obtained from a 105,000 frame exposure of the Fermilab Hybrid Proportional Wire Chamber - 30 inch Bubble Chamber System, in a tagged beam of negative particles of 147 GeV/c momentum. The portion of the hybrid system upstream of the bubble chamber provides for the identification of incoming particles by Cerenkov counters, and for the precise determination of their direction by proportional wire counters. Proportional wire chambers in the downstream portion of the hybrid system provide precise measurement of the momentum and direction of fast forward-going charged particles emerging through the fringing field of the bubble chamber magnet. The bubble chamber itself serves as the target and provides 4π sensitivity for all charged particles produced in any interaction in the chamber and considerable detection efficiency for associated V^0 's and γ 's as well. This system and its properties have been described in considerable detail in previous Progress Reports and Renewal Proposals, as well as in published papers.

Analysis of the data obtained in this exposure has continued to yield significant results. During the past year journal articles and letters have been published, or submitted for publication, concerning the exclusive channel $\pi^-p \rightarrow \pi^-\pi^-\pi^+p$, the production of Δ^{++} hyperons, and the systems X produced in the interactions $\pi^-p \rightarrow \pi^-_{fast} + X^+$ and $\pi^-p \rightarrow p + X^-$.

In addition, contributed papers on two-particle rapidity correlations,

production of strange particles, and diffractive production of three-pion systems have been presented at meetings of the American Physical Society. A number of contributed papers have also been given on the performance of the prototype forward gamma detector (FGD) described in our previous Progress Report. Several other papers are now in preparation. Some of this work is briefly described below.

(i) Inclusive Cross Sections for Strange Particle and γ Production in π^-p Interactions at 147 GeV/c.

In scanning for events in the bubble chamber, all features of event topology, including all apparently associated V^0 's and electron pairs, were noted. These have been measured and reconstructed, and have been processed through the kinematic fitting program SQUAW, testing each for fits to neutral decays of K_S^0 's, Λ , and $\bar{\Lambda}$, and pair production. The results of the fits have been checked on the film for ionization consistency. Of a total of 1896 fitted neutrals, 270 remained ambiguous between fits, and were apportioned with account taken of p_T distributions and χ^2 probability. Table I gives the numbers of K_S^0 , Λ , $\bar{\Lambda}$ and γ 's seen in the detection volume of the chamber, and the inclusive cross sections for the production of each of these, obtained after weighting for decay probability, branching ratios, scanning efficiency, and measuring efficiency.

In Figure 1 are plotted the Feynman x distributions for K_S^0 , Λ , and $\bar{\Lambda}$. Each event is entered with its overall efficiency weight. A striking feature is that both K_S^0 and $\bar{\Lambda}$ are produced in the central region, while Λ production extends from the central region into the region of target fragmentation. These features are also seen in Fig. 2, where the center-of-mass rapidity y is plotted for each weighted event.

Fig. 1

Fig. 2

Table I

Inclusive Cross Sections for Strange Particle and γ Production in $\pi^- p$ Interactions at 147 GeV/c

Reaction	Number of Decays (or Pairs)	Cross Section (mb)
$\pi^- p \rightarrow K_S^0 X$	505	3.67 ± 0.28
$\pi^- p \rightarrow \Lambda X$	238	1.65 ± 0.19
$\pi^- p \rightarrow \bar{\Lambda} X$	32	0.38 ± 0.12
$\pi^- p \rightarrow \gamma X$	1121	129.0 ± 8.4

Further studies of strange particle and γ production are in progress. Some preliminary results on the multiplicity $\langle n_X \rangle$ of the systems X produced with the strange particles in the reactions $\pi^- p \rightarrow KX$ and $\pi^- p \rightarrow \Lambda X$ are discussed in Section (ii) below.

(ii) Average Charged Multiplicities in Semi-Inclusive Reactions.

In the Progress Report of June 1976, we reported on studies of the inclusive reaction $\pi^- p \rightarrow \pi^-_{\text{fast}} X$, and on the results of comparisons among the reactions $\pi^- p \rightarrow X$, $pp \rightarrow X$, $\pi^- p \rightarrow pX$ and $\pi^- p \rightarrow \pi^-_f X$. These results have been published in Physical Review Letters (see Section C, Reference 254). We are now in the process of extending these studies to include a broad range of inclusive and semi-inclusive reactions produced in $\pi^- p$ interactions at 147 GeV/c.

The dependence on various kinematic variables of $\langle n_X \rangle$, the average charged particle multiplicity of the system X from semi-inclusive hadron-hadron reactions of the general type

$$ab \rightarrow cX, \quad (1)$$

has previously been studied^{1-6*} both theoretically and experimentally; and has been compared with the average total charged multiplicity in inelastic hadron-hadron reactions of the type

$$ab \rightarrow X. \quad (2)$$

Various theoretical models for multiparticle production in reactions of type (2), which have been discussed in review articles by W. R. Frazer⁷ and E. L. Feinberg,⁸ have made predictions for the dependence

* All footnotes are placed at the end of each major section. (See page 25.)

of $\langle n_X \rangle$ on s , the square of the center-of-mass energy of the reaction. These models include the multiperipheral model and Regge-Mueller analysis which predict a linear dependence of $\langle n_X \rangle$ on $(\ln s)$,⁷ the Cheng-Wu model which predicts $\langle n_X \rangle \propto s^a$, where $a > 0$,⁷ and the Fermi statistical model and Belenjkii-Landau hydrodynamic model which both predict $\langle n_X \rangle \propto s^{1/2}$.⁸ Subsequently, M. Ganetto et al.⁹ have proposed using the Polya-Eggenberger formula for multiplicity distributions which predicts $\langle n_X \rangle \propto s^{1/8}$; and D. M. Tow¹⁰ has pointed out that the inclusion of a secondary trajectory in a Regge-Mueller analysis predicts a term in $s^{-1/2}$ as well as one in $(\ln s)$. The reaction

$$pp \rightarrow X \quad (3)$$

is the most extensively studied of reactions of type (2), and a plot of the available data over the region $10 < s < 2 \times 10^4$ (GeV)² shows qualitatively that no simple $(\ln s)$ or power law dependence can fit the data over this whole region, although the data over various more limited energy intervals can quite readily be fitted by such expressions,^{9,11,12} as well as by more complicated ones. Over the whole range of s , only functions of the form $A + B(\ln s)^2$, $A + B(\ln s) + C(\ln s)^2$, and $A + B(\ln s) + Cs^{-1/2}$ give reasonable χ^2 values.¹²

Data also exist for the following specific examples of reaction (2):

$$\pi^+ p \rightarrow X \quad (4)$$

$$\pi^- p \rightarrow X \quad (5)$$

$$K^+ p \rightarrow X \quad (6)$$

$$K^- p \rightarrow X \quad (7)$$

$$\bar{p}p \rightarrow X, \quad (8)$$

but over much more limited regions of s than for reaction (3). All of these can, in general, be fitted by

$$\langle n_X \rangle = A + B(\ln s),$$

as well as by any of the other expressions which fit the data for the reaction (3).^{7,10,12-15} Furthermore, the coefficients obtained are very similar for all reactions. Wroblewski¹⁶ pointed out that if $\langle n_X \rangle$ is given as a function of available energy Q rather than s , where $Q = \sqrt{s} - M_a - M_b$, the data for reactions (3) and (4) could be fitted simultaneously by

$$\langle n_X \rangle = A' + B'(\ln Q^2).$$

This approach was extended to reactions (3), (4), (5), (6) and (7) with reasonable success by Ammosov et al.¹³

An analogous situation has been observed in semi-inclusive reactions of the type represented by reaction (1). For such reactions, M_X^2 is the square of the total energy in the center of mass system of the recoil system X , and hence corresponds, for reactions of type (1), to s for reactions of type (2). A linear dependence of $\langle n_X \rangle$ on $(\ln M_X^2)$ has been predicted by several theoretical models such as the triple-Pomeron description¹ of the high-mass diffractive region ($10 \leq M_X^2 \leq s/10$ (GeV)²) and the ABFST multiperipheral model² for $M_X^2 > 20$ (GeV)². Moreover, the slope of the linear increase of $\langle n_X \rangle$ with $(\ln M_X^2)$ has been predicted to be independent of s , t , and the type of incident particle, and to be identical to the slope of the linear increase with $(\ln s)$ of the average total charged multiplicity for reactions of type (2).¹ These predictions have thus far been verified for the reaction

$$pp \rightarrow pX$$

(9)

at four energies,^{3,4} for the reaction

$$\pi^- p \rightarrow pX \quad (10)$$

at 205 GeV/c^{5,6} and for reaction (10) and

$$\pi^- p \rightarrow \pi^-_{\text{fast}} X \quad (11)$$

at 147 GeV/c, as described in our Physical Review Letter (Section C, Ref. 254).

The linearity of the dependence of $\langle n_X \rangle$ on $(\ln M_X^2)$ in reactions of type (1) has been observed, not only for hadron-hadron interactions, but also for weak and electromagnetic processes.¹⁷ Brodsky and Gunion¹⁸ have described the similarity between hadronic reactions of types (1) and (2) and the reaction $e^+e^- \rightarrow X$ (hadrons) in terms of a color-gauge-theory model. This model presumes that the hadron multiplicity depends only on the underlying quark configuration of the interacting particles.

Note that thus far we have discussed only the slope of the $(\ln M_X^2)$ dependence. Whitmore and Derrick¹⁹ proposed a parameterization for reactions of type (1) in terms of available energy, analogous to that employed by Wroblewski for reactions of type (2). For inclusive reactions of type (1), Q is defined as $Q = M_X - M_b$, if c is fragmented from a . These authors point out that this is equivalent in a standard exchange picture to the reactions $Eb \rightarrow X$, where E is a virtual exchanged object: Pomeron, Reggeon, pion, or any combination of them. (See Figure 3(a).) They obtain a roughly universal dependence,¹⁹ of the form

$$\langle n_X \rangle = A + B (\ln Q^2),$$

for reactions (3), (5), (9) and (10). We, on the other hand, have pointed

Fig. 3

out that there are significant differences between the data for reactions (10) and (11) and for (3) and (5), even when presented in terms of available energy. These differences can be seen in Figures 3(b) and 4 and in Table 2, and they show a systematic displacement such that in every case involving a π^- interaction on a real proton ($\pi^- p \rightarrow X$) or on a virtual exchanged object ($\pi^- E \rightarrow X$), a higher $\langle n_X \rangle$ is observed at given M_X^2 than for a proton interacting on a proton or virtual exchanged entity ($pp \rightarrow X$ or $pE \rightarrow X$). These differences have been discussed in terms of a simple model in our Phys. Rev. Letter.

The various models also suggest a dependence of $\langle n_X \rangle$ on t , but do not predict a unique functional form.^{1,2} Studies of reaction (9) and (10) at 205 GeV/c⁶ and at the I.S.R.²⁰ do not indicate a significant t dependence for these reactions.

The similarities and differences observed, and the light that detailed examination of these might shed on the structure of the interacting particles, have prompted us to extend our studies of reactions of type (1) to include the following, in addition to (10) and (11):

$$\pi^- p \rightarrow \pi_{\text{fast}}^- pX \quad (12)$$

$$\rightarrow \Delta^{++} X \quad (13)$$

$$\rightarrow p^0 \bar{K} \quad (14)$$

$$\rightarrow \Delta^0 X \quad (15)$$

$$\rightarrow K_s^0 X, \quad (16)$$

and to compare these, where possible, to data obtained with other projectile particles, and with reactions of type (2).

Fig. 4

Table 2. Values of the coefficients from fits of the average charged multiplicity $\langle n_X \rangle = A + B (\ln s' (M_X'^2))$ and $\langle n_X \rangle = A' + B' (\ln Q'^2)$, over the whole t region, to the data for the six reactions of Figure 4. $Q'^2 = Q^2/Q_m^2$, $s' = s/s_m$, and $M_X'^2 = M_X^2/M_m^2$, where Q_m^2 , s_m , and M_m^2 are the middle values of Q^2 , s , and M_X^2 in each fit (see arrows in Figure 4). Thus, A and A' are equal to the fitted value of $\langle n_X \rangle$ at the middle point. δ and δ' are the differences between those points for each pair of reactions.

Reaction	$\langle n_X \rangle = A + B (\ln s' (M_X'^2))$			$\langle n_X \rangle = A' + B' (\ln Q'^2)$			Data from Reference
	A	B	δ	A'	B'	δ'	
(i) $\pi^- p \rightarrow X$	5.27 ± 0.03	1.42 ± 0.04	0.53 ± 0.05	5.57 ± 0.04	1.25 ± 0.06	0.27 ± 0.06	13 (a)
$pp \rightarrow X$	4.74 ± 0.04	1.40 ± 0.06		5.30 ± 0.04	1.26 ± 0.05		13
(ii) $\pi^- p \rightarrow pX$	5.69 ± 0.06	1.32 ± 0.09	0.57 ± 0.09	5.67 ± 0.06	1.30 ± 0.09	0.30 ± 0.10	5
205 GeV/c							
$pp \rightarrow pX$	5.12 ± 0.07	1.39 ± 0.09		5.37 ± 0.08	1.23 ± 0.12		3,4
(iii) $\pi^- p \rightarrow pX$	5.22 ± 0.04	1.63 ± 0.07	0.89 ± 0.12	5.28 ± 0.04	1.60 ± 0.07	0.55 ± 0.12	Our exp.
147 GeV/c							
$\pi^- p \rightarrow \pi_f^- X$	4.33 ± 0.11	1.60 ± 0.19		4.73 ± 0.11	1.40 ± 0.17		Our exp.

(a) The data of the highest two points (50 and 100 GeV/c) were taken from Refs. 21 and 22.

The dependence of $\langle n_X \rangle$ on M_X^2 for reactions (13) and (15) is shown in Figure 5, together with corresponding results for reaction (10). These data have been fitted to expressions of the form $\langle n_X \rangle = A + B (\ln M_X^2) + C|t|$, and/or $\langle n_X \rangle = A + B (\ln M_X^2)$, and the fitted coefficients are given in Table 3. As can be seen from both Figure 5 and Table 3, the $\langle n_X \rangle$ dependence on $(\ln M_X^2)$ for these three interactions are consistent with each other within the experimental uncertainties, and in fact they are consistent with the $(\ln M_X^2)$ dependence of reaction (11). Reactions (10), (13) and (15) show no significant dependence on $|t|$, while reaction (11) does.

$\langle n_X \rangle$ vs M_X^2 for reaction (16) is shown in Figure 6. This figure, and the fitted coefficient of $(\ln M_X^2)$ given in Table 3, show that the behavior of K_S^0 production is very different from the others studied. This is undoubtedly connected to the fact that, as has previously been seen, K_S^0 production appears to be sharply limited to the central region in x , and to a very narrow band in M_X^2 , while the other interactions studied in this way all have components of production in the fragmentation regions of the target or projectile.

In addition to the dependence of $\langle n_X \rangle$ on M_X^2 and t , the differential cross sections $d\sigma/dM_X^2$ and $d\sigma/dt$ are also being determined and analyzed. In particular, the triple-Regge formalism is being applied to $d\sigma/dM_X^2$ for reactions (10) and (11), and it appears that a good description of the data is obtained when parameters of a triple-Regge fit from the reaction $pp \rightarrow pX$ are used, together with the assumption of factorization of the Pomeron and Reggeons.

Fig. 5

Table 3. Values of coefficients obtained from fits to the data of our experiment at 147 GeV/c for various reactions, for expressions (i) and (ii).

$$(i) \quad n_X = A + B (\ln M_X^2)$$

$$(ii) \quad n_X = A + B (\ln M_X^2) + C |t|.$$

Reaction	Form of Fit	A	B	C	Range
$\pi^- p \rightarrow pX$ (10)	(i)	-1.7 ± 0.5	1.8 ± 0.1		$20 < M_X^2 < 200 \text{ GeV}^2$ $ t < 1.4 (\text{GeV}/c)^2$
	(ii)	-0.9 ± 0.5	1.5 ± 0.1	0.6 ± 0.3	$20 < M_X^2 < 200$ $ t < 1.4$
$\pi^- p \rightarrow \Delta^{++} X$ (13)	(ii)	-1.9 ± 0.2	1.6 ± 0.5	0.7 ± 0.9	$20 < M_X^2$ $ t < 1.0$
$\pi^- p \rightarrow X$ (15)	(i)	-2.2 ± 1.6	1.9 ± 0.3		$20 < M_X^2$ All $ t $
	(ii)	-2.3 ± 1.9	1.9 ± 0.5	0.1 ± 0.5	$20 < M_X^2$ $ t < 2.0$
$\pi^- p \rightarrow \pi_{\text{fast}}^- X$ (11)	(i)	-2.1 ± 0.6	1.6 ± 0.1		$20 < M_X^2 < 140$ $ t < 2.0$
	(ii)	-1.7 ± 0.6	1.4 ± 0.1	1.2 ± 0.2	$20 < M_X^2 < 140$ $ t < 2.0$
$\pi^- p \rightarrow K_S^0 S$ (16)	(i)	-25.3 ± 8.0	6.1 ± 1.5		$20 < M_X^2$ All $ t $

Fig. 6

(iii) Inclusive Δ^{++} Production in $\pi^- p$ Interactions at 147 GeV/c.

Inclusive production of the Δ^{++} resonance, i.e., the reaction $\pi^- p \rightarrow \Delta^{++} X$, has been intensively investigated and results have been reported in a paper submitted to the Physical Review (Section C, Ref. 255). In this experiment, the Δ^{++} has been found to be produced in comparable amounts in 4-, 6-, 8- and 10-prong events. Production cross sections have been determined by fitting the $p\pi^+$ mass distributions by the sum of a Breit-Wigner resonance shape and a third-order polynomial background, and subtracting the background from the sum. This has been done for the whole sample, and separately for events of different prong count. The results are shown in Table 4.

The distributions in rapidity and in Feynman x of the Δ^{++} are shown in Figures 7 and 8, respectively. Figure 7 shows that the Δ^{++} tends to be produced near the lowest possible center-of-mass rapidity, but note that there is no leading Δ^{++} peak apparent in the x distribution (Fig. 8).

The $|t_{p\Delta}|$ distribution for the Δ^{++} region is plotted in Figure 9(a). The unusual flatness of this distribution results from the large $t_{\min}$ values associated with the high masses recoiling against the Δ^{++} . In contrast to this flat t distribution, the distribution in $t' \equiv t - t_{\min}$ shown in Figure 9(b) has a steep exponential decrease. Fits to the form $d\sigma/dt' = Ae^{bt'}$ yield slopes of $b = 53 \pm 0.8 \text{ (GeV/c)}^{-2}$ over the range $|t'_{p\Delta}| < 0.28 \text{ (GeV/c)}^2$ and $b = 2.6 \pm 0.4 \text{ (GeV/c)}^{-2}$ over the range $0.28 < |t'_{p\Delta}| < 0.88 \text{ (GeV/c)}^2$.

Table 4. Topological distributions of events and the resulting cross sections
for Δ^{++} (1232) production in the reaction $\pi^- p \rightarrow \Delta^{++} X$ at 147 GeV/c.

Number of Charged Prongs	Number of Events with Identified Protons	$\sigma(\Delta^{++})$ in millibarns			
		Number of Events with Δ^{++} (a)	From fitting all $p\pi^+$ combinations (b)	From fitting the $p\pi^+$ combination with smallest $Y(p\pi^+)$ (b)	From fitting the $p\pi^+$ combination with smallest $Y(p\pi^+)$ and $ t_{p\Delta} < 1.0 \text{ (GeV/c)}^2$ (b)
All	2227	471 $\pm$ 60	1.61 $\pm$ 0.26	1.56 $\pm$ 0.23	1.13 $\pm$ 0.16
4	747	137 $\pm$ 31	0.38 $\pm$ 0.13	0.38 $\pm$ 0.13	0.34 $\pm$ 0.06
6	620	141 $\pm$ 29	0.45 $\pm$ 0.09	0.40 $\pm$ 0.09	0.26 $\pm$ 0.07
8	480	95 $\pm$ 30	0.39 $\pm$ 0.13	0.41 $\pm$ 0.12	0.20 $\pm$ 0.08
10	254	67 $\pm$ 26	0.40 $\pm$ 0.14	0.26 $\pm$ 0.10	0.11 $\pm$ 0.06
12-16	126	6 $\pm$ 2	0.08 $\pm$ 0.15	0.02 $\pm$ 0.12	0.06 $\pm$ 0.07

(a) Not corrected for unidentified protons.

(b) Corrected for unidentified protons.

Fig. 9

The transverse momentum squared, P_T^2 , distribution for the Δ^{++} region is shown in Figure 9(c). A fit (not shown) to the expression $d\sigma/dP_T^2 = A'e^{-b'P_T^2}$ over the range $P_T^2 < 0.2 \text{ (GeV/c)}^2$ yields a slope of $b' = 6.7 \pm 0.5 \text{ (GeV/c)}^{-2}$. This is essentially the same as the slope b obtained above for the t' distribution. Similar t' and P_T^2 slopes have been found for Δ^{++} production in π^-p interactions at other energies,²³⁻²⁵ as well as in pp interactions.²⁶

The breaks seen in the 205 GeV/c P_T^2 and t' distributions²⁶ are apparent in our data as seen in Figure 9, but our data for both distributions are also consistent with single straight lines. The break in P_T^2 in Figure 9(c) appears to occur near 0.1 (GeV/c)^2 . The slope obtained for $P_T^2 < 0.12 \text{ (GeV/c)}^2$ is $b' = 7.8 \pm 1.0 \text{ (GeV/c)}^{-2}$, while for $0.2 < P_T^2 < 0.8 \text{ (GeV/c)}^2$, the slope is $4.4 \pm 0.4 \text{ (GeV/c)}^{-2}$. When the slopes are determined over the wider ranges $|t'| \leq 1.2 \text{ (GeV/c)}^2$ and $P_T^2 < 0.8 \text{ (GeV/c)}^2$, we obtain the slopes $b = 3.4 \pm 0.3 \text{ (GeV/c)}^{-2}$ and $b' = 5.7 \pm 0.3 \text{ (GeV/c)}^{-2}$.

The cross section for the inclusive production of Δ^{++} in pp interactions for seven experiments at momenta between 12 and 400 GeV/c has been found to vary as $p_{\text{lab}}^{-0.29 \pm 0.03}$.²⁶ Fewer measurements have been made of the Δ^{++} cross sections for π^-p interactions. Those measurements which are available have been extracted under such different conditions that a study of the energy dependence is difficult. A summary of the cross sections obtained at various energies and the conditions of measurement are given in Table 5.

The energy dependence for the four methods of extraction of the signal is as follows:

- (1) The cross section obtained by fitting the total distribution

Table 5. Cross sections (in millibarns) for Δ^{++} production in the reaction
 $\pi^- p \rightarrow \Delta^{++} X$ under various conditions of extraction.

	Incident Momentum				
	11.2 GeV/c [23]	15 GeV/c [24]	16 GeV/c [25]	147 GeV/c This experiment	205 GeV/c**
(1) Fit to total distribution		$1.3 \pm 0.1^*$		1.61 ± 0.26	
(2) $ t < 1.0 \text{ (GeV/c)}^2$ and $1.12 < M(p\pi^+) < 1.32 \text{ GeV}$		$1.03 \pm 0.11^\dagger$		1.24 ± 0.07	1.19 ± 0.1
(3) $ t < 0.6 \text{ (GeV/c)}^2$ and $1.12 < M(p\pi^+) < 1.36 \text{ GeV}$			$0.71 \pm 0.05^\dagger$	0.85 ± 0.06	0.8 ± 0.1
(4) $x(\pi^+) < 0$ and $x(p) < 0$ and $1.12 < M(p\pi^+) < 1.32 \text{ GeV}$		$2.1^\dagger$		2.25 ± 0.09	

† Extracted from information given in the referenced paper.

$*$ Unpublished data, M. I. T.

** H. H. Bingham et al., LBL-3855 preprint, May 1975.

to an appropriate Breit-Wigner shape over a smooth polynomial background is the same (1.3, 1.6 mb) within errors at 15 and 147 GeV/c.

(2) The cross section for $p\pi^+$ combinations having $|t_{p\Delta}| < 1.0 \text{ (GeV/c)}^2$ and a mass between 1.12 and 1.32 GeV appears constant within errors at 1.0-1.2 mb at the momenta indicated, which range from 15 to 205 GeV/c.

(3) The cross section for $p\pi^+$ combinations having $|t_{p\Delta}| < 0.6 \text{ (GeV/c)}^2$ and a mass between 1.12 and 1.36 GeV appears constant within errors at 0.7 - 0.85 mb at momenta ranging from 16 to 205 GeV/c.

(4) The cross section for $p\pi^+$ combinations having negative Feynman x for both the proton and the π^+ of the Δ^{++} , and a mass between 1.12 and 1.32 GeV, is the same within errors (2.1, 2.25 mb) at 11.2 and 147 GeV/c.

Thus we conclude that, independent of the method of extraction, the Δ^{++} cross section is consistent with being constant from 15 to 205 GeV/c in πp interactions. The cross sections extracted from the fits (method 1) are more reliable since a mass cut includes a substantial amount of background. Comparing these results with those shown for pp reactions in Figure 5 of Reference 26, we observe that: (1) both reactions are consistent with energy independence at high energies ($p_{\text{lab}} > 50 \text{ GeV/c}$); and (2) the energy independence of the Δ^{++} cross section extends to lower energies in $\pi^- p$ reactions than in pp reactions.

The data thus far presented indicate that the Δ^{++} production process is consistent with a one-pion-exchange (OPE) model: The $t'_{p\Delta}$ and P_T^2 distributions are exponentials with steep slopes, and the x -distribution of the Δ^{++} has a steep rise near $x = -1$ and a broad maximum near $x = -0.85$,

consistent with triple-Regge predictions for $\pi\pi$ -Pomeron and $\pi\pi$ -Reggeon couplings.²⁷ In addition, we have found the spin density matrix elements to be consistent with absorptive OPE in the triple-Regge model.²⁸

On the other hand, we also have evidence that the Δ^{++} is sometimes, at least, produced as the product of a system of higher mass. For example, the effective mass of the $\Delta^{++}\pi^-$ system, shown as the unshaded histogram in Figure 10(a), has a low-mass enhancement typical of diffractive phenomena.^{29,30} The shaded histogram in Figure 10(a) is the effective mass of all $p\pi^+\pi^-$ combinations such that the $p\pi^+$ mass is in the Δ^{++} region, the $p\pi^+$ rapidity is the lowest in the event, and the π^- is the lowest-rapidity negative meson in the event; here the low-mass enhancement is more prominent, with relatively few events above 3 GeV. This latter histogram is displayed by topology in Figures 10(b) - (e). The shapes of the distributions are the same for all topologies, suggesting that a large fraction of the Δ^{++} in all topologies might be the decay product of a higher mass system. To find the fraction of Δ^{++} possibly produced in conjunction with a low-mass $\Delta^{++}\pi^-$ system, we show in Figure 11 the effective mass of the lowest-rapidity $p\pi^+$ combination for each event in which any π^- formed a low-mass (less than 2.68 GeV) $p\pi^+\pi^-$ system with this $p\pi^+$. The shaded histogram of Figure 11 is the effective mass of the lowest-rapidity $p\pi^+$ combination for each event in which no π^- formed a low-mass $p\pi^+\pi^-$ system with the $p\pi^+$. Over 90% of the Δ^{++} are associated with a low-mass $\Delta^{++}\pi^-$ system with mass less than 2.68 GeV.

The two apparently contrasting views of Δ^{++} production, i.e., production via OPE, or production via target fragmentation into $\Delta^{++}\pi^-$, are both compatible with a diagram of the sort shown in Figure 12. In this diagram the production of the $\Delta^{++}\pi^-$ system is represented by the exchange of an effective Regge

Fig. 10

Fig. 11

Fig. 12

trajectory α , and the interaction between the Δ^{++} and the π^- is represented by an amplitude M . The amplitude M for the $\Delta^{++}\pi^-$ low-mass enhancement should contain a term for pion exchange and a term for N^* production, perhaps similar to the amplitudes found in diffractively produced nucleon-pion low-mass enhancements, (i.e., when α is the Pomeron trajectory and X is a single π^-) at other energies.³¹ Some authors have replaced the amplitude M by an effective trajectory of α' ,³² using a triple-Regge formalism, and conclude that at least two trajectories having different t -dependences are needed, or at least two terms are needed in the amplitude M . It is well known from studies of a Deck model³³ or a double-peripheral model³⁴ that, when a π is exchanged at the lower vertex of the diagram (i.e., when α' is the pion trajectory), a kinematic low-mass enhancement results between the two particles at the bottom of the diagram, which are the Δ^{++} and π^- in this case.

It is interesting to note that a theoretical attempt has been made to describe properties of inclusive Δ^{++} production by assuming that the Δ^{++} is a decay product of a diffractively produced system.^{35,36} Using a sum of diffractively produced N^* 's and the Mueller-Regge formalism, the authors of Reference 35 were able to reproduce the observed $\Delta^{++}\pi^-$ low-mass enhancement, the x and the steep p_T^2 distributions of the Δ^{++} , as well as other features of the production data.

b) A Study of π^+p , pp and π^-p Interactions at 147 GeV/c
in the Proportional Wire Chamber-Bubble Chamber Hybrid
System (FNAL Experiment 299).

The primary purpose of this experiment is to study the characteristics of high energy interactions as a function of the quantum numbers of the incident projectile particles: π^+ , p , K^+ , and π^- .

This experiment was originally approved for 600,000 pictures, with probable extension to 1.2 million pictures. The first 158,000 frames were obtained in a beam of positive particles, divided approximately equally between π^+ mesons and protons, with only a small number of K^+ .

An enrichment of the K^+ component of the beam to about 10 percent was achieved for the second positive beam run, which took place at the end of 1976. The linking of the electronic data with the tracks in the bubble chamber allows us to use the upstream Cerenkov signal to identify each interacting beam particle, so that we obtain data simultaneously for all the kinds of particles present in the beam, and can make comparisons with a minimum of systematic errors.

The second run was further enhanced by the use of a prototype of the forward gamma detector planned for future exposures. This prototype is full scale except for area, which is 30 cm x 30 cm in cross section rather than the final 75 cm x 75 cm. This prototype data will allow us to analyze the forward-going electromagnetic radiation produced in the observed interactions, within the small solid angle subtended.

The second run consisted of about 240,000 pictures. All of the original

158,000 frames, and over 60% of the film of the second run, have been scanned and predigitized, and precision measurements are well under way.

Our film analysis procedures have been considerably refined on the basis of our experience with E-154. In addition, considerable effort has been put into the improvement of the geometry programs which reconstruct the bubble-chamber events in space, and which link the trajectories of the outgoing tracks in the chamber with their continuations in the downstream counter system.

c) The Argonne π^+p Bubble Chamber Experiment.

During the past year the last events of this study of π^+p interactions at 4.1 GeV/c were processed through the MIT PEPR system. Initially, the 395,000 pictures of this exposure were scanned and measured only for four-pronged events and for those with 2-prongs plus a V^0 . This sample was chosen in order to examine in detail the possible split nature of the A_2 meson.

Later the remaining events on the film were scanned, IPDed, and finally PEPRed in order to complete our investigation of quasi-two-body reactions and resonance production at 4.1 GeV/c. Linnea Dunn and Martin Heller have been working during the year on PEPRing the final events, and Heller has begun analyzing the data for his Ph.D. thesis. Thus far he has been primarily investigating the one-constraint final state $p\pi^+\pi^0$.

The predominant quasi-two-body channels for this final state are:

$$\pi^+ p \rightarrow p \rho^+ \text{ and } \Delta^{++} \pi^0 .$$

These channels are obscured, however, by the diffractive dissociation of the target proton, the $\Delta^{++} \pi^+$ channel, and general phase space production of single π^0 's, as well as misidentified cases of elastic scattering and multiple π^0 production.

In order to be able to separate the competing channels as clearly as possible, a careful study of different techniques was begun. The prism plot method developed by the MIT group³⁷ and the cluster-recognition method of Ludlam and Slansky³⁸ have been investigated thus far. Of these, the former appears to be better suited for the separation of three-body states. A preliminary analysis using the prism plot method on about one-half of our total data yields the cross sections listed in Table 6. Also listed on this table are essentially all the results published on this reaction over the momentum range from 3.6 to 16 GeV/c. Our values are quite consistent with the general trends, but notice that there are some wild fluctuations in the table for this relatively simple reaction. Clearly, more precise and definitive values are needed.

The best possible separation of the channels is important not only to determine the correct cross sections, but also for the detailed study of the dynamics of particular channels. Using the same data sample as above, we have been attempting to fit the data for the $p \rho^+$ and the $\Delta^{++} \pi^0$ reactions by a wide variety of theoretical models.

Table 6

A Comparison of Channel Cross Sections at Various Energies
for the Reaction $\pi^+ p \rightarrow p \pi^+ \pi^0$ (in microbarns)

Beam Momentum	Total σ	Phase Space	$p p^+$	$\Delta^{++} \pi^0$	$\Delta^+ \pi^+$	Diff. Diss.	Ref.
3.6	2510±200		800±60	430±30			a
3.9	2300±60	40±20	850±40	420±30	230±40	400±50	b
4.0	2310	1550±310	520±99	350±70			c
4.1	1900±40	580±40	750±30	220±20	100±20	250±20	d
5.0	1300±30		430±20	220±10	100±10		e
5.5				176±20			f
8.0	740±60		141±10	110±8			g
18.0	352± 5	1±0.3	59± 2	55±2	25± 1	176± 3	h

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To date, a duality model of Harari's,³⁹ called the dual absorptive model, appears to fit the characteristics of both of these reactions the best, with vector mesons being exchanged in the t-channel. Rho-meson exchange appears to dominate the Δ^{++} production, and omega exchange appears predominant in the pp^0 reaction. This study is continuing and should be concluded during the coming year.

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II. Experimental Runs in Progress and in Preparation.

a) High Statistics Study of π^0 Production in 150 GeV/c π^-p Interactions (FNAL Experiment 393).

As described last year, this experiment was approved for 400,000 pictures. The Forward Gamma Detector was designed for use in this experiment, to yield, for the first time, accurate π^0 and γ information correlated with other bubble chamber and proportional wire chamber data for charged particles from π^-p interactions. In addition, the experiment was designed to allow further study of a possible new phenomenon we had observed in E-154, in which unexpected large amounts of forward-going electromagnetic radiation were found associated with two-prong interactions.

Much effort and expense have gone into the construction of the Forward Gamma Detector during the past year (see subsection d, below) following the successful testing of the prototype described last year, and reported in several contributed papers (see Section C, References 260, 261, and 262).

In spite of the new areas of physics to be explored by this experiment, and in spite of the commitment of interest, enthusiasm, time, money, and energy by the experimenters, and in spite of Fermilab's commitment to the experimenters as evidenced by the Laboratory's approval of the experiment, this approval was withdrawn without prior notice or discussion during the summer of 1977. This was part of a blanket action, in which approval of all experiments scheduled for the hybrid system was withdrawn. At the same time, Fermilab indicated that it would strongly support experiments with the hybrid system, with the addition of the charged particle identifier in the downstream system.

This support has been reiterated and reemphasized in the strongest terms in subsequent discussions between our Consortium and Fermilab. Fermilab has made a definite commitment to take two million pictures with the improved hybrid system starting in the fall of 1978. In view of this, and of our strong interest in the production of π^0 's and other particles which decay into photons, we have submitted a new proposal to Fermilab. This new proposal, P-570, described in the next section, combines features of E-393 and FNAL Proposal 488, submitted in May 1976, for a study of heavy particle production and dynamics near $x = 0$, as a function of incident particle quantum numbers.

b) Proposal for the Study of Particle Production and Dynamics as a Function of Incident Particle Quantum Numbers (FNAL Proposal 570).

This is a proposal for a comprehensive experiment to examine the dynamics of hadron production for a variety of incident particles.

The primary object of this experiment is the study of the production characteristics of particles and resonances in interactions with target protons, and to study the dependence of these characteristics on the quantum numbers of the projectile particles. Such dependences may be a direct consequence of the kinematic distribution of quarks in the incident channel, and so can give information on the structure of the interacting particles.

The hybrid system is being upgraded for the purposes of this and future studies, by the addition of instruments in the downstream system

for the identification of charged particles (ISIS) and for the measurement of electromagnetic decays of forward-going neutral particles (FGD). Specifically, we propose a study of the production of $\pi^0, \pi^\pm, \Lambda^0, K_S^0, K^\pm, p$ and $\bar{p}$ in multiparticle final states, with tagged positive and negative beams of 200 GeV/c momentum incident on protons in the 30-inch bubble chamber. The positive beam will be composed of approximately 10% K^+ , with the remainder consisting of approximately equal numbers of π^+ and protons, while the negative beam will consist of about 20% $\bar{p}$ and 80% π^- . The use of these tagged beams will enable us to study the dependence of the interaction characteristics on the quantum numbers of the incident particles, with minimum systematic errors and minimum set-up time.

Some specific topics are listed here, and are described in somewhat more detail in the accompanying Renewal Proposal:

(i) Single-particle distributions for identified charged and neutral particles.

(ii) Multiplicity studies, in reactions of the type $a + b \rightarrow c + X$, where a and c take on many identities in this single experiment, as well as in interactions of the type $a + b \rightarrow X$.¹

(iii) Correlation studies,²⁻⁵ including the question of neutral-charged particle correlations about which little is known. Questions of local conservation of transverse momentum, strangeness and other quantum numbers will be checked in a definitive way, not possible when only charged particles are identified.^{6,7}

(iv) A systematic study of resonance production in the inclusive reactions

$$\begin{pmatrix} \pi^{\pm} \\ K^+ \\ p^{\pm} \end{pmatrix} + p \rightarrow \begin{pmatrix} \eta^0 \\ \rho^{\pm}, \rho^0 \\ K^{*\pm}, K^{*0} \\ \phi^0 \\ \omega^0 \\ \Delta^{++}, Y^* \end{pmatrix} + X.$$

Of these reactions, only those leading to ρ^0 and Δ^{++} have been studied in any detail at Fermilab energies. The connection of resonances with clusters will be clarified.^{8,9}

(v) Four-constraint fits extended to events with one, two and even three π^0 's and events with charged K's.

(vi) Investigation of the large amounts of forward-going neutral energy observed in our experiment E-154 in low multiplicity events.

In addition, some more speculative areas include:

(vii) A search for a possibly new phenomenon where both projectile and target end up near $x = 0$.¹⁰

(viii) A search for new particles that decay into one or more heavy particles and several pions.

(ix) A study of pairs of identical heavy particles to compare with the Bose-like behavior seen in identical pion pairs.

c) A Study of the Detailed Characteristics of Hadron-Nucleus Collisions Using the Fermilab Hybrid Spectrometer (Fermilab Proposal 565).

This proposal was submitted to Fermilab in May 1977, and was expected to come up for consideration in the Fall. Its fate is uncertain, to say the most, in the light of the withdrawal of approval of previously approved hybrid experiments. We plan to press for consideration of this proposal.

Previous experiments^{11,12-15} have indicated that the nucleus provides a powerful tool for the study of strong interactions, particularly for the investigation of the nature of the state of hadronic matter that exists between the instant of collision of two hadrons and the final production of particles.¹⁶ Many efforts have been made to interpret the general features of multiparticle production in hadron-nucleus interactions in terms of parton models; at present, existing data are inadequate to distinguish among these models.¹⁷⁻²⁰

We are proposing, therefore, to study with precision the dependence on incident particle, energy, and target of multiparticle production in hadron-nucleus collisions. Metallic foils of aluminum, silver and gold placed within the 30-inch chamber will be used as targets; and the hybrid bubble chamber spectrometer with the downstream particle identifier will be used as the detector.

For each target and each incident particle and energy, the A dependence of the average multiplicity and the rapidity distributions of outgoing particles will be investigated. The hybrid system will provide 4π coverage, good spatial resolution of tracks, good momentum measurements

up to the highest energy, as well as particle identification of pions, kaons and protons. The visual observation of the interaction vertex in the bubble chamber will keep systematic errors at a minimum, allowing a one percent determination of multiplicities. This is essential for a definitive test of the models which have been developed. The hybrid spectrometer will measure the true rapidity distribution of the secondary particles, unlike other experiments which have yielded only the pseudo-rapidity.

In addition, it will be possible to detect and study the decays of associated strange particles as a function of A . This will be the first comprehensive study of this subject.

Data will be taken with protons of the highest energy available at the time of the experiment, and in a positive secondary beam of pions and protons at half that maximum energy, to give both a dependence on energy and a dependence on incident particle quantum numbers. All the target foils will be in place at one time, so that data for Al, Ag and Au, as well as for hydrogen, will be obtained simultaneously.

This experiment is described in somewhat more detail in the accompanying Progress Report.

d) Improvements in the Hybrid System.

The experiments described in Sections a) - c) above all depend on one or the other, or both, of two new instruments which will greatly enhance the analytic power of the hybrid system. These are the photon detector and the downstream charged particle identifier. Figure 1 shows the proposed layout of the advanced downstream system including a two-module ISIS (I1,I2) system for charged particle identification and the Forward Gamma Detector (FGD). Drift chambers are shown in place of the proportional wire chambers used heretofore. These will increase both the momentum and solid angle acceptances of the downstream system, particularly in the intermediate momentum range from 5 to 40 GeV/c.

At the Particle Identifier workshop held at Fermilab May 7-8, 1976,²¹ agreement was reached by the bubble chamber community to a proposal which would provide for identification of charged particles produced in the central region (5 - 50 GeV/c) and for "leading particles" (50 - 100 GeV/c).

The momentum region 5 - 50 GeV/c is to be covered by an ISIS system, while the higher momentum region is to be covered by a multi-cell Cerenkov detector. The FGD and the Cerenkov detector cannot be in place at the same time, so both are to be mounted on rails for easy interchange.

Our Consortium has been working on the FGD for some time, and we have taken the responsibility for developing and building the ISIS system also. Progress on these detectors is described below:

(i) Forward Gamma Detector.

Downstream Hybrid Spectrometer System

Fig. 1

This detector consists of three parts -- a converter, a vertex locator, and an absorber.

The converter itself consists of four radiation lengths of lead glass, rather than lead sheet, to initiate the showers. This thickness insures that at least 99% of all incident photons will induce showers in the converter. At this depth, the number of shower particles will be at least half the maximum, providing a good signal in the scintillator hodoscope -- the vertex locator -- which is situated directly behind the converter. This hodoscope consists of three planes of plastic scintillator "fingers", made of elements 1 cm thick and 1.5 cm wide. The central plane of fingers is oriented vertically, while the other two planes are set at $+45^\circ$ and -45° respectively. This hodoscope establishes the spatial characteristics of the shower, so the shower centroid can be determined. Immediately downstream of the hodoscope is the absorber, consisting of 24 additional radiation lengths of lead glass, to ensure full absorption of the shower energy.

Since all the elements of the FGD are active, the total energy of each shower, from initiation in the converter to full absorption in the absorber, is measured.

The active area of the device is 75 cm x 75 cm. With the detector center 7 meters downstream of the bubble chamber center, we will be able to detect photons within approximately 50 mrad of the beam line. The minimum and most likely angle between the two γ 's from π^0 decay is

$$\sin(\theta/2) = \frac{m_{\pi} c^2}{E_0}.$$

$$\therefore, \quad \theta \approx 0.27/E_0 \text{ radians,}$$

where E_0 is the π^0 energy in GeV.

As described in last year's Progress Report, extensive tests have been carried out with a prototype of the FGD. This prototype had an effective area of 30 cm x 30 cm, and had the total depth of lead glass of the full FGD in the three components. It was tested with tagged electron beams of measured mean energy ranging from 26 to 103 GeV, and results showed that electromagnetic shower energies could be determined with a full width at half maximum resolution of $\delta E/E = 0.27/\sqrt{E}$, and that the shower centers could be located within a standard deviation of about 1.4 mm. The test results have been presented in contributed papers (Section C, 260 to 262), and an instrumentation paper describing design and performance in detail is being prepared.

All the components of the full scale FGD have been constructed, the scintillator hodoscope by our Italian collaborators, and the converter and absorber by American members of the Consortium. The assembly and preliminary testing of the complete instrument at Fermilab have been in progress since July 1977. Professors Shapiro and Widgoff each spent about two weeks working on the FGD at Fermilab between July 15 and August 15. Beam will be available for tests of the device starting about mid-October. Professors Shapiro and Widgoff, and Dr. Brick, all plan to spend substantial amounts of time at Fermilab working on the beam tests.

(ii) Identification of Charged Particles by Ionization Sampling (ISIS).

ISIS (Identification of Secondaries by Ionization Sampling) makes use of the relativistic rise of ionization loss, dE/dx , to distinguish among particles of different mass.²² This rise is due to the effect of the relativistic expansion of the transverse electric field of a moving particle. Figure 2 shows the calculated dependence of dE/dx on particle momentum p for pions, kaons and protons, in a mixture of Argon and CO_2 at atmospheric pressure.²² The difference in expected dE/dx for the different particles is 10% or more over the range from 5 GeV/c to about 100 GeV/c. Above 100 GeV/c, the curves all tend to the same plateau level, as the polarization of the medium screens the electric field at large impact parameters.

Individual measurements of energy loss are subject to large fluctuations, and so it is necessary to make many measurements of dE/dx along a track in order to achieve the required resolution of a few percent. A series of such measurements along a track will be distributed in a Landau distribution; the peak positions for different tracks will correspond to their relative ionizations and their widths to the expected resolution. This expected resolution depends both on the statistics of the amount of ionization in each sample, and on the number of samples.

Detailed design studies have been carried out during the past year, to determine the optimum dimensions and structure of the Fermilab ISIS. A two-module system is planned, as shown in Figure 1. ISIS-1 is 1 meter long, with its entrance plane at $x = 2.375$ m ($x = 0$ at the center of the bubble chamber) and ISIS-2 is to be 2 meters long, with its entrance plane

Fig. 2

at $x = 3.6$ m. The dimensions in the y and z directions will be $1 \text{ m} \times 1 \text{ m}$, and the wires will be parallel to the z direction, the direction of the bubble chamber magnetic field.

Calculations have been done for the Fermilab ISIS with a maximum of 192 samples, yielding an expected peak width of 8.1% FWHM. Figure 3 shows the expected ionization-loss distribution in ISIS for 20 GeV/c protons, kaons and pions, where the assumed ratio of numbers of particles is $\pi:K:p = 10:1:1$. Similar plots were generated for other particle momenta, and particle identification as a function of momentum was estimated from these figures by making two partitions in mean ionization loss, one corresponding to the point where a particle is as likely to be a kaon as a proton, and one corresponding to the point where a particle is as likely to be a kaon as a pion. All particles with a mean ionization loss less than the first partition are identified as protons, and all particles with a mean ionization loss greater than the second partition are identified as pions. The remaining particles, with ionization loss between the two partitions, are identified as kaons. The efficiency of ISIS for identifying protons is $> \sim 80\%$ for the momentum range from 5 to 80 GeV/c. The percentage of kaons which are correctly identified falls from 75% at 7 GeV/c to 50% at 43 GeV/c. Some improvement of the particle identification may be possible if one uses the width of the dE/dx distribution, as well as the mean.²³ This possibility is being studied.

The first module of ISIS is now being assembled. After preliminary testing at MIT it will be shipped to Fermilab at the beginning of October. It is scheduled for beam tests beginning in late October 1977.

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23. Time Projection Chamber Group Proposal to PEP.

III. Associated Matters.

Dr. David Brick traveled to CERN this past January, acting as a courier between the American members and the European members of the Consortium. Six American couriers and six European couriers travel across the Atlantic each year, at roughly one month intervals, in order to coordinate the work of the group. Dr. Brick worked two weeks at CERN, during which considerable time was spent, together with many European members, on the development of a new series of programs for the reconstruction of bubble chamber-hybrid system events.

Mr. Donovan Lewis joined our group this year as a Research Assistant. His primary duty is to conduct the flow of the data handling and processing smoothly through all stages from the initial scanning and measuring to the production of a final Data Summary Tape. He also acts as a supervisor for the scanners and will help operate the MIT PEPR system when needed.

Professors Shapiro and Widgoff are spending approximately four weeks each this year at Fermilab helping to assemble and test the forward gamma detector and the ISIS detector. Dr. Brick will also help with the tests in December.

IV. Scientific Personnel Associated with the Bubble Chamber-Hybrid System Program.

A. M. Shapiro	--	Professor
M. Widgoff	--	Professor
D. H. Brick	--	Research Associate
D. Lewis	--	Research Assistant
L. Dunn	--	Graduate Research Assistant
M. Heller	--	Graduate Research Assistant

B. Electronic Detector and Spark Chamber Program.

I. Data Analysis in Progress.

a) A $\bar{p}p \rightarrow$ Bosons (in the T and U-mass region)
AGS Spark Chamber Experiment (AGS #527).

The physics of this experiment (and AGS #622, mentioned below) is primarily directed to searching for high mass high spin bosons, however it is also very closely related by crossing symmetry to that of backward scattering experiments. Typical reactions are $\bar{p}p \rightarrow \pi^0\pi^0$, $\eta^0\eta^0$, $\pi^0\eta^0$, π^0f^0 . The point of the experiment is to study the angular distributions of these reactions as a function of incident antiproton energy. The energy region involved permits the study of the mass range up to 2500 MeV. This range continues to be a very perplexing one in particle physics as there are persistent suggestions for at least eight mesons of as yet undetermined quantum numbers. The explicit nature of the quantum numbers in the final states mentioned above, together with an analysis of their angular distributions will permit unambiguous determination of the parameters for any of these heavy mesons if they indeed exist. In addition, by crossing symmetry, these final states are closely related to backward meson scattering, the interchange of the roles of the s- and t-channel resonances and Regge trajectories in these processes presents an ideal situation in which to study the predictions of models involving "duality" such as the Veneziano model.

Approximately 750K total photographs were taken for this experiment. These pictures being evenly divided for scanning and measuring amongst the collaborators -- Bari (Italy), Brown and MIT.

Our first scanning and measuring indicated we might expect angular distributions at the lower mass range containing roughly 500 events each in the

channel $\bar{p}p \rightarrow \pi^0\pi^0$ with a mass resolution of 8 MeV or with higher statistics with somewhat coarser binning. The mass interval covered is continuous from 2080 MeV to 2580 MeV and since the cross section is falling as a power of s there are fewer events at the higher masses. Although no experiment has been done previously on $\pi^0\pi^0$ (or other neutral non-strange channels) this one has nearly a factor of 5 improvement over the mass resolution in a related $\bar{p}p \rightarrow \pi^+\pi^-$ experiment. In addition to $\pi^0\pi^0$, we have determined from our electronic rates that there are roughly 250 microbarns in other channels leading to two or more gamma rays in the final state. These could be from $\pi^0\eta^0$, $\pi^0\omega^0$, π^0f^0 , $2\pi^0\omega^0$, as well as from simple phase space. This cross section corresponds to about ten times that in $\pi^0\pi^0$ and so, although more difficult to analyze, are expected to provide adequate angular distributions even with severe kinematic cuts. If resonances occur these data will provide branching ratios and additional isospin information.

We have pointed out previously the complete extraction of all of the physics which it is possible to study in this film is a formidable task because of the high gamma ray multiplicity and the large number of energy steps. Consequently, we adopted the strategy early in our analysis that we would concentrate first upon the reactions $\bar{p}p \rightarrow \pi^0\pi^0$, $\pi^0\eta^0$ and $\eta^0\eta^0$ which require measurement of multiplicities of 1 through 5 gamma rays. Also we decided to begin by an energy selection which "clumped" the energies but distributed the clumps over the full energy range. Proceeding in this way we have completed nearly all of the data at Brown. We are in a situation which is now routine production for the entire data processing chain -- scanning through computing. Last year at this time we reported results at thirteen energies. We now have results at twenty-four energies. At many of these energies this represents all

of the data in the channels discussed however at the remaining energies there is more data to come from our colleagues in Italy. The data so far are of two types in three channels:

- a) partial cross sections as a function of incident antiproton momentum in $\bar{p}p \rightarrow \pi^0\pi^0$, $\pi^0\eta^0$, and $\eta^0\eta^0$,
- b) differential cross sections at each momentum for $\bar{p}p \rightarrow \pi^0\pi^0$ and $\pi^0\eta^0$.

Before discussing our understanding thus far of the significance of these data we briefly point out that the features of the data are generally smoothly falling partial cross sections in $\pi^0\pi^0$ and $\pi^0\eta^0$, although the possibility of very narrow structure is not completely ruled out yet (we return to this point below) but a comparatively flat partial cross section for $\eta^0\eta^0$. The first of these cross sections are shown in Figures 1; the $\bar{p}p$ total cross section¹ is shown in Figure 5 and the $\bar{p}p \rightarrow \pi^+\pi^{-(2)}$ is shown in Figure 6 for reference.

Considerable progress has been made on the analysis of this experiment during the past contract interval. Data at new energies has continued to come in from scanning-measuring and to be added to our energy dependent study. As has been previously discussed our strategy has been to distribute the energies being scanned and measured at any one time so that the full range was always covered but in a finer grid as time progressed. We now have processed at least half and usually all Brown data at every energy point.

Table I shows the measured cross sections at each of the energies for $\bar{p}p \rightarrow \pi^0\pi^0$. They are plotted in Figure 1. The Legendre polynomial coefficients which were obtained by fits of Legendre series to these angular distributions as a function of energy are shown in Figures 1 and 2 and are listed in Table II.

Largely because of the presence at Brown this past year of Professor D. C. Peaslee we have made good progress toward an amplitude analysis of these data based upon a model suggested by the data and containing several resonances.

Briefly, the method utilizes conventional amplitude analyses but in which partial waves believed to contain resonances are parametrized by Breit-Wigner double level formulas as well as single level ones. Because of the striking nature of the angular distributions -- they possess relatively stable minima and maxima where the minima have nearly zero cross sections -- interference between (or dominance of) pure angular momentum states with little and smoothly varying background is suggested. Starting values are chosen to be those suggested by the position of structure in the highest Legendre polynomial coefficient coupled with the observation as to whether the positions of minima in the angular distributions are suggestive of helicity-flip or non-flip dominance. In addition, different representations which emphasize maximal magnitudes possible for the amplitudes resulting from interference of two angular momentum states are used. This analysis approach is well underway and has been applied to each of the coefficients in $\bar{p}p \rightarrow \pi^0\pi^0$. Using these results as new starting values a more global, simultaneous fit to all the coefficients is in progress.

It is possible, however, to give some preliminary results from the work so far which we believe are probably conclusive.

- a) We have no strong evidence for narrow resonances; however, we may have evidence for several broad (~ 200 MeV) resonances. Recently, at CERN, in production experiments⁽³⁾ (e.g., $\pi^-p \rightarrow p$ (fast forward) + $N\pi$ + x , $x \rightarrow \bar{p}p$) narrow structures have been seen at x masses

of 2.02 , 2.2 , and $2.9 \frac{\text{GeV}}{c}$. Data from our experiment, previously published in Phys. Letts 57B (1975), 189 bears on the possible narrowness of the $2.2 \frac{\text{GeV}}{c}$ state. It is interesting to note that all of the CERN evidence so far are in states involving antiprotons-- but not their annihilation -- thus they may be candidates for baryonium⁽⁴⁾ in some models. Their absence in pure annihilation states such as ours could be important⁽⁵⁾.

- b) In particular, we believe we have established an $I = 0$ resonance in $J^P = 4^+$, $M = 2350 \pm 60$ MeV, $\Gamma = 190 \pm 60$ MeV with $\gamma_{\ell=5}/\gamma_{\ell=3} = -0.5$. The γ 's are the reduced partial widths for the entering $\bar{p}p$ orbital angular momentum states. The evidence comes from the fact that the highest, required Legendre coefficient is A_8 , that the spin-flip contribution is very small, and the structure in A_8 (see Figure 2) is well fitted by this hypothesis. The parameters of this resonance are in good agreement with fits obtained by the Rutherford Laboratory -- Queen Mary College Group⁽²⁾ in their study of $\bar{p}p \rightarrow \pi^- \pi^+$.
- c) Also established is a strong $J = 2$, $J = 4$ interference below 2290 MeV with the $J = 4$ resonance mentioned above excluded as a source. Our current interpretation (subject to completion of our full amplitude analysis) is that the "H"-meson ($J = 4^+$, $M = 2050$ MeV) interfering with either a $J = 2^+$ resonance of similar mass or non-resonant $J = 2$ background is responsible. The evidence for this derives primarily from the maximal negative value of A_6 (see Figure 2), the smallness of our $M = 2350 \frac{\text{MeV}}{c}$ resonance, the smallness of the spin flip amplitudes, and the general structure of A_2 and A_4 .

- d) We have separated the isotopic spin 0 and 1 contributions to $\bar{p}p \rightarrow \pi\pi$. If we let $\sigma_{00} \equiv$ cross section for $\bar{p}p \rightarrow \pi^0\pi^0$, $\sigma \equiv$ cross section for $\bar{p}p \rightarrow \pi^+\pi^-$, $\sigma_1 \equiv I = 1$ cross section, and $\sigma_0 \equiv I = 0$ cross section then

$$\sigma_0 = 3\sigma_{00}$$

$$\sigma_{+-} = \sigma_1 + \frac{2}{3}\sigma_0$$

This experiment alone measures σ_0 directly. The Rutherford -Q.M. group measure σ_{+-} . We have combined these data and extracted the σ_0 and σ_1 cross sections. The result is shown by the points in Figure 3. The Rutherford -Q.M. have done an amplitude analysis of $\frac{d\sigma}{d\Omega}(\pi^+\pi^-)$, from this they have provided us with the fractions of $J = 0, 1, 2, 3, 4$, and 5 contributions to $\frac{d\sigma}{d\Omega}(\pi^+\pi^-)$, using these we have calculated $I = 0$ and $I = 1$ "predicted" curves also shown in Figure 3. While the general magnitudes agree, in detail they are quite different; in particular the curves give an excess in $I = 0$ and a deficit in $I = 1$, relative to our data.

Also using their amplitudes we can predict the $\hat{\pi}^0\hat{\pi}^0$ angular distributions at selected energies and subject them to comparison with our measured data. Again, the results are qualitatively similar but clear disagreements exist on forward peaks. This is due chiefly to $J = 2, J = 4$ interference on which they have no evidence. This comparison is shown in Figure 4.

- e) Our early observation that the ratios of the cross sections $\pi^0\pi^0, \pi^0\eta^0, \eta^0\eta^0$ is 1:1:1 is still maintained.

PI PI CROSS SECTION IN MICROBARNES.

DATE 08/14/77

NOMINAL PLAB	CORRECT PLAB	C.M. ENERGY	GOOD TRIG	RATE FULL	RATE EMPTY	CROSS SECTION	ERROR
1.140	1.125	2.124	7366.	1.335	0.095	49.5	3.3
1.170	1.155	2.134	7920.	1.311	0.095	44.9	3.0
1.200	1.184	2.144	5201.	1.286	0.094	38.3	3.2
1.249	1.233	2.161	3924.	1.229	0.093	36.5	3.6
1.300	1.283	2.178	6029.	1.213	0.091	32.8	2.8
1.325	1.308	2.187	7274.	1.213	0.091	36.9	2.8
1.353	1.335	2.196	4290.	1.152	0.090	29.9	3.2
1.379	1.361	2.205	7593.	1.126	0.089	26.1	2.3
1.408	1.389	2.215	6601.	1.098	0.087	28.1	2.4
1.465	1.446	2.235	5874.	1.069	0.086	22.8	2.4
1.493	1.473	2.245	9101.	1.027	0.086	17.5	1.6
1.525	1.505	2.256	2409.	1.035	0.085	20.2	3.4
1.554	1.534	2.266	8720.	0.994	0.084	17.4	1.7
1.587	1.566	2.277	7804.	0.995	0.083	12.3	1.1
1.652	1.630	2.300	8072.	1.075	0.082	9.4	1.3
1.683	1.661	2.311	19322.	1.074	0.081	9.8	0.9
1.719	1.696	2.323	9161.	1.150	0.080	14.8	1.4
1.752	1.729	2.335	11829.	1.053	0.080	10.9	1.0
1.789	1.765	2.348	5923.	1.202	0.080	12.2	1.6
1.823	1.799	2.360	16008.	1.023	0.081	9.9	0.9
1.862	1.838	2.373	21534.	1.053	0.082	9.2	0.7
1.938	1.913	2.400	5385.	0.968	0.104	7.8	1.2
1.983	1.957	2.415	6179.	0.962	0.104	9.0	1.4
2.017	1.990	2.427	10149.	0.959	0.105	7.3	0.8

TABLE I

LEGENDRE COEFFICIENTS FOR OUR PI PI DATA.
NORMALIZED SO THAT A0 = (CROSS SECTION)/2PI

DATE 08/14/77

PLAB	A0	ER	A2	ER	A4	ER	A6	ER	A8	ER
1.125	7.87	0.52	10.09	1.43	14.27	1.88	-6.73	-1.97	1.79	2.15
1.155	7.15	0.47	6.45	1.21	8.83	1.59	-8.83	-1.83	2.52	2.09
1.184	6.09	0.52	6.10	1.37	5.46	1.80	-9.19	-2.17	-0.99	-2.54
1.233	5.81	0.57	3.79	1.48	6.06	1.90	-9.93	-2.30	-2.39	-2.80
1.283	5.22	0.45	2.90	1.13	6.28	1.51	-7.61	-1.75	2.97	2.02
1.308	5.87	0.44	0.84	1.04	6.44	1.35	-11.12	-1.57	2.01	2.00
1.335	4.77	0.52	2.61	1.29	1.80	1.74	-5.76	-2.09	4.27	2.61
1.361	4.16	0.36	1.08	0.87	2.32	1.13	-8.85	-1.38	0.61	1.66
1.389	4.48	0.39	-0.56	-0.91	2.90	1.17	-9.59	-1.40	2.14	1.81
1.446	3.64	0.38	-2.73	-0.85	2.54	1.09	-8.11	-1.29	3.38	1.69
1.473	2.79	0.26	0.33	0.58	0.63	0.76	-6.90	-0.96	2.15	1.17
1.505	3.21	0.54	-1.20	-1.25	1.57	1.60	-7.62	-2.04	1.59	2.68
1.534	2.77	0.27	-2.34	-0.58	1.34	0.74	-5.42	-0.85	4.12	1.13
1.566	1.96	0.18	-1.95	-0.39	1.34	0.51	-3.98	-0.57	4.10	0.74
1.630	1.49	0.21	-1.40	-0.48	0.62	0.66	-3.66	-0.77	3.59	0.97
1.661	1.56	0.14	-1.39	-0.31	0.87	0.43	-2.57	-0.48	2.98	0.89
1.696	2.36	0.22	-1.89	0.48	1.85	0.70	-1.86	0.77	5.43	0.97
1.729	1.74	0.16	-0.02	-0.35	0.54	0.51	-1.69	-0.59	3.75	0.74
1.765	1.94	0.26	-0.71	-0.60	1.79	0.91	0.27	0.97	5.93	1.23
1.799	1.57	0.14	0.11	0.33	1.72	0.47	-0.19	-0.54	3.22	0.67
1.838	1.46	0.11	0.08	0.27	1.64	0.40	0.31	0.43	3.73	0.53
1.913	1.25	0.19	0.76	0.49	0.98	0.68	-0.05	-0.82	0.72	1.03
1.957	1.43	0.21	1.94	0.60	2.52	0.86	2.87	0.99	3.97	1.16
1.990	1.17	0.13	0.79	0.33	0.48	0.48	-0.26	-0.60	1.36	0.69

TABLE II

$\bar{P}P \rightarrow \pi^0 \pi^0$ CROSS SECTION

BARI-BROWN-MIT

Fig. 1

$$\bar{P} P \rightarrow \pi^0 \pi^0$$

BARI-BROWN-MIT

Fig. 2

$\bar{p}p \rightarrow \pi\pi$

Fig. 3

Fig. 4

$\bar{P}P$ TOTAL CROSS SECTION

Fig. 5

$\bar{P}P \rightarrow \pi^+ \pi^-$ CROSS SECTION

Fig. 6

In the coming months we expect to complete this analysis and begin on $\pi^0\eta^0$ (see accompanying Renewal Proposal).

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- (4) See, for example, G. F. Chew, Proc. of IIIrd European Symposium on $\bar{N}N$ Interactions, Pergamon Press p. 515, 1976 and G. Veneziano and B. C. Rossi, Th 2287, CERN 1977.
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b) Search for Narrow $\bar{p}p$ Total Cross Section Resonances and for Resonances in $\bar{p}p$ States of Definite G-Parity in the T-Region 2130-2250 MeV (AGS #622)

As was mentioned last year, the motivation for AGS #622 came largely because of its complementary relation to our AGS #527 and the nature of the currently, somewhat confused situation in high-mass boson spectroscopy (see e.g., Proceedings of Vth International Conference on Experimental Meson Spectroscopy -- 1977, Weinstein and V. Goeler editors (in press), -- the

subsequent year has not clarified the situation). Briefly this situation is that mesons seen in some types of experiments are not seen in others of a different type (or occasionally even the same type) while some that have been seen via particular decay channels have no unambiguous quantum number assignments.¹ Our AGS #622 was designed to improve the situation in the former while AGS #527 was designed for the latter purpose of unambiguous quantum number assignment.

For the narrow resonance search we extracted from this run a total cross section measurement which complements the classical Abrams et al. experiment,² by virtue of the fact that AGS #622 has better mass resolution by about a factor of five, finer mass (or incident momentum) steps but somewhat poorer statistics on the individual points. These features are important because they permit the elimination or possible identification of fine structure in the total cross section at a level less than half a percent variation from the smooth Abrams curve. This point took on additional impetus with the discovery of the well-known ψ -J-particle, and the suggestion of lower mass states from quark and dual⁴ theories, as well as emulsion results from FNAL.³

A special feature of our early result is that unlike production experiments (such as in missing mass spectrometers) which measure only the product of a total width and a production cross section we are able to extract the partial width -- cross section product as it relates to the $\bar{p}p$ channel of a possible resonance coupled to bosons.

This portion of the experiment has been completed and is published in Physics Letters⁵ and in a conference report.⁶ In these publications it is shown that no structure exists at a level exceeding 7 MeV-mb for the product of cross section and partial width. If a resonance existed within these limits

at this momentum then its spin would be expected to be < 5 from impact parameter consideration. Were the spin equal to 5 the above width cross section limit implies that the width must be less than 165 kilovolts. This limit compares favorably with some of the widths found in the J/ψ complex of mesons. Furthermore we find that the broad (85 MeV) enhancement observed in the $\bar{p}p$ cross section persists without modification in an observation with mass resolution 5 times that of Abrams et al.

The principal assumption involved in the second portion of the experiment was that if any resonant $\bar{p}p$ states exist they will be in a state of definite G-parity. We chose the 2190 MeV (T-meson) mass region because of the rather strong evidence that there is both a total cross section enhancement as well as a unique channel ($\rho\rho\pi$) enhancement in that vicinity. More recently, a CERN group (see last entry in Ref. 1) has found evidence for a narrow state in the $\bar{p}p$ effective mass ($2.2 \text{ GeV}/c^2$) produced in 9 and 12 GeV/c incident $\pi^- p \rightarrow p$ (fast forward) + $\bar{p}p + N\pi$. This region is of course also covered in AGS #527 using our neutral two-body trigger. This part of AGS #622 then consists of a determination with moderately high mass resolution ($\approx 8 \text{ MeV}$ intervals) of the number of even and odd pion final states produced in $\bar{p}p$ annihilation and amounts to a determination of the number of π^0 's produced in the annihilation since the total number of charged mesons is even due to charge conservation. We would hope to be able to detect energy dependent structure at the $< 2\text{-}3\%$ level above background. As was mentioned at the time of the proposal, an interesting by-product of this work would be the first complete determination of the total (i.e., including π^0 's) multiplicity distribution of pions in $\bar{p}p$ annihilation as well as a new measurement of $\bar{p}p$ total cross sections with high mass resolution.

It will be recalled that our plan last year was to do only scanning and no measuring on the film since we did not require measuring for the G-parity resonance portion of the experiment. We had quite complete scanning information on two rolls of film but we deferred any further production scanning in order to devote our limited scanning power to AGS #527. Instead we shipped a large portion of this film to one of our collaborators, Professor David C. Peaslee, at the Australian National University in Canberra where he recently set up a scanning group. We thereby hoped to keep data production on a manageable time scale. The scanning is now complete and the data transferred to magnetic tapes containing the resulting topologies.

Analysis has begun and preliminary results can be reported in the following draft of a note by Professor Peaslee.

"The primary result is that within the errors of the experiment no significant variation with energy was observed in the pion yields from $\bar{p}p$ annihilation. The easiest way to display this fact is in Table I, which shows the relative probabilities of π^+ and γ distributions, averaged over the nine momentum bins. For each momentum bin, the statistical error in the probability distribution can be taken as $1/\sqrt{5000} \sim 1\%$. But this is just the order of the mean fluctuation of each entry in Table I taken over the nine momentum bins. It is therefore not possible at this statistical level to say anything about the variation with p_L of the probability distributions averaged to give Table I.

Table I - Probabilities of $\pi^\pm$ and γ distribution

$\gamma \backslash \pi^\pm$	0	2	4	6	8
0			.05	.02	
2		.10	.16	.05	.01
4	.01	.12	.12	.03	
6	.01	.09	.07	.01	
8	.01	.05	.03	.01	
10		.02	.01		
12		.01			

(All entries with uncertainties $\pm .001$; values ≤ 0.005 are blank entries.)

From more detailed distributions giving the complete probabilities for each momentum bin, and including entries for all events from 0 to 12 γ 's and 0 to 10 $\pi^\pm$, we obtain the following averages:

$$\bar{n}(\pi^+) + \bar{n}(\pi^-) = 3.4 \pm 0.1$$

$$\bar{n}(\pi^0) = 2.0 \pm 0.1$$

where $\bar{n}(\pi^0) = 1/2 \bar{n}(\gamma)$ is assumed. The uncertainties quoted represent average fluctuations among different momentum bins; as in the discussion of Table I, these are of just the same order as expected from counting statistics in each bin.

The correlation between charged and neutral pions is negative.

$$\bar{n}(\pi^\pm) \bar{n}(\pi^0) - \bar{n}(\pi^\pm) \bar{n}(\pi^0) = -0.42 \pm 0.03$$

The ratio of odd G-parity to even G-parity annihilations is

$$R = \sigma(G \text{ odd}) / \sigma(G \text{ even})$$

$$= 1.14 \pm 0.08$$

The same remarks about fluctuations apply as in the preceding paragraph.

These results agree entirely with those obtained from bubble chamber measurements⁷ at $p_L = 1.6$ GeV/c and therefore indicate no appreciable change in the gross features of $\bar{p}p$ annihilation over the entire range $p_L = 1.2$ to 1.6 GeV/c. This means that whatever resonance effect are present in this region of $\bar{p}p$ annihilation have a very small signal-to-background ratio.

It is possible that the smaller magnitude in the negative charged-neutral pion correlation obtained here as compared with Ref.⁷ is a real effect. Our data seem to show that $\bar{n}(\pi^0) \rightarrow \sim 1$ for high charge multiplicities."

Although these data are essentially complete there are still possible systematic biases which must be pursued and we hope to complete their evaluation soon.

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c) A Nucleon-Nucleon and Meson-Nucleon Interaction Experiment Using the Single Arm Spectrometer at Fermilab (FNAL EXPT. #96).

This experiment, which involved the construction of the Single Arm Spectrometer (SAS) in the Meson Laboratory Area, was on elastic and inelastic meson and nucleon scattering from hydrogen and deuterium. This first experiment was run and the equipment for it was constructed, by a collaborative group composed of individual physicists from ANL, Bari (Italy), Brown, CERN, Cornell, MIT, Stanford, and FNAL. As was expected, subgroups of this original collaboration have now begun to perform successive experiments using the resulting SAS (for example, see Section I(c) and Section II below).

Briefly, this experiment centered on scattering of $\pi^{\pm}$, $K^{\pm}$, $\bar{p}$, and p from hydrogen and deuterium for both elastic scattering ($\frac{d\sigma}{dt}$) and for a limited

sub-set -- charge non-changing) inelastic scattering ($\frac{d\sigma}{dtdM^2}$).

In last year's Progress Report we discussed in considerable detail the hydrogen data. That work is now complete and has resulted in roughly a dozen papers and three invited talks at the annual meeting of the A.P.S and of the Division of Particle and Fields. We will not discuss it further here.

The deuterium data is being done completely at Brown and the results will constitute the work contained in the Ph.D. thesis of Mr. Lorne Levinson. The topics being investigated and our progress on them so far is as follows.

The original data set we are working from is summarized in Table 1 which gives the kinematic coverage of the elastic scattering data.

Table 1.

Kinematic coverage of Deuterium Data

energy	particle sign	t	particle id
50	+	.05 - .37	pi,k,p
50	-	.03 - .51	pi,k,p
140	+	.07 - .80	pi,k,p
140	-	.07 - .60	pi,k,p

About half the running was taken with the beam pitched down (the variation in scattering angle is achieved by changing the incident beam direction with respect to the fixed SAS). For these events recoil particle information, most significantly a dE/dx pulse height, was recorded. The deuterium target data was taken intermixed with hydrogen target data at the same kinematic points. The goals in the analysis of this data are:

- (1) To measure the hadron-deuteron differential, quasi-elastic scattering cross-section. By this is meant elastic scattering of the hadron from one or both constituent nucleons of the deuteron and resulting in the deuteron breakup. Glauber theory¹ expresses the sum of the quasi-elastic + elastic cross-section in terms of the single nucleon elastic scattering amplitudes and the deuteron form factor. Hadron-neutron elastic differential cross-sections can then be extracted from the quasi-elastic + elastic scattering and the hydrogen target data.
- (2) To measure the hadron-deuteron differential elastic scattering cross-section. By this is meant scattering where the deuteron remains in the final state.
- (3) A check on the validity of the Glauber theory using $\pi^{\pm}p$ cross-sections and the $\pi^{\pm}n$ cross-sections extracted from the $\pi^{\pm}d$ data.

The strengths of this data matches these goals very well.

- (1) The ability to do accurate comparisons between π, K, p incident particle reactions since data for all three was collected simultaneously.
- (2) The ability to use $hp \rightarrow hp$ cross-sections measured on the same apparatus at almost the same time in the $hn \rightarrow hn$ cross-section extraction. This also allows an accurate comparison between hn and hP elastic scattering.
- (3) A sufficient number of events assures small random errors and hence relevant comparisons between the reactions measured.

- (4) Good missing mass resolution (less than a pion mass) excludes particle production processes from the elastic signal.
- (5) dE/dx information for the recoil particle serves to identify the recoil particle as a p, d, or n. This identification is only partly successful (see below).

For the hadron-deuteron quasi-elastic scattering, Glauber Theory gives as the sum of the quasi-elastic and elastic scattering:

$$\begin{aligned}
 & (1 + p^2) \{fn^2(q) + fp^2(q) + 2 S(q) fn(q) fp(q)\} \\
 & + \frac{(1+p^2)}{\pi k} fn(q) \int S(\vec{q}' - \vec{q}/2) fn(\vec{q}/2 + \vec{q}') fp(\vec{q}/2 - \vec{q}') d^2\vec{q}' + \text{term } (n \leftrightarrow p) \\
 & + \frac{(1+p^2)^2}{(2\pi k)^2} \int fn(\vec{q}/2 + \vec{q}') fp(\vec{q}/2 - \vec{q}') \int fn(\vec{q}/2 + \vec{q}'') fp(\vec{q}/2 - \vec{q}'') S(\vec{q}'' - \vec{q}') d^2\vec{q}'' d^2\vec{q}'
 \end{aligned}$$

$$\text{where } \vec{q}^2 = t$$

$S(t)$ is the deuteron form factor, $\exp(-33*t)$. Since the expression above is the sum of both breakup and coherent scattering (but not particle production) the identity of the recoil particle need not be known. In the t region .06 to .4, the first term ("single scattering") dominates (see Figure 1), the second ("single-double interference" is about 10-12%, and the third ("double scattering") is < 2%; also the $(1+S)$ factor becomes very nearly 1.

The content of the data in this t region is then primarily the single nucleon elastic cross-sections. This is highly agreeable to the task of extracting the hadron-neutron cross-section but necessitates accurate measurements to test the validity of the Glauber Theory; namely the 2nd or 3rd terms

and the $1+S(t)$ structure. The neutron cross-section extraction is done by simultaneously fitting the hydrogen target data and the deuterium target data to equation (1). At present the fit is done using the form:

$$f(t) = A \exp(-b \cdot t) + C \exp(-d \cdot t)$$

as the single nucleon elastic amplitude. This differs from the usual parametrization² of the elastic cross-section as $A \exp(-b \cdot t + c \cdot t^2)$ or $A \exp(-b \cdot t) + C \exp(-d \cdot t)$ but allows the interference integral to be done analytically. A sample data is shown in Figure 2.

For hadron-deuteron elastic scattering the Glauber Theory result for elastic deuteron scattering is

$$\begin{aligned} & (1 + \rho^2) S^2(q/2) \{f_n^2(q) + f_p^2(q) + 2 f_n(q) f_p(q)\} \\ & - \frac{1+\rho^2}{\pi k} S(q/2) [f_n(q) + f_p(q)] \int S(q') f_n(\vec{q}/2 + \vec{q}') f_p(\vec{q}/2 - \vec{q}') d^2 \vec{q}' \\ & + \frac{(1+\rho^2)^2}{(2\pi k)^2} \left| \int S(q') f_n(1/2 \vec{q} + \vec{q}') f_p(1/2 \vec{q} - \vec{q}') d^2 \vec{q}' \right|^2 \end{aligned}$$

where $q^2 = t$.

Note that the form factor appears as a factor in both the single scattering and interference terms. Since $S(t) = \exp(-33 \cdot t)$, the elastic cross-section falls very quickly with increasing momentum transfer, even with respect to the break-up reactions. The deuteron is weakly bound. The measurement of this cross-section requires that the recoil particle be identified as a deuteron. Now the kinetic energy of the recoil particle is $T = t/2m$ so we can calculate the expected energy loss in a scintillator for a deuteron versus a proton at a given t measured by the fast arm. dE/dx vs. t is given in Figure 3. When the energy loss in the target, etc. and the finite thickness of the scintillator is taken into account, the curves are given in Figure 4. The energy loss

of the events for one data run are plotted in Figure 5. The spread from the exact curves are due to:

- (1) Energy resolution of the scintillator..
- (2) Relative calibration error of the 16 dE/dx counters.
- (3) Fermi momentum broadening of the proton recoil energy spectrum.
- (4) Proton spectators whose Fermi momentum is in the counter acceptance.
- (5) Protons from quasi-elastic double scattering processes looking like deuterons.

Since even at the moderate t of .2 the elastic cross-section is 1/10th the breakup cross-section, the contamination of the deuteron signal is appreciable. Studies of the above effects have been made in an attempt to estimate this contamination. At present the plan is to do the recoil separation only for t between .11 and .16, where it is cleanest. It is intended that a test of factorization be made at that t by comparing $hd \rightarrow hd$ and $hp \rightarrow hp$ cross-sections for $h = \pi^{\pm}, k^{\pm}, \bar{p}, p$.

To test the Glauber theory we make use of I-spin invariance in strong interactions. The $\pi^- N$ cross-section is known by I-spin invariance to be equal to $\pi^+ p$. By comparing $\pi^- N$ extracted from the deuterium target data with the $\pi^+ p$ data taken on the same spectrometer we have a check on the validity of the Glauber formalism. Several corrections to the Glauber theory have been attempted by theorists, including inelastic rescattering and meson exchange effects. An accurate comparison of the simple theory with the data is needed to estimate these effects. No such comparison has been made above 30 GeV.

Fraction Interference & Double Scattering

Fig. 1

pp and pd Scattering at 50 GeV

Fig. 2

Ionization loss $-1/\rho \text{d}E/\text{d}x$ vs t for CH

Fig. 3

Fig. 4

RUN 13648 D_2

Fig. 5

Data Summary Tapes have been made for all the data. The 50 GeV π^+ , π^- , and p events have been identified as having p, n, d, or ambiguous recoils and raw cross-sections for these 4 recoil types have been calculated. Raw cross-sections for k^+ , k^- , and $\bar{p}$ have not yet been made. In order to get enough of these "minority" events, the non-uniform acceptance region of the spectrometer must be used. These cross-sections will then be normalized by multiplying them by the ratio of uniform to non-uniform acceptance cross-sections of the pion.

Preliminary fits for the 50 GeV $\pi^\pm$ and protons to the quasi-elastic + elastic Glauber expression are being made. These fits need to be refined by correcting for Coulomb-nuclear interference, macroscopic double scattering, and other effects.

The elastic deuterium scattering analysis will use the existing recoil separated raw cross-sections to calculate a cross-section at $t = .13$. This analysis and the factorization test will be done after the quasi-elastic analysis is completed.

We expect to complete all of this work in the coming contract year.

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d) An Experiment to Study "Inclusive" Reactions Using the
FNAL Single-Arm Spectrometer (FNAL #118).

This is an experiment to study inclusive reactions including particle multiplicity detection. The experiment began testing a year ago last summer and in the late fall we had our first data run. We have had four subsequent data taking sessions.

We are making an experimental study of the so-called "inclusive reactions" -- they are ones in which some particles or property of the final state is studied without trying to specify what else is happening in the reaction -- these reactions are usually represented by $a + b \rightarrow c + \text{anything}$. More specifically, we are making an investigation of these processes by measuring the momentum spectra of final state hadrons with high precision over a range of production angles and incident energies with the use of the FNAL focussing spectrometer which has been constructed for Experiment #96, as mentioned above.

The spectrometer has developed into quite a versatile facility -- for example, the "tune" (i.e., the spatial and magnetic configuration of the magnet and detector elements in the spectrometer) can be changed conveniently. This has been done for E-118; the experiment required different phase space acceptance and focal conditions than did E-96. The new conditions were established by computer simulation and implemented very simply. By employing an array of Cerenkov counters in the spectrometer set to be sensitive to different masses, the momentum distribution of protons, π^+ , and K^+ are simultaneously measured. The spectra of final state π^- , K^- , and $\bar{p}$ are simultaneously measured with reverse magnetic fields. With the use of Cerenkov counters in the incident beam

as well, reactions resulting from protons, anti-protons, $K^\pm$ mesons, and $\pi^\pm$ mesons are also simultaneously measured over the part of the kinematic range covered in this experiment in which incident intensities are about 10^7 particles per pulse or less. Multiwire proportional chambers and segmented, lucite Cerenkov counters surround the target and give the particle multiplicity for each event. With this combination of apparatus, precise inclusive spectra are measured for all particle types over a range of Feynman X from ~ 0 to 1.0 and over transverse momentum, p_T , from ~ 0.2 to 1.5. Incident particle momenta are 100 and 175 GeV/c of both negative and positive charge. Both like and un-like charges are accepted by the spectrometer. The charged particle multiplicities associated with each event are determined as is the pseudo-rapidity for each of the particles. Since our multiplicity detector covers virtually 4π for these secondaries both the target and projectile regions are covered as well as the central one.

As a consequence, the kinematic range and statistical accuracy will be extended by this experiment at high s for incident protons and negative pions as well as provide completely new and previously unknown data with kaons, positive pions and anti-protons incident in addition to most final state particles for any of the projectile types. These data are crucial for all models of strong interactions. These models are outlined in several excellent review articles.^{1,2,3,4}

The apparatus performed beautifully during our runs and the quality of the data appears to be excellent.

During the past contract year we have had our final two extensive running periods at Fermilab on this experiment and some data analysis was begun.

The first running period took place during the Fall and early winter. Immediately after that run, preliminary analysis was begun in two areas of physics which gave early indications in the on-line monitoring of being especially interesting. These were in the areas of narrow resonance (e.g., ρ, K^*) production at moderate Feynman-x and in the area of Δ^{++} (and $\overline{\Delta^{++}}$) total cross sections. (These preliminary results are discussed further below.) This analysis was interrupted by our final data taking run in the Spring and early Summer. All data taking at Fermilab for E-118 was completed in July.

The preliminary data analysis resulting from our work between the two Fermilab runs are as follows:

(a) Resonance production by OPE: The conventional wisdom has been that at moderately high values of Feynman-x for most inclusive reactions ($a + b \rightarrow c + X$), the triple Regge formalism provides a description of the dominant processes and will provide a useful tool in extracting important parameters governing the strong interactions. Reactions such as $pp \rightarrow pX$ have been extensively studied this way. Also reactions in which particle "a" and particle "b" have the same sign have been so analyzed -- e.g., $pp \rightarrow \pi^+ X$. Not until E-118 have extensive data become available on so-called "double charge exchange" reactions -- those in which particles "a" and "b" have opposite charge.

Specifically, the reactions we have analyzed are

$$\pi^+ p \rightarrow \pi^- X \quad (a)$$

$$K^+ p \rightarrow \pi^- X \quad (b)$$

$$pp \rightarrow \pi^- X \quad (c)$$

in the kinematic regime of 100 GeV/c incident momentum, $0.2 < x < 1.0$, and two $p_{\perp}$ values of 0.3, 0.5 (GeV/c)² for the exiting π^- . The data points for these reactions analyzed so far are shown in Figure 1 -- they are the values of the invariant cross section versus $(1 - x)$. In triple Regge models, these cross sections are expected to fall as powers of $(1 - x)$. The striking feature of the $p_{\perp} = 0.3$ (GeV/c)² data for reactions (a) and (b) is that they do not show this behavior over the full $(1 - x)$ range, but rather have structure yielding much higher rates at high values of x . In contrast, reaction (c) is very adequately described by $(1 - x)$.⁴ As is expected, and experimentally observed in $\pi^- p \rightarrow \pi^+ \pi^- X$ bubble chamber work, that production of well known, narrow resonances such as ρ^0 occurs at these incident energies and very high- x for the emergent π^+ . Although such resonances are not expected at lower x values it is suggested by our data that such production may actually be occurring since $\rho^0 \rightarrow \pi^+ \pi^-$ (with the π^- detected in the spectrometer) is an obvious way to obtain additional numbers of π^- above the power law rate. Following this lead, we have attempted to fit the data with a combination of resonance production via one pion exchange (OPE) and "central region" production of pions. For reaction (a) the resonances included were $\rho^0 \rightarrow \pi^+ \pi^-$ and $f^0 \rightarrow \pi^+ \pi^-$, while for reaction (b) $K^*(890) \rightarrow K^+ + \pi^-$ and $K^*(1420) \rightarrow K^+ + \pi^-$ were used. Reaction (c) does not require any resonances. The dotted curves shown in Figure 1 are the resulting resonance contributions (no free parameters). The dashed curves show a power law in $(1 - x)$ obtained from the $pp \rightarrow \pi^- X$ data whose scale is determined by the ratios of measured inelastic cross sections. The solid curve is then the combined contribution. Note that there are no free parameters and the result is an excellent description of the

Fig. 1

$\pi^+ p \rightarrow \pi^- X$ 100 GeV $X = .80, .84, .88$ $P_1 = 0.3$

Associated Multiplicity vs. n and ϕ

461512

K62 10 X 10 TO THE 100 METER 10 X 25 CM KLOFFEL & ESCHERICH 1981

$$\frac{dn}{dn}$$

$0^\circ < |\phi| < 90^\circ$
(SAS at $\phi=0$)

$$\frac{dn}{dn}$$

$90^\circ < |\phi| < 180^\circ$

Fig. 2

$$\pi^+ \rightarrow \pi^-$$

$$.3 \leq x \leq .4$$

$$.6 \leq x \leq .7$$

$$.8 \leq x \leq .88$$

$$\eta = -\ln t_y (\theta/2)$$

Fig. 3

Fig. 4

data. Further evidence supporting this model is provided by associated multiplicity, rapidity, and azimuthal angle distributions for the other particles accompanying the fast π^- -- this is provided by the vertex detector. Figures 2, 3 and 4 illustrate this showing that for these kinematic values of x and $p_{\perp}$ for the π^- in the spectrometer, events are dominated by those with an accompanying particle at ϕ in the opposite hemisphere with rapidity about 4 (as would be expected for the π^+ from $\rho^0 \rightarrow \pi^+ \pi^-$).

The conclusion that there is substantial ρ , f , and K^* production which extends to $x < 0.7$ does not depend on the model for parametrizing "central region" π^- production. Almost any function rapidly falling in $(1 - x)$ gives a reasonable fit. For example, models based upon quark-parton models⁵ have been tried and while giving slightly better overall fits do not significantly change the amount of resonance production needed.

A Physical Review Letter is being prepared on this work. In addition, substantially more data relating to this effect was taken in our last run and will be analyzed in the near future.

One important consequence of these results will be the need for any experiment to adequately remove these effects from any high energy meson induced data before a triple Regge analysis can be applied. This data should provide a complete set of parameters useful to any experiments in the Fermilab energy regime.

(b) Total cross sections for Δ^{++} and $\overline{\Delta^{++}}$.

The reactions

$$\pi^- p \rightarrow pX \quad (d)$$

$$\pi^- D \rightarrow pX \quad (e)$$

$$\pi^+ p \rightarrow \overline{p}X \quad (f)$$

$$\pi^+ n \rightarrow \overline{p}X \quad (g)$$

in which the exiting p (or $\overline{p}$) has very high $x(\geq 0.94)$ are currently of great interest from several points of view.

Briefly, they encompass direct extraction of $I = 1$ and $I = 2$ cross sections involving antinucleons, tests of sum rules based on Regge amplitudes, indirect measurement of Δ^{++} and $\overline{\Delta^{++}}$ cross sections on n and p, quark model inequalities, and searches for exotic resonances coupled to the nucleon-antinucleon system.

Table I contains a sub-set of the data used in the preliminary analysis of reactions (d) - (g), as well as calibration data on reactions $pd \rightarrow \pi^- X$ and $pp \rightarrow \pi^- X$ at 100 GeV/c. Figures 5 and 6 are plots of these data for reactions (d) and (e) -- the dotted curves are simple fits to the parametrization, $E \frac{d^3\sigma}{dp^3} = A + BM^3$. The isospin 1 and 2 cross sections can be extracted from these data via the relations, $\sigma(I = 2) = \sigma(\pi^- d) - \sigma(\pi^- p)$ and $\sigma(I = 1) = 1/3[5\sigma(\pi^- p) - \sigma(\pi^- d)]$. The resulting plots for $\sigma(I = 1)$ and $\sigma(I = 2)$ are shown in Figures 7 and 8, respectively with the same parametrization as above.

Possible structure in the $I = 2$ cross section is of extreme interest presently because of the possible existence of narrow states coupled to the baryon-antibaryon system. Some states have recently been suggested from recent CERN experiments⁶ of a rather different sort.

Looking at Figure 9, it can be seen that our experiment should be able to assess states of the sort suggested as a special class of "exotics" by Rosner⁷ or "baryonium" by Chew.⁸ Because a "mesonic" object of charge 2 emerges as particle X, this would be an especially clean identification should a signal be evident. On the evidence so far from this small sub-set of the data two points can be made: the overall $I = 2$ cross section is very small; secondly, the possible narrow structures are not statistically significant in a Durbin-Watson test. More data has been taken in our final runs at Fermilab on these reactions and will be analyzed soon.

As can be seen from Figure 10 these data can be analyzed from a completely different point of view -- that of the triple Regge model. In the usual notation of the triple Regge formalism

$$\frac{s}{\pi} \frac{d\sigma}{dt dM^2} \approx \frac{1}{16\pi^3} (1-x)^{1-2\alpha_L(t)} \beta_{EFF}^2(t) (M^2)^{\alpha_{EFF}^{(0)}-1}.$$

Reaction (d) requires an exotic exchange and should give an unusual α_{EFF} if present while (e) has a conventional exchange. We find that α_{EFF} is consistent with Pomeron exchange over most of the M^2 range with suggestions of departure from that α_{EFF} at low M^2 ; data on α_{EFF} for reaction (e) is inconclusive. The new data taken and mentioned above is designed to clarify these points.

These data can also be addressed from the related points of view of sum rules and "quark annihilation mnemonics". Lipkin⁹ has devised a sum rule relating reactions (d) - (g) which tests for the presence of a "third" component in addition to the usual Pomeron and meson components in dual models. This "third" component would be coupled to the baryon-anti-baryon system. When done for all reactions in the same kinematic regime, as is the case here then the sum rule results effectively in the relation

$$[\sigma(p\Delta^{++}) - \sigma(P\Delta^{++})] - [\sigma(n\Delta^{++}) - \sigma(n\Delta^{++})] = 0$$

when there is no third component. Our data so far are consistent with the absence of this "third" component.

There are many models for quark annihilation -- e.g., only quarks and antiquarks of the same flavors can annihilate. The Lipkin mnemonic¹⁰ is based on this example and results in the prediction that if "hadron A contains an antiquark $\bar{q}_i$ corresponding to a quark q_i in hadron B, then $\sigma_{TOT}(AB)$ will have a non-pomeron contribution of 'one unit' (σ_x). If the antiquarks $\bar{q}_j$ in A are all different from quarks q_i in B then leading non-pomerons² contribution should vanish". To date this is borne out in existing data for Kp , πp , and $\bar{p}p$ cross sections, but Δ^{++} and Δ^{++} (which are pure $\bar{u}$ and u systems, respectively) would provide unique checks. If we designate $\sigma(\mathbb{P})$ as the pomeron and $\sigma(x)$ as the non-pomeron contribution mentioned then

$$\sigma(\pi^- p \rightarrow pX) = \sigma(\mathbb{P}) + 2\sigma(x)$$

$$\sigma(\pi^- n \rightarrow pX) = \sigma(\mathbb{P}) + \sigma(x)$$

$$\sigma(\pi^+ p \rightarrow \bar{p}X) = \sigma(\mathbb{P})$$

and we can extract $\sigma(\mathbb{P})$ and $\sigma(x)$ from our data. We find, $\sigma(x) = 0.34 \pm 0.07$ and $\sigma(\mathbb{P}) = 0.12 \pm 0.05$. Again, more data will give better determination over different M^2 intervals.

Analysis work on all of the other inclusive reactions, $a + b \rightarrow c + x$ where $a = \pi^\pm, K^\pm, p, \bar{p}$ and $c = \pi^\pm, k^\pm, \bar{p}, p$ in all possible combinations, from data taken in this experiment has only just begun. It will constitute a large part of our research effort in the coming year.

Cross Section Data

100 GeV/c

Channel	$\bar{x}$	Flux $\times 10^9$	Events	$E \frac{d^3\sigma}{dp^3} (\mu\text{b/GeV/c}^2)$
$\pi^- d \rightarrow pX$	.92	6.11	158	9.81 ± 0.78
$\pi^- p \rightarrow pX$	(Mass 3.0-4.6 GeV/c ²)	4.21	119	6.16 ± 0.57
$\pi^- n \rightarrow pX$				3.65 ± 0.97
$\pi^- d \rightarrow pX$	.94	2.73	52	6.92 ± 0.96
$\pi^- p \rightarrow pX$	(2.3-4.2)	2.53	55	4.54 ± 0.61
($\pi^- n \rightarrow pX$)				2.38 ± 1.18
$\pi^- d \rightarrow pX$	.95	2.67	50	6.66 ± 0.94
$\pi^- p \rightarrow pX$	(1.9-4.0)	2.00	44	4.50 ± 0.68
($\pi^- n \rightarrow pX$)				2.16 ± 1.16
$\pi^- d \rightarrow pX$	.96	2.86	51	6.21 ± 0.87
$\pi^- p \rightarrow pX$	(1.2-3.8)	.81	20	4.95 ± 1.11
($\pi^- n \rightarrow pX$)				1.26 ± 1.41
$\pi^- d \rightarrow pX$	.97	9.97	132	4.52 ± 0.39
$\pi^- p \rightarrow pX$	(0.5-3.5)	7.74	123	3.12 ± 0.28
($\pi^- n \rightarrow pX$)				1.40 ± 0.48
$\pi^+ d \rightarrow \bar{p}X$	.94	1.43	3	0.94 ± 0.55
$\pi^+ p \rightarrow \bar{p}X$	(2.3-4.2)	0.85	4	1.22 ± 0.61
$\pi^+ n \rightarrow \bar{p}X$				-0.28 ± 0.81

H2 03/09/77 23.37.51

Fig. 5

D2 03/09/77 23.37.51

Fig. 6

I1 03/09/77 23,37,51

Fig. 7

12 03/09/77 23,37,51

Fig. 8

SOME Possible Quark-Duality Diagrams:

$$\Delta^{++} P \rightarrow$$

$$\Delta^{++} N \rightarrow$$

$$\Delta^{++} P(\text{or } N) \rightarrow$$

$$\pi^- N \rightarrow PX$$

Fig. 9

Fig. 10

REGGE MODEL:

$$\pi^- p \rightarrow p X$$

(or N)

$$\pi^+ p \rightarrow \bar{p} X$$

(or N)

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II. Experimental Runs in Progress and in Preparation

- a) An Experiment to Study the A-Dependence of Inclusive Processes and Their Associated Multiplicity Using the FNAL Single-Arm Spectrometer (FNAL #451).

During the past year we submitted two new proposals for experiments to be done at Fermilab with our collaborators at Bari, Fermilab, and MIT.

The first of these is an experiment to study the A-dependence of inclusive reactions over a wide range of kinematics using the M-6 single arm spectrometer facility along with a detector for π^0 's produced at large p_t . The multiplicity detector of experiment E118 will be used to obtain the associated charged multiplicity and pseudo-rapidity distribution associated with each event.

The principal objective is to explore these processes over a wide range of A, x, and p_t . In particular, we will run at 175 GeV/c with π^+ , K^+ , and p, incident on H_2 , Be, Al, Cu, Sn, and Pb. We will obtain data on the A-dependence of the inclusive distributions of π^+ , K^+ , and p^+ produced from these targets for values of x from 0.1 to 0.95 and from $p_t \approx 0$ to $p_t \approx 1.25$. Simultaneously data will be obtained for the inclusive π^0 distribution for $1.0 \lesssim p_t \lesssim 4.0$. Statistical errors will range from about 2% at the smallest transverse momenta to about 15% at the largest transverse momenta.

The π^0 detector will consist of an array of lead-glass preceded by a shower hodoscope of lead-scintillator construction. It will subtend 20 mster. between 70 and 210 mr. in the laboratory. The transverse momentum of the π^0 will be determined to about 10%. Cronin et al.¹ and Lederman et al.² have shown that the A-dependence of the inclusive π^0 cross section

increases from $A^{2/3}$ to $A^{4/3}$ going from $p_t \approx 0$ to $p_t \approx 4$, a result which is totally unexpected from current models. We will be able to measure the correlation of this phenomenon with the associated multiplicity and incident particle type.

This measurement will provide extensive information on leading particle effects in inclusive production from nuclei. Most current models predict a weak A-dependence for the leading particle and make predictions sensitive to the space-time development of the hadron cascade. In addition, spectrometer events with $x \lesssim 0.3$ should show the onset of the strongly A-dependent part of the rapidity distribution. The position of this feature as a function of energy is a crucial test for some models. The substantial particle identification power of the SAS facility will allow simultaneous measurement of all combinations of π^+ , K^+ , and p^+ in the beam and in the spectrometer. In this way, the dependence of the hadron-nucleus cross sections and multiplicities on the identity of the incident and produced particle may be compared.

This proposal was approved in a proposal presentation meeting of the P.A.C. at Fermilab last summer.

Our first run is scheduled to begin in March 1978.

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b) An Experiment to Search for Heavy Long-Lived
Particles at Fermilab. (FNAL #469)

This is the second proposal submitted by the group for this year. Utilizing the existing apparatus and unique properties of the M6E beam - Single Arm Spectrometer we propose a relatively short experiment which will search for stable and long-lived particles which:

- (a) improves the sensitivity over previous experiments by two orders of magnitude;
- (b) extends the energy range of such searches at FNAL to 400 GeV;
- (c) is sensitive to masses over a range from 1 GeV to nearly the kinematic limit without exclusion of fractional or multiply-charged particles;
- (d) studies the particles (especially in the 2 GeV "anti-deuteron" peak) as to their hadronic interaction.

Although searches for long-lived particles (mean lifetime $\geq 10^{-8}$ sec) more massive than the proton have been undertaken whenever a new accelerator has been commissioned, these searches are usually motivated by the desire to look for new phenomena when a new energy regime becomes accessible. However, there are sometimes compelling reasons to push some measurements to new limits. Such is the case now because recent theoretical predictions and experimental discoveries have suggested that new degrees of freedom and new families of particles exist.¹ These create a new interest in looking for massive particles, both short- and long-lived with increased sensitivity.

We propose to use the long flight paths and substantial Cerenkov counter power uniquely available in the M6E-Single Arm Spectrometer Facility

to study the production of long-lived charged particles in 400 GeV/c p-Be collisions. Studies of this kind have been undertaken at Fermilab,² at the ISR,³ at Serpukhov,⁴ and at lower energies.⁵ In these experiments, deuterons, antideuterons, and tritons have been observed. At energies greater than 30 GeV/c no other particles of mass greater than the anti-deuterons (anti-tritons were reported at London by a Russian group but we have not seen a published report) have been found at a level of $\sim 7 \times 10^{-7}$ of the light particle flux. Our objectives are (1) to improve this sensitivity to $\sim 10^{-10}$ of the light particle flux -- an improvement at least by a factor of 200; (2) to accurately measure the deuteron to anti-deuteron ratio to test models of the production of these particles; (3) to study the properties of the particles in the 2 GeV/c² peak to make sure that they are all conventional hadrons; and (4) to extend the range of mass searches at Fermilab to 400 GeV.

Our proposed experimental technique is as follows: Since the M6 beam has a narrow momentum acceptance ($\pm 1/2\%$), the problem of measuring the mass of a particle of known charge reduces to determining its velocity. We will use a combination of time-of-flight and Cerenkov counters which are available.

Light particles of mass less than 1.1 GeV/c² are efficiently rejected by two threshold Cerenkov counters, C2 and C3, counting π , K, p, and the differential counter D1, set to count protons. This light particle veto is designated as

$$L = C2 + C3 + D1 .$$

Based on our previous experience with these counters in E96 and E118, we expect the inefficiency for counting a light particle will be between 10^{-8} and 10^{-10} .

To measure the velocities of particles surviving this veto, we will use both Cerenkov counter and time-of-flight techniques. The two techniques are complementary in the following sense: the Cerenkov counters perform best at the lower end of the mass range (near where they are conventionally operated) while the time-of-flight differences between heavy and light particles increase as the mass increases.

All accepted events are also monitored by a "muon identifier" located at the end of M6-SAS to check on the hadronic-like nature of all detected particles.

By performing this experiment it is clear that a significant improvement of the limits on long-lived heavy particle production can be achieved with a relatively small investment of beam time. Only minor additions and alterations to existing equipment are required. The Cerenkov counters, which are the key to the experiment, have been operating for two years and their properties are well understood. With standard time-of-flight techniques we will achieve acceptable resolution; any improvements will allow us to extend the overlap of the mass range. The high quality of the beam, the sophistication of the apparatus and the large number of cross checks lead us to believe that our backgrounds will be very small.

We have requested 150 hours of beam time to perform this experiment. The proposal was presented and received favorable discussion at the Fermilab P.A.C. proposal presentation meeting a year ago and again this past summer; a decision on whether to run it or not rests on possible related results from FNAL #104-354 and the scheduling details of the projected Meson Laboratory "Pause".

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c) Proposal for a Large Facility at PEP (PEP-8)

Last year, this group together with our MIT collaborators, joined groups from Cal Tech (Barish, Pine, et al.) and SLAC (De Staebler, Taylor, Wockticki, et al.) in proposing to construct a major facility for use at PEP. Also proposed were a comprehensive set of experiments encompassing jet production, weak-electromagnetic interference, two photon physics and heavy lepton searches.

A large effort was required to adequately prepare such an extensive program and its descriptive documentation (copies of the PEP-8 Proposal are available from the authors or on file at SLAC, BNL, and Fermilab libraries). We were enthusiastic about the resulting proposal. It was well received by the PEP Program Committee and it was a serious contender for approval; unfortunately, it was not one of the three major facilities approved. The SLAC Directorate have encouraged us to submit more modest scope devices at the next proposal submission period (31 October) -- this we intend to do and this topic is further discussed in the accompanying Renewal Proposal.

III. Associated Matters

During the past contract year the group had the very welcome addition of Professor David C. Peaslee. Professor Peaslee was a Visiting Professor in the Department of Physics. He taught elementary particle physics at both the graduate and undergraduate level as well as make important contributions in the research activities of the group. His contributions to the analysis of the $\bar{p}p$ experiment have been absolutely vital to us.

Professors Massimo and Lanou had academic leaves last year (Semester I and I-II, respectively) and both devoted full time to the research of this group. This was especially valuable because of the large amount of effort required simultaneously last year for E118 running, $\bar{p}p$ and E118 analysis, and preparation of new experiments.

Both Professors Cutts and Lanou were participants at BNL in the ISABELLE Summer Study held during the last two weeks of July. This work resulted in papers which they authored and which will appear in the proceedings.

Dr. Robert Dulude was an active participant in the Gordon Conference on elementary particles held at Tilton Academy (Tilton, New Hampshire) during August.

Mr. R. K. Thornton, previously a Research Assistant in this group, has recently accepted a position as Assistant Professor of Physics at Tufts University.

IV. Scientific Personnel Associated with the Counter-Spark Chamber Program.

R. E. Lanou, Jr.	--	Professor
J. T. Massimo	--	Professor
D. C. Peaslee	--	Visiting Professor
D. Cutts	--	Assistant Professor
R. S. Dulude	--	Research Associate
B. H. Hughlock	--	Graduate Research Assistant
L. J. Levinson	--	Graduate Research Assistant

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