PROGRESS REPORT OF A RESEARCH PROGRAM
IN EXPERIMENTAL HIGH ENERGY PHYSICS

Progress Report
for Period September 1, 1975 - August 31, 1976

MASTER

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

Brown University
Providence, Rhode Island

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ABSTRACT

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

The experiments of the electronic detector-spark chamber group include the following: 1) a search for high mass boson resonances and determination of quantum numbers in antiproton-proton systems; 2) a nucleon-nucleon and meson-nucleon elastic and quasi-elastic scattering experiment at the highest energies; 3) a study of inclusive scattering, 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 produced by 100 GeV pions in association with direct leptons.

The bubble chamber - hybrid system group is primarily engaged in several experiments at the Fermilab. A study of π^-p interactions at 147 GeV/c is being completed, and a larger investigation of π^+p , K^+p , pp , and π^-p collisions at 147 GeV/c has begun. To the proportional hybrid system has been added a prototype forward gamma detector, enabling the precision measurement of up to 6 photons (3 π^0 's and/or η^0 's). Major aspects of multiparticle production using four different projectiles are being pursued. A precision intercomparison of corresponding processes produced by the different projectiles is underway, using identical experimental conditions.

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 year (1 September 1975 - 31 August 1976). This work has been supported by the U.S. Energy Research and Development Administration under Contract E(11-1)-3130 (Task B-Experimental).

This report is divided as follows:

A. Electronic Detector-Spark Chamber Program

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

B. 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

C. Papers Published During the Preceding Year and Papers in Press

A. 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 the 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.

Running at the AGS for this experiment was completed in early January 1973. Approximately 750K total photographs were taken. 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 about two thirds of the data. 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 six energies. We now have results at thirteen 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 $\eta^0\eta^0$.

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 $\eta^0\eta^0$. These three cross sections are shown in Figures 1, 2, and 3; the $\bar{p}p$ total cross section¹ is shown in Figure 4 and the $\bar{p}p \rightarrow \pi^+\pi^{-(2)}$ is shown in Figure 5 for reference.

In Figures 6, 7 and 8 are shown the angular distribution of $\pi^0\pi^0$ and $\pi^0\eta^0$ at each of the thirteen energies (note: the curves shown are those representing the best fits to the data for a Legendre polynomial expansion with only even terms included as a result of quantum symmetry constraints). As an alternative way of displaying this same data we present the energy dependence of the Legendre polynomial coefficients determined from these fits. (Figures 9, 10, and 11)

Several features of these angular distributions are worth pointing out:

- a) the $\pi^0\pi^0$ distributions have quite striking features characteristic of relatively pure angular momentum states, but the features vary smoothly as a function of energy. The Legendre coefficients similarly show no narrow structure. There is a noticeable forward-backward peak growing at the highest energies.

¹ Abrams et al., Phys. Rev. D1, 1917 (1971).

² Eisenhandler et al., Nucl. Phys. B96, 109 (1975)

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

Figure 1

Figure 2

$PP \rightarrow \eta^0 \eta^0$ CROSS SECTION

Figure 3

$\bar{P}P$ TOTAL CROSS SECTION

Figure 4

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

Figure 5

Figure 6

($\bar{p}p \rightarrow \pi^0\pi^0$ center of mass fitted angular distributions.)

PLAB - 1.200

PLAB - 1.300

PLAB - 1.353

PLAB - 1.408

PLAB - 1.465

PLAB - 1.554

($\bar{p}p \rightarrow \pi^0 n^0$ fitted distributions)

$\cos \theta^*$

Figure 7

PLAB - 1.587

PLAB - 1.683

PLAB - 1.719

PLAB - 1.752

PLAB - 1.789

PLAB - 1.823

($\bar{p}p \rightarrow \pi^0 \eta^0$ fitted distributions)

$\cos \theta^*$

Figure 8

A2 (I=0)

A4 (I=0)

A6 (I=0)

A8 (I=0)

Figure 9

Legendre polynomial coefficients derived from $\bar{p}p \rightarrow \pi^0\pi^0$

A2 LEG COEF FROM BEST FIT

A4 LEG COEF FROM BEST FIT

Figure 10

Legendre coefficients derived from $\bar{p}p \rightarrow \pi^0\pi^0$

A8 LEG COEF FROM BEST FIT

A8 LEG COEF FROM BEST FIT

Figure 11

Legendre coefficients derived from $\bar{p}p \rightarrow \pi^0\pi^0$

- b) the $\pi^0\eta^0$ distributions are different in significant detail from those of $\pi^0\pi^0$, but again have smoothly varying features except perhaps at the four highest energies.

In this initial treatment of the data, the mass intervals included in each angular distribution are roughly 30 MeV in width; this is a factor ten larger than the ultimate resolution in the data but was chosen for our first pass because it proved a convenient size for uncovering possible systematic errors. In the near future we expect to re-bin the data in a way appropriate for checking structure at the resolution limit. It is apparent from these angular distributions that there is no single (or few) resonance(s) of width this order of magnitude which dominates the behavior. More sophisticated analysis is required; acting on a suggestion by D. C. Peaslee a type of partial wave analysis has been started on these data but so far has produced no conclusive results. It is worth noting that the $\pi^0\pi^0$ state is 0^+ ($= 1^G$) while the $\pi^0\eta^0$ state is 1^- ; we can combine our data with that of Eisenhandler et al.² on $\bar{p}p \rightarrow \pi^+\pi^-$ to extract the distributions for the $\pi\pi$ state in 1^+ -- these results are shown in Figure 12. Again the same type of features are prevalent: smoothly varying behavior but detailed structure suggestive of pure states, these states being different still from the 1^- distributions.

From a different point of view, namely that of Regge exchange models, preliminary analysis of our highest energy indicates that this may have some validity. The suggestive experimental feature which leads one to believe such a treatment might be appropriate is the growth of a narrow forward-backward peak (actually, because of the $\pi^0\pi^0$ symmetry it does not distinguish between the two) at the higher energies. Consequently, we have used the crossing

² Eisenhandler et al., Nucl. Phys. B96, 109 (1975).

A2 (I-1)

A4 (I-1)

A6 (I-1)

A8 (I-1)

Figure 12

Legendre coefficients for $1^-(I^G)$ derived from
 $pp \rightarrow \pi^0\pi^0$ and $pp \rightarrow \pi^+\pi^-$

relationships between $\bar{p}p \rightarrow \pi\pi$ and the various πp backward scattering experiments to make comparison at our highest point as a preliminary test. The results are shown in Figure 13. In making these comparisons we have assumed separately either N_α exchange dominance or N_δ exchange dominance -- the latter is the most promising and is the assumption used in Figure 13. As is well known³, πp backward charge⁴ exchange is dominated by N_α exchange and this is born out by its failure to coincide with the $\bar{p}p \rightarrow \pi^0\pi^0$, $\bar{p}p \rightarrow \pi^+\pi^-(2)$ and backward π^-p elastic⁵ which agree among themselves. The only exchange possible in π^-p elastic is N_δ which lends credence to the assumption of N_δ dominance in the $\bar{p}p$ two body annihilation. Encouraged by this we are planning to extend the analysis.

In summary, all of these results are quite unexpected and potentially quite interesting because while there were several options among the predictions for what would be seen in these experiments -- potential models⁶, narrow resonances⁷, exchange reactions³ -- none of them appear to be the complete story upon initial examination. Now that we have a substantial statistical sample we are just beginning more sophisticated and extensive analyses. This will be the main work on this experiment in the next year. The addition of Dr. Robert Dulude to the group and the visit next year of Professor David Peaslee (see Associated Matters section and our Renewal Proposal) leads us to expect much progress on this experiment.

Mr. Ronald K. Thornton completed his Ph.D. thesis work on this experiment this year. The work centered upon a detailed analysis of all three reactions $\bar{p}p \rightarrow \pi^0\pi^0$, $\eta^0\pi^0$, $\eta^0\eta^0$ at an incident momentum of 1.862 GeV/c and are reported in Reference 220.

³ Barger et al., Nucl. Phys. B68, 206 (1974).

⁴ De Marzo et al., Phys. Lett. 56B, 487 (1975).

⁵ Carroll et al., Phys. Rev. Lett. 20, 607 (1968)

Isospin factors assume u channel Δ dominance

$\square$ ($\bar{p}p \rightarrow \pi^0\pi^0$) $\times 9/4$	$S = 5.67 (GeV)^2$	This expt.
$\diamond$ ($\bar{p}p \rightarrow \pi^+\pi^-$) $\times 1$	$S = 5.78 (GeV)^2$	Ref. 2
$\times$ ($\pi^+p \rightarrow \pi^+\pi^-$) $\times C_f$	$S = 5.56 (GeV)^2$	Ref. 3
$\oplus$ ($\pi^+p \rightarrow \pi^0\pi^0$) $\times C_f \times 9/2$	$S = 5.78 (GeV)^2$	Ref. 4

$C_f \equiv$ crossing factor (Equation 2)

Figure 13

Some of these data were presented at the IVth International Conference on $\bar{N}N$ Interactions held at Syracuse last year. The papers are published in the conference proceedings, Reference 217 and 218.

⁶ Dover and Kahane, B.N.L. Preprint

⁷ Donnachie and Thomas, Nuovo Cimento 26A, 317 (1975).

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 Experimental Meson Spectroscopy - 1972, A. I. P. Conference Proceedings No. 8, Rosenfeld & Lai, editors -- subsequent years have 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 assignments¹. 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. experiment², 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

¹ W. A. Cooper et al., Phys. Rev. Lett. 20, 1059 (1968).
G. Kalbfleisch et al., Phys. Lett. 29B, 259 (1969).
P. Yamin et al., Bull. Am. Phys. Soc. 18, 125 (1973).
R. Donald et al., Nucl. Phys. B61, 333 (1973).
R. Donald et al., Phys. Lett. 40B, 586 (1972).
W. Kienzle, Phys. Rev. D11, 3520 (1973).
W. Apel et al., Phys. Lett. B57, 398 (1975).
W. Blum et al., Phys. Lett. B57, 403 (1975).
C. Baltay et al., Phys. Rev. Lett. 35, 891 (1975).

² Abrams et al., Phys. Rev. D1, 1917 (1970); see also Alspector et al., Phys. Rev. Lett. 30, 511 (1973).

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 FNAL³.

A special feature of our 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 report⁶. 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

³ Hoshino et al., Nagoya University Report #DPNU-3 (1975).

⁴ For reviews of these predictions see A. Astbury, in CERN Report No. 74-18, 1974 (unpublished), p. 46, or R. H. Dalitz, in Experimental Meson Spectroscopy-1974, AIP Conference Proceedings No. 21, Particles and Fields Subseries No. 8, edited by D. A. Garelick (American Institute of Physics, New York, 1974), p. 75.

⁵ De Marzo et al., Phys. Lett. B57, 189 (1975).

⁶ Peaslee et al., Proc. of IVth Int. Conf. on $\bar{N}N$ Interactions, Sec. I-84, Volume I (Syracuse, 1975).

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. This region is of course also covered in AGS #527 using our neutral two-body trigger. This part of AGS #622 would then consist of a determination with high mass resolution (≈ 8 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 2-3% 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 have 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 has recently set up a scanning group. We thereby hoped to keep data production on a manageable time scale. So far he has produced data on about

70K events and the data which was transferred to magnetic tapes containing the resulting topologies was studied in the U.S. As a feasibility study, initial analysis for the number of π^0 has been aimed at trying to isolate possible major sources of systematic error. This has been attempted by comparison of those topologies (e.g., $\bar{p}p \rightarrow n\pi^+ n\pi^- \pi^0$) where there is only one missing π^0 and therefore can be checked against bubble chamber data⁷. Checks can also be made against very sparse heavy-liquid data⁸ which have very different systematic biases but can detect more than one π^0 . To date, we find that such tests indicate we do have significant bias if we use the simplest approach. More sophisticated analysis shows promise for minimizing the biases but is too early to tell at what sensitivity the G-parity test can be made.

⁷ Burns et al., Nucl. Phys. B73, 219 (1974)
Burns et al., Nucl. Phys. B85, 337 (1975)
Burns et al., Phys. Rev. D12, 638 (1975)
Donald et al., Nucl. Phys. B6, 174 (1968).
Donald et al., Nucl. Phys. B11, 551 (1969).
Eastman et al., Nucl. Phys. B51, 29 (1973).

⁸ Fett et al., Paper submitted to Syracuse Symposium on $\bar{N}N$ Interactions (1975) (Volume I, Sec. III-88).

c) A Nucleon-Nucleon and Meson-Nucleon Interaction Experiment
Using Counter-Spark Chambers at FNAL (FNAL #96).

This experiment completed its data taking runs a little over a year ago. Its original design was to measure elastic scattering and quasi-two-body elastic scattering of K^+ , K^- , p , and $\bar{p}$ on hydrogen and deuterium (neutron) targets up to 200 GeV/c incident momentum and at $|t|$ values of .04 to 1.2 (GeV/c)²; however, it additionally includes data from the so-called triple Regge region. It has been described extensively in previous Progress Reports and Renewal Proposals.

The spectrometer (which has been adopted as a facility by FNAL) is of flexible design and can operate either with 8μ steradians acceptance and $\pm 0.03\%$ momentum precision up to 200 GeV/c or can be changed to give considerably larger acceptance at lower momenta. It is equipped with differential and threshold Cerenkov counters as well as scintillation counters, hodoscopes, and multi-wire proportional chambers. The collaboration assembled to construct and carry out this experiment consisted of individual physicists from ANL, Bari, Brown, CERN, Cornell, MIT, Stanford and FNAL.

In the course of the entire experiment approximately 400 raw data tapes were written containing about 12×10^6 events. Analyses of these data have been underway at Brown, Cornell, FNAL, MIT and SLAC. Preliminary results, chiefly related to the important question of asymptotic behavior of slopes of $d\sigma/dt$ at small momentum transfer in elastic scattering, have been reported by ourselves and collaborators in invited papers at XVII International Conference on High Energy Physics (London), the annual meeting of the APS (Anaheim), X Rencontre de Moriond (Phenomenology of Hadronic Structure) at Meribel, France, and at various regional meetings of the A.P.S.

The elastic angular distributions have been published in Physical Review Letters (Ref. 215).

The experiment has and is producing an enormous amount of data on a variety of hadron physics questions. What follows is a brief summary of final and preliminary results in those areas where progress has reached a reasonably conclusive level:

The t-dependence of elastic scattering. Preliminary results on this problem have been discussed in previous Progress Reports. We now have final results for the six hadrons π^+ , π^- , K^+ , K^- , p and $\bar{p}$ scattering on protons at five momenta 50, 70, 100, 140 and 175 GeV/c. This then produces thirty angular distributions. The number of data points is too great to reproduce here but we present in Figure 1 a typical plot taken from our 100 GeV/c data as an example (compendia of these are available upon request). The overall precision of the data is quite good -- $\pm 3\%$ on the absolute normalization, $\pm 0.5\%$ on slope determination and $\pm 3\%$ on the quadratic slope parameter. The overall t-scale is known to approximately 1.5%. The data has been parametrized with fits of the form $d\sigma/dt = A \exp(Bt + Ct^2)$ -- a so-called quadratic exponential. This parametrization gives a good representation of the data over the entire t-range. This form was proposed by Van Hove¹ on theoretical grounds. Table I contains a tabulation of the parameters of these fits.

Total elastic and inelastic cross sections. From the above mentioned data the total elastic cross sections can be calculated via the expression

$$\sigma_{el} = \int_{|t|=0}^{|t|=0.8} A \exp(Bt + Ct^2) dt$$

¹ Van Hove, Rev. Mod. Phys. 36 (1964) 655.

$$27.5e^{8.7t + 2.0t^2}$$

$$18.0e^{7.8t + 1.9t^2}$$

$$73.6e^{10.7t + 1.5t^2}$$

$$28.5e^{9.2t + 2.4t^2}$$

$$21.0e^{9.0t + 2.0t^2}$$

$$91.3e^{11.9t + 1.4t^2}$$

Figure 1. Typical Elastic Differential Cross-Sections. (Curve is best fit.)

Table I. Quadratic Exponential Fits

FITS TO FUNCTION $A \exp(B \cdot T + C \cdot T^2)$
OPTICAL THEOREM POINT (OTP) INCLUDED AS DATA POINT WITH 3 PER CENT UNCERTAINTY

	OTP	A		B		C		D(-.2)		PROB	DEGR
PI P-50	29.500	31.293+-	0.417	-9.609+-	0.114	3.090+-	0.155	-0.450+-	0.057	0.093	16
PI P-70	29.400	28.900+-	0.460	-9.094+-	0.108	2.391+-	0.433	-8.136+-	0.050	0.904	11
PI P-100	29.300	28.496+-	0.430	-9.242+-	0.139	2.420+-	0.221	-8.271+-	0.062	0.014	17
PI P-140	29.600	29.169+-	0.495	-9.246+-	0.160	2.419+-	0.262	-8.279+-	0.070	0.220	16
PI P-175	29.500	30.203+-	0.509	-9.508+-	0.117	2.318+-	0.169	-8.461+-	0.050	0.002	17
K P -50	21.000	21.227+-	0.605	-8.940+-	0.325	2.491+-	0.597	-7.952+-	0.143	0.512	12
K P -70	21.000	20.949+-	0.505	-8.809+-	0.385	2.225+-	1.072	-7.919+-	0.165	0.099	10
K P -100	21.300	21.044+-	0.565	-9.037+-	0.351	2.774+-	0.655	-7.928+-	0.142	0.284	14
K P -140	21.500	21.393+-	0.597	-9.052+-	0.325	2.440+-	0.727	-8.073+-	0.126	0.525	11
K P -175	21.500	22.222+-	0.563	-9.244+-	0.252	2.840+-	0.510	-8.103+-	0.104	0.679	13
P P -50	95.200	99.167+-	1.651	-12.649+-	0.230	3.264+-	0.469	-11.344+-	0.698	0.260	15
P P -70	94.000	89.523+-	1.750	-12.630+-	0.328	3.417+-	0.569	-11.463+-	0.153	0.605	11
P P -100	90.300	91.255+-	2.512	-11.942+-	0.469	1.416+-	1.315	-11.376+-	0.220	0.662	13
P P -140	88.500	89.310+-	2.551	-12.571+-	0.436	4.080+-	1.223	-10.971+-	0.242	0.931	10
P P -175	80.400	87.572+-	2.433	-13.075+-	0.279	4.691+-	1.101	-11.196+-	0.193	0.900	12
PI P+50	27.400	27.291+-	0.400	-8.725+-	0.125	1.756+-	0.193	-8.006+-	0.059	0.247	17
PI P+70	27.400	27.339+-	0.450	-8.607+-	0.146	1.876+-	0.256	-7.859+-	0.056	0.793	15
PI P+100	27.700	27.451+-	0.707	-8.763+-	0.105	1.860+-	0.272	-7.999+-	0.091	0.599	15
PI P+140	28.000	28.789+-	0.491	-9.009+-	0.146	2.232+-	0.244	-8.116+-	0.063	0.795	17
PI P+175	28.500	28.000+-	0.384	-9.064+-	0.105	2.323+-	0.163	-8.154+-	0.044	0.494	16
K P +50	16.600	16.594+-	0.417	-7.577+-	0.306	1.115+-	0.586	-7.131+-	0.124	0.655	14
K P +70	17.200	17.265+-	0.419	-8.076+-	0.303	2.188+-	0.638	-7.201+-	0.107	0.608	14
K P +100	16.200	10.040+-	0.527	-7.773+-	0.308	1.856+-	0.523	-7.031+-	0.134	0.615	11
K P +140	16.900	18.657+-	0.469	-8.304+-	0.217	2.163+-	0.384	-7.450+-	0.090	0.337	15
K P +175	19.700	19.705+-	0.345	-8.413+-	0.161	2.126+-	0.279	-7.562+-	0.072	0.557	15
P P +50	76.200	75.946+-	0.931	-10.281+-	0.137	1.527+-	0.270	-9.670+-	0.055	0.994	14
P P +70	75.800	75.551+-	1.135	-10.553+-	0.156	1.840+-	0.294	-9.817+-	0.056	0.045	15
P P +100	75.500	73.672+-	1.660	-10.693+-	0.177	1.498+-	0.297	-10.074+-	0.077	0.460	16
P P +140	76.300	75.564+-	1.311	-11.269+-	0.140	2.543+-	0.245	-10.252+-	0.062	0.532	17
P P +175	76.000	76.456+-	1.310	-11.252+-	0.135	2.319+-	0.249	-10.324+-	0.054	0.093	13

since contributions from $|t| > 0.8$ are less than 0.5% due to the falling of the elastic cross section by more than two orders of magnitude in the range $0.0 < |t| < 0.8$. These results are tabulated in Table II. Using the precision total cross section results of another Fermilab experiment² it is possible to combine them with our elastic measurements to determine the total inelastic cross sections. These results are also contained in Table II. As an example, Figure 2 and 3 show a plot of the ratio of the elastic to total cross section for protons on protons and for kaons on protons for this experiment and the world sample. Since protons have been measured by other means in many other experiments and over a wider energy range, this comparison serves to "calibrate" our method. The kaon data has never existed before and is shown to fit smoothly onto lower energy data and indicates the flattening of the previous drop in energy dependence.

In general, where we have energies which overlap with other experiments at the extremities of our range (Serpukhov and ISR) the agreement is good.

Some conclusions can be drawn from the above results:

- 1) The cross sections are quite well described by the quadratic exponential form over the whole t -range from -0.04 to $-0.8 \text{ GeV}/c^2$.
- 2) There are no dips observed in $d\sigma/dt$ within the limits of our resolution.
- 3) pp and K^+p elastic scattering show strong "shrinkage" via the slope parameter B .
- 4) $\bar{p}p$ shows strong "anti-shrinkage" in the same parameter.
- 5) The slope parameters for π^+p , π^-p , and K^-p show little energy dependence in this range. (Figure 4 shows points (3), (4) and (5).)
- 6) The behavior of the pp and K^+p slopes is consistent with the simple

² Carroll et al., Phys. Rev. Lett. 33 (1974) 928.
Carroll et al., Phys. Rev. Lett. 33 (1974) 932.

Table II.

TOTAL ELASTIC CROSS SECTIONS CALCULATED FROM 3 PER CENT FIT

	TOTAL ELASTIC CROSS SECTION (MB)	TOTAL CROSS SECTION (MB)	TOTAL INELASTIC CROSS SECTION (MB)	TOTAL ELASTIC TOTAL
PI P+50	3.29 +- .1053	23.07 +- .1153	19.78 +- .1542	0.142 +- .0046
PI P+70	3.35 +- .1223	23.16 +- .1158	19.81 +- .1685	0.145 +- .0053
PI P+100	3.30 +- .1507	23.29 +- .1164	19.99 +- .1905	0.142 +- .0065
PI P+140	3.39 +- .1226	23.43 +- .1171	20.04 +- .1696	0.145 +- .0053
PI P+175	3.37 +- .1027	23.50 +- .1180	20.23 +- .1584	0.143 +- .0044
K P +50	2.27 +- .0877	18.03 +- .0901	15.76 +- .1258	0.126 +- .0049
K P +70	2.30 +- .0990	18.36 +- .0918	16.06 +- .1350	0.125 +- .0054
K P +100	2.47 +- .1135	18.85 +- .0942	16.38 +- .1475	0.131 +- .0061
K P +140	2.40 +- .1004	19.23 +- .0961	16.83 +- .1390	0.125 +- .0053
K P +175	2.30 +- .0637	19.59 +- .0979	17.09 +- .1288	0.128 +- .0043
P P +50	7.61 +- .2894	38.14 +- .1907	30.53 +- .3457	0.199 +- .0076
P P +70	7.41 +- .3125	38.24 +- .1912	30.83 +- .3563	0.194 +- .0082
P P +100	7.07 +- .3522	38.39 +- .1919	31.32 +- .4011	0.184 +- .0092
P P +140	7.00 +- .2801	38.57 +- .1928	31.57 +- .3401	0.182 +- .0073
P P +175	7.05 +- .2803	38.76 +- .1938	31.70 +- .3408	0.182 +- .0073
PI P-50	3.48 +- .1057	24.01 +- .1200	20.53 +- .1506	0.145 +- .0045
PI P-70	3.39 +- .1415	24.00 +- .1200	20.61 +- .1555	0.141 +- .0059
PI P-100	3.28 +- .1096	23.96 +- .1198	20.68 +- .1623	0.137 +- .0046
PI P-140	3.26 +- .1244	24.00 +- .1200	20.64 +- .1729	0.140 +- .0052
PI P-175	3.38 +- .1126	24.17 +- .1208	20.79 +- .1651	0.140 +- .0047
K P -50	2.54 +- .1140	20.25 +- .1012	17.71 +- .1525	0.125 +- .0037
K P -70	2.53 +- .1210	20.30 +- .1015	17.77 +- .1580	0.125 +- .0060
K P -100	2.51 +- .1166	20.41 +- .1020	17.90 +- .1550	0.123 +- .0037
K P -140	2.52 +- .1238	20.50 +- .1025	17.98 +- .1607	0.123 +- .0061
K P -175	2.59 +- .1187	20.70 +- .1035	18.11 +- .1575	0.125 +- .0058
P P -50	8.20 +- .3950	43.86 +- .2193	35.66 +- .4518	0.187 +- .0091
P P -70	7.30 +- .4708	43.00 +- .2150	35.70 +- .5175	0.170 +- .0110
P P -100	7.80 +- .5923	42.04 +- .2102	34.24 +- .6341	0.185 +- .0143
P P -140	7.52 +- .5969	41.80 +- .2090	34.28 +- .6325	0.180 +- .0143
P P -175	7.12 +- .5247	41.60 +- .2080	34.48 +- .5644	0.171 +- .0126

Figure 4

Slope Parameter in Elastic Scattering

Regge picture that reactions requiring exotic, s-channel quantum numbers should be dominated by the Pomeron pole. In fact, we can extract the parameters of the assumed Pomeron trajectory which are $\alpha(t) = (0.98 \pm 0.007) + (0.22 \pm .03)|t|$ and they are quite close to the form usually favored in such models. Figure 5 illustrates this extraction.

- 7) The $d\sigma/dt$ for particle and anti-particle exhibit "cross-overs" (that is, they have different slopes and different $|t| = 0$ intercepts such that at some particular value of $|t|$ they have equal $d\sigma/dt$ and then cross-over). For $K^\pm$ and $p^\pm$, the slopes are sufficiently different that they can be used to extract³ the effective radius of interaction for the charge conjugation $C = \pm 1$ exchanges. It is found that $R_+/R_- = 1$ to better than 10% for both particle types.
- 8) As was mentioned, the elastic cross sections for all cases fall rapidly with energy in a manner consistent with power law behavior but then level off at high energy and become nearly constant. The rapid fall off at low energy is consistent with the simple Regge pole prediction⁴ that $\sigma_{el} = K s^{-2\alpha'} |<t>|$ where $<t>$ is the average value of $|t|$. The levelling off is taken to be associated with the decreasing Pomeron slope (α') and decreasing $<t>$. The fact that the elastic cross section becomes constant or slowly falling is in dramatic contrast with the rising inelastic cross section which then seems to account for the rise in the total cross section seen to begin at these energies.

³ Davier and Harrari, Physics Letters 40B (1972) 281.

⁴ Barger and Cline, "Phenomenological Theories of High Energy Scattering", W. A. Benjamin Co., N.Y. (1969) 66.

Figure 5

- 9) "Geometric scaling", which is the hypothesis that the scattering amplitude depends upon only the ratio of impact parameter and a radial scale variable containing s ($A(s,b) = A(\frac{b}{R(s)})$), seems to be obeyed very well over this energy range. As examples of the predictions⁵ for geometric scaling are that the ratios B/σ_{tot} and the curve $\frac{1}{\sigma_{\text{tot}}} \times \left(\frac{d\sigma}{dt}\right)_{\text{el}}$ vs. $\sigma_{\text{tot}} \cdot t$ should be independent of energy (B is the elastic slope parameter). Figure 6 (and its attached Table III) give examples of this agreement. The importance of this sort of test is that if geometric scaling is obeyed, certain models are excluded or must be otherwise modified; for example, conventional Regge models with poles and cuts do not exhibit geometric scaling behavior.
- 10) An impact parameter analysis of the elastic differential cross sections show that the meson-baryon interaction is 20% more transparent and has an interaction radius about 6% smaller than the baryon-baryon interaction. The increase in the pp total cross section as a function of energy is shown to come only from an increase in the pp interaction radius, while for the K^+p case such an increase could also come from an increase in the central opacity. Figure 7 shows some of the data upon which these conclusions are derived.
- 11) A simple quark model⁶ suggests several rules among the amplitudes:

$$\text{Test 1 : } \frac{\frac{2}{3} a(\pi^- p) + \frac{1}{3} a(\pi^+ p)}{\frac{1}{2} a(K^+ p) + \frac{1}{3} a(\bar{p} p)} - 1 = 0$$

⁵ Buras et al., Nuclear Physics 71B (1974) 481.

⁶ Lipkin, Physics Letters B56 (1975) 76.

Table III. Ratio $B^{\text{eff}}/\sigma_{\text{tot}}$, where $B^{\text{eff}} \equiv$ effective slope at $|t| = 0.2 \text{ (GeV/c)}^2$.

GeV/c		$B^{\text{eff}}/\sigma_{\text{tot}}$		$B^{\text{eff}}/\sigma_{\text{tot}}$
50	$\pi^+ p$	$.350 \pm .006$	$\pi^- p$	$.354 \pm .005$
100		$.342 \pm .009$		$.338 \pm .007$
140		$.348 \pm .009$		$.342 \pm .009$
50	$K^+ p$	$.376 \pm .021$	$K^- p$	$.385 \pm .021$
100		$.373 \pm .020$		$.386 \pm .024$
140		$.390 \pm .017$		$.391 \pm .017$
50	pp	$.251 \pm .004$	$\bar{p}p$	$.260 \pm .007$
100		$.263 \pm .007$		$.257 \pm .010$
140		$.267 \pm .004$		$.267 \pm .013$

Figure 6: Scaled elastic scattering data: $\left(\frac{1}{\sigma_{\text{tot}}^2} \cdot \frac{d\sigma}{dt} \right)$ vs. $\left(\sigma_{\text{tot}} \cdot t \right)$ for the $K^+ p$, pp , and $\bar{p}p$ reactions, at two energies. [Units are $\text{mb}^{-1} (\text{GeV/c})^{-2}$ vs. $\text{mb} (\text{GeV/c})^2$]

Figure 7. Preliminary results for the elastic scattering amplitude $a(R)$ and the inelastic overlap function $I(R)$, in impact parameter space, at two momenta.

$$\text{Test 2: } \frac{a(K^-p) - 1/2 a(K^+p) + 1/3 a(pp)}{1/2 a(\pi^-p) + 1/2 a(\pi^+p)} - 1 = 0$$

Figure 8 shows that these rules are not well satisfied over the full range of impact parameter space. The observed differences might be used as theoretical input for the quark spatial distribution in hadrons.

In addition to the work represented by the results given above, further work has been proceeding in the area of the inelastic data taken during the experiment. In particular attention has been given to extracting the data for the inclusive hadron exchange reactions:

$$\pi^+ + p \rightarrow K^+ + \text{anything}$$

$$\pi^- + p \rightarrow K^- + \text{anything}$$

$$\pi^- + p \rightarrow \bar{p} + \text{anything}$$

$$\pi^+ + p \rightarrow p + \text{anything}$$

$$p + p \rightarrow \pi^+ + \text{anything}$$

$$p + p \rightarrow K^+ + \text{anything}$$

and inelastic diffraction scattering through

$$\pi^\pm + p \rightarrow \pi^\pm + M_X$$

$$K^\pm + p \rightarrow K^\pm + M_X$$

$$p^\pm + p \rightarrow p^\pm + M_X$$

Work has also been progressing on the data taken using deuterium as a target, the preliminary effort has been spent in trying to understand the re-coil arm of the system which is important if the maximum information is to be extracted from the deuterium data. Mr. Lorne Levinson, part of whose Ph.D. thesis will contain data from this portion of the experiment, is responsible for this area.

Figure 8

II. Experimental Runs in Progress and in Preparation.

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

A little over a year ago the FNAL Program Committee approved our proposal to study inclusive reactions including particle multiplicity detection. The experiment began testing late last summer and in the late fall we had our first data run. A second data run is in progress now.

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^+ mesons, and π^+ 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 and positive charge for these first data runs but will be extended to other momenta and negative charge in later runs. 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 has been performing beautifully during our runs so far and the quality of the data appears to be excellent. Figure 1 shows data

¹ L. Foa, Physics Reports, 22C (1975) 1-56.

² H. Boggild and T. Ferbel, Am. Rev. Nucl. Sci. 12 (1975) 451-513.

³ R. Slansky, Physics Reports 11C (1974) 99.

⁴ J. Whitmore, Physics Reports 10C (1974) 273.

46 5810

$\frac{d\sigma}{d^3p}$

mb/GeV^2

K·E SEMI-LOGARITHMIC 3 CYCLES x 140 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

FIG 1A

46 5810

$E \frac{d\sigma}{d^3p}$

nb/GeV^2

K·E SEMI-LOGARITHMIC 3 CYCLES x 140 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

0

175 GeV

$P_L = 0.5$

(E118 RAW ON-LINE)

FIG. 1B

taken in our current run just as it comes on-line; no corrections have been made such as Cerenkov efficiency, detailed spectrometer acceptance, etc. For calibration against cross sections previously measured in other experiments^{2,4}, the $pp \rightarrow pX$ and $pp \rightarrow \pi^+X$ for example, these raw data agree quite satisfactorily; reactions such as $\pi^+p \rightarrow \pi^-X$ are completely new in this kinematic range. While these runs have been going on work has been progressing at Brown adapting some of the so-called "Rapid-Off-Line" computer programs, developed for use during our runs at FNAL, so that they may be used in the final analysis system here.

We expect to continue running during the coming year and look forward to an important experiment of high quality.

b) 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 have submitted three 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 $p_t \sim 0$ to $p_t \sim 1.25$. 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.⁵ and Lederman et al.⁶ have shown that the A-dependence of the inclusive π^0 cross section increases from $A^{2/3}$ to $A^{4/3}$ going from $p_t \sim 0$ to $p_t \sim 4$, 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. All current models predict a weak A-dependence for the leading particle. 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 favorably received in a proposal presentation meeting of the P.A.C. at Fermilab this Spring. A decision on it is expected this summer.

⁵ Cronin et al., Phys. Rev. D11 (1975) 3105.

⁶ Lederman, "Proc. of VI Int. Conf. on High Energy Physics and Nucl. Struct.", (1975) Santa Fe, New Mexico.

c) An Experiment to Study Characteristic
Hadron Signatures Associated with Directly
Produced Electrons at FNAL (FNAL #457).

In this second proposal we intend to investigate the anomalous production of leptons in hadron reactions using the FNAL cyclotron magnet facility in conjunction with a direct electron trigger. The large aperture of the magnet plus the existing detector array will make it possible to study the topology of the anomalous events for distinctive signatures such as invariant mass peaks or accompanying π 's or K^0 's. The use of an electron trigger instead of a muon trigger allows better off-line noise suppression as well as overall event reconstructability.

Preliminary to performing such an experiment, however, it is important to perform an experimental test of the effectiveness of such a trigger since all of the physical parameters are not yet known. Consequently, we are proposing a test (Phase I) first and if this is successful will submit a full proposal (Phase II).

The tests in Phase I concern the offline rejection of Dalitz pair electrons by our system (see Phase II outline), and require only minor modifications to the existing cyclotron magnet spectrometer.

A. The ability to follow tracks to a vertex wholly within the magnet must be tested. We propose to do this using computer-aided scanning. The presently available 1 meter X 1 meter proportional chambers would be configured inside the magnet for a run with a solid target placed at the front edge of the magnet.

B. The detection efficiency and unambiguous spatial measurement of photons in the magnetostrictive spark chambers can be tested simultaneously with "A". It will be necessary to intersperse the chambers with lead sheets in the present locations.

To carry out these tests, we have made the following requests of FNAL: permission to reconfigure the proportional chambers inside the cyclotron magnet and 100 hours of running time with a 100 GeV pion beam incident on a solid target.

The physics of the experiment concerns the recently discovered narrow width resonances which are most easily explained by postulating the presence of a new and heavy quark with a new quantum number. The narrowness is then explained by a Zweig rule disallowing decays into the usual mesons. The new mesons do not possess a new quantum number that would be carried by the quark, i.e. they are all of the type $c\bar{c}$ (c is the new quark).

An extension of this idea would lead one to expect new particles carrying this new quantum number, c . Like strange particles, they would only decay weakly into $c = 0$ particles (e.g. π -mesons). One would also expect semi-leptonic decays of these particles leading to the appearance of directly produced charged leptons⁷.

Experimental evidence suggests that there are charged leptons in hadronic events whose source is incompatible with their production by pairs (see for example, Lederman, Stanford Lepton Photon Conference, August 1975). These two phenomena taken together suggest that "charmed" mesons are present in hadron reactions. The level of anomalous charged lepton production (e or μ to $\pi = 10^{-4}$) suggests that the fraction of events with such particles followed by a decay into charged lepton is one in 1600.

Further evidence for this hypothesis is seen in the experiments at SPEAR⁸. An increase in hadron production relative to μ -pair production in e^+e^- annihilation is seen as the total of c-of-m energy increases beyond 4 GeV. This can

⁷ Gaillard, Lee, and Rosner, Rev. Mod. Phys. 47 (1975) 277.

⁸ Many papers contained in "Proceedings of Lepton-Photon Conference" (1975) Stanford University.

be interpreted as an energy threshold in charmed particle pair production. Although not yet confirmed, there may be unique mass states when they reconstruct masses from the charged particles that they measure. It would be expected that charmed states would decay down to the lowest mass state which would decay hadronically as well as semileptonically.

While there are many searches underway at FNAL and elsewhere to find out what is produced with the anomalous single leptons in hadron reactions, we believe this proposal to be a promising solution.

A low-noise μ -trigger can be made only by blocking the background $\pi \rightarrow \mu\nu$ decays over nearly half the solid angle, but this prevents the observation and mass reconstruction of multi-prong hadron products.

A low-noise e-trigger is harder to achieve, but the backgrounds are such that their repression need not interfere with the reconstruction of multi-prong hadron states. This proposal is for an electron trigger with good on-line and excellent off-line noise rejection, leaving full solid angle for observing associated multi-hadron states. This low-noise e-trigger will remain excellent for tagging $e\mu$ coincidences even when a half-plane is blocked off to suppress the μ -decay background.

The purpose of the experiment in Phase II would then be to find events containing a directly produced charged lepton (e or μ) with the expectation of seeing the topology, character, and energy distribution in such events and to ensure that the events to be observed contain a rich sample of such directly produced particles. We include the possibility that such events are produced in pairs (e^+e^- or $\mu^+\mu^-$), or even as $e\mu$ pairs.

The SPEAR experience indicates that the search for unique mass states is difficult even with a presumably rich sample of "charmed" particles. We will require that the event sample to be used for mass -- or odd signature -- searches be relatively uncontaminated by conventional events masquerading as

direct lepton production (i.e., signal/background ≈ 1 or better). We also require a large efficiency ($\sim 90\%$) for finding and measuring charged tracks. This is a difficult experiment and some of the difficulties are enumerated below. Events triggered on μ -mesons suffer from a background coming from π -decays in flight. Various methods can be used to minimize or select out such events. To try to overcome this an absorber may be placed close to the target to minimize the π flight paths; this unfortunately will mask analysis of other particles leaving the target. Also with good enough event reconstruction, the kink from the decay may be seen in some fraction of the events. If the decay occurs in a magnetic field, a change in curvature may be detected as well. This technique requires high precision measurements which are not available in any apparatus we know of. At best, these methods will produce a sample of events where there is a comparable amount of π decay background. For the e-trigger presents two large problems: electrons are present from Dalitz decay of the π^0 (1 in 80 decays therefore 3 in 80 events -- $\bar{n}(\eta^0) \approx 3$ at 100 GeV). The target itself and other materials convert some of the π^0 gamma rays. Secondly, the electron is usually identified in a high Z shower counter (an electro-photometer). π -mesons through nuclear interactions will occasionally give a hadronic shower whose pulse height is nearly equal to that from the same momentum electron. This becomes severe, considering the relatively large number of π 's produced. (10^4 to 1)

An oral presentation of this proposal was made at the P.A.C. meeting last Fall. Due to the very large over-subscription of running time assigned to current experiments in the Muon beamline no action was taken. No time has been set for when this proposal will be acted upon.

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

This is the third new proposal submitted by the group 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 "antideuteron" 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 such 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^{7,9}. These create a new interest in looking for

⁹ See for example: Augustin et al., Phys. Rev. Lett. 33 (1974) 1406.
Abrams et al., Phys. Rev. Lett. 33 (1974) 1453.
Aubert et al., Phys. Rev. Lett. 33 (1974) 1404.
Perl et al., Phys. Rev. Lett. 35 (1975) 1489.
Benvenuti et al., Phys. Rev. Lett. 34 (1975) 419.
Krishnaswamy et al., Phys. Lett. 57B (1975) 105.
De Rujula, Georgi, Glashow, Phys. Rev. Lett. 35 (1975) 628.
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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 Fermilab¹⁰, at the ISR¹¹, at Serpukhov¹², and at lower energies¹³. In these experiments, deuterons, anti-deuterons, 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.

¹⁰ Appel et al., Phys. Rev. Lett. 32 (1974) 428.
Leipuner et al., Phys. Rev. Lett. 31 (1973) 1226.
SAS Group, Fermilab Report - NAL 73/83 EXP 7100.096.

¹¹ Bott-Bodenhausen et al., Phys. Lett. 40B (1972) 693.
Alper et al., Phys. Lett. 46B (1973) 265.

¹² Bushnin et al., Phys. Lett. 29B (1969) 48.
Binon et al., Phys. Lett. 30B (1969) 506.
Binon et al., Phys. Lett. 30B (1969) 510.
Antipov et al., Phys. Lett. 29B (1969) 245.
Antipov et al., Nucl. Phys. B27 (1971) 374.

¹³ Dorfan et al., Phys. Rev. Lett. 14 (1965) 995.
Dorfan et al., Phys. Rev. Lett. 14 (1965) 999.
Dorfan et al., Phys. Rev. Lett. 14 (1965) 1003.
Allaby et al., Nuovo Cim. LXIV (1969) 75.

Our proposed experimental technique is as follows: Since the M6 beam has a narrow momentum acceptance ($\pm 1\%$), 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 counter techniques to accomplish this. The detectors of the facility which are relevant to this experiment are the five threshold Cerenkov counters and three differential Cerenkov counters which are available.

Light particles of mass less than $1.1 \text{ GeV}/c^2$ 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

$$\ell = C2 + C3 + D1$$

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 few weeks ago.

III. Associated Matters

During the past contract year the group had the very welcome addition of Dr. Robert Dulude as a Research Associate. Dr. Dulude received his Ph.D. last year from Purdue University where he participated in research related to the study of hadronic interactions. At Brown he has been assisting in our current Fermilab experiment, the $\bar{P}P$ studies, and plans for new experiments.

Professor Cutts has been invited and will participate as one of the Faculty Lecturers in the International School of Sub-Nuclear Physics (The Ettore Majorana Center in Erice, Sicily). The course is entitled "Understanding the Fundamental Constituents of Matter" and Professor Cutts will speak about Fermilab experiments in hadron physics as done principally with the Single-Arm Spectrometer.

Serving as group spokesman for FNAL #469, Professor Cutts presented the proposal in a talk before the Fermilab Physics Program Advisory Committee at its May meeting.

Professor Lanou has been invited and will participate in the Third European Symposium on Antinucleon-Nucleon Interactions to be held in Stockholm, Sweden during 9-13 July.

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

R. E. Lanou, Jr.	--	Professor
J. T. Massimo	--	Professor
D. Cutts	--	Assistant Professor
R. S. Dulude	--	Research Associate
R. P. Himmer	--	Graduate Research Assistant
L. J. Levinson	--	Graduate Research Assistant

B. Bubble Chamber - Proportional Hybrid System Program.

I. Data 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 are based on 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 hybrid system, in which the hydrogen bubble chamber serves as target, provides for the identification of incoming particles by Cerenkov counters, the precise determination of their direction by upstream proportional wire chambers (PWCs), and for precise momentum and direction measurement of the fast forward charged particles by PWCs downstream of the bubble chamber. The latter provides 4π sensitivity for all charged particles produced in a collision, and considerable detection of neutral V's and gamma rays as well. This system and its properties have been described in considerable detail in previous Progress Reports and Renewal Proposals.

Analysis of the data has continued vigorously during the past year. Papers and Letters have been published concerning the cross sections and charged multiplicity distributions of π^-p and K^-p interactions, inelastic two-prong events, ρ^0 production, and evidence for the emission of clusters of charged particles. (See Section C, References 230-233.) In addition, two contributed and one invited paper were presented at the January 1976 meeting of the American Physical Society, and four papers at the April 1976 meeting of the APS (References 227-229 and 234-237). Three other papers have been submitted for publication, (References 238-240) and others are in preparation. Some of the results are briefly discussed here.

(i) Cross Sections and Charged Particle Multiplicity Distributions for π^-p and K^-p Interactions at 147 GeV/c.

Since each particle traversing the counter telescope upstream of the bubble chamber was identified by means of its Cerenkov signal, the interactions of the 147 GeV/c π^- and K^- mesons in the bubble chamber were separately and individually identified and analyzed. The topological cross sections for π^-p and K^-p interactions are given in Table I, and some moments of the distributions are given in Table II (see also Section C, Reference 230). The statistical errors given there reflect the fact that the π^- mesons constitute 94.2% and the K^- only 1.9% of the beam particles entering the bubble chamber. However, our K^- data are the first such obtained at a momentum above that of the Serpukhov experiment at 33.8 GeV/c.^{1*}

The variation of $\langle n \rangle$ with energy has been studied for both π^-p and K^-p interactions. In particular, both logarithmic and power law variation with s/s_0 ($s_0 = 1(\text{GeV}/c)^2$), as suggested by various models, have been tried. For π^-p interactions, data at four beam momenta -- 50, 100, 147 and 205 GeV/c,² have been fitted, with the following results:

$$\langle n \rangle = (2.02 \pm 0.01)(s/s_0)^{0.231 \pm 0.001},$$

$$\chi^2/\text{NDF} = 0.08/2, \quad \text{confidence level} = 0.96;$$

and

$$\langle n \rangle = (-1.2 \pm 0.1) + (1.53 \pm 0.03)\ln(s/s_0),$$

$$\chi^2/\text{NDF} = 1.0/2, \quad \text{confidence level} = 0.61.$$

Both laws fit the data well, over the momentum region covered. For the K^-p data, the results are:

* All footnotes are placed at the end of each major section. (see pg. 54)

Table I. Topological cross sections at 147 GeV/c.

Number of Charged Prongs		Cross Sections for $\pi^- p$ Interactions (mb)		Cross Sections for $K^- p$ Interactions (mb)	
2		5.04	± 0.15	4.27	± 0.53
	Elastic	3.24	± 0.14	2.74	± 0.42
	Inelastic	1.80	± 0.12	1.53	± 0.32
4		4.12	± 0.10	3.59	± 0.47
6		4.47	± 0.10	4.75	± 0.58
8		4.30	± 0.11	3.27	± 0.47
10		3.09	± 0.09	3.27	± 0.47
12		1.78	± 0.07	1.32	± 0.32
14		0.83	± 0.05	0.47	± 0.21
16		0.39	± 0.03	0.16	± 0.11
18		0.15	± 0.02	0.32	± 0.16
20		0.054	± 0.010	0.11	± 0.05
22		0.0070	± 0.0036		
24		0.0048	± 0.0028		
26		0.0016	± 0.0016		
Total		24.24	± 0.29	21.5	± 1.0

Table II. Moments of multiplicity distributions at 147 GeV/c.

	$\pi^- p$	$K^- p$
$\langle n \rangle$	7.40 $\pm$ 0.04	7.33 $\pm$ 0.21
$\langle n(n-1) \rangle$	59.9 $\pm$ 0.7	58.7 $\pm$ 3.7
$\langle n^2 \rangle$	67.3 $\pm$ 0.7	66.0 $\pm$ 3.9
f_2 (a)	5.14 $\pm$ 0.22	5.0 $\pm$ 1.1
D (b)	3.54 $\pm$ 0.03	3.51 $\pm$ 0.17
$\langle n \rangle / D$	2.09 $\pm$ 0.02	2.09 $\pm$ 0.09

(a) $f_2 = \langle n(n-1) \rangle - \langle n \rangle^2$

(b) $D = (\langle n^2 \rangle - \langle n \rangle^2)^{1/2}$

$$\langle n \rangle = (1.37 \pm 0.06)(s/s_0)^{0.31 \pm 0.01} ,$$

$$\chi^2/\text{NDF} = 16.6/4, \quad \text{confidence level} = 0.002 ;$$

and

$$\langle n \rangle = (-0.78 \pm 0.73) + (1.39 \pm 0.07)\ln(s/s_0) ,$$

$$\chi^2/\text{NDF} = 17.0/4, \quad \text{confidence level} = 0.002 .$$

The fit for the K^-p data has been extended over a much larger momentum interval than was used for the π^-p data (from 8.25 GeV/c to 147 GeV/c), and the low confidence levels indicate that the parameters of the fits are not constant over the whole range.

Assuming Feynman scaling at asymptotic values of s , Koba, Nielsen and Olesen (KNO)³ have shown that as $s \rightarrow \infty$, the quantity $\langle n \rangle \sigma_n / \sigma_{\text{inel}}$ becomes a function of only $n/\langle n \rangle$:

$$\lim_{s \rightarrow \infty} (\langle n \rangle \sigma_n / \sigma_{\text{inel}}) = \psi(n/\langle n \rangle) .$$

This prediction appears to be well satisfied even at rather low momenta as shown by Figures 1 and 2, for π^-p and K^-p data respectively.^{1,2,4}

The universality of this scaling is impressive: The similarity of the π^-p and K^-p results is evident in Figures 1 and 2; and Figure 3 shows the 147 GeV/c π^-p and K^-p data of our experiment, together with a curve which was obtained from an empirical fit to the data for pp collisions in the momentum interval 50-500 GeV/c.⁵ There is no apparent dependence of the KNO scaling function on the identity of the incident hadron.

A related scaling function which emphasizes lower multiplicities is^{2(c),6}

$$\lim_{s \rightarrow \infty} (n \sigma_n / \sigma_{\text{inel}}) = \phi(\langle n \rangle / n) .$$

Figure 1

Figure 2

Figure 3

We have plotted $n\sigma_n/\sigma_{inel}$ as a function of $\langle n \rangle/n$ for our π^-p and K^-p data in Figure 4, together with a solid line drawn by eye through points, not shown, from π^-p , π^+p and pp data in the momentum range 50-300 GeV/c. Again, no significant dependence on momentum or nature of the incoming hadron is evident, within statistical errors.

This analysis has been described in detail in a paper published in Nuclear Physics B (Reference 230).

(ii) Average Charged Multiplicity in $\pi^-p \rightarrow \pi^-_{fast} + X$ at 147 GeV/c.

A number of studies have been made of the missing mass X recoiling against the outgoing proton in various reactions, but our experiment is the first to report on the variation of the average charged multiplicity $\langle n_X \rangle$ of the system X produced in the inclusive reaction

$$\pi^-p \rightarrow \pi^-_{fast} + X, \quad (1)$$

with the square of the invariant mass of X , M_X^2 , and with the square of the four-momentum transfer t between the incoming and fast outgoing π^- mesons. A fast π^- is defined as one with Feynman x greater than 0.5, where $x = 2p_L^*/\sqrt{s}$ and p_L^* is the longitudinal momentum of the π^- in the center of the mass system. This analysis is made possible by the good momentum resolution ($\Delta p/p < 0.09$) of the hybrid system for fast forward particles.

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 description⁷ of the high-mass diffractive region ($10 < M_X^2 < (s/10)\text{GeV}^2$, where s is the square of the total center-of-mass energy), and the ABFST multiperipheral model⁸ for $M_X^2 > 20 \text{ GeV}^2$. Moreover, the slope of the linear increase of $\langle n_X \rangle$ with

Figure 4

$\ln M_X^2$ has been predicted to be independent of s , t , and the type of the incident particle, and to be identical to the slope of the linear increase with $\ln s$ of the average total charged multiplicity, $\langle n_c \rangle$, in hadron-hadron reactions.⁷ These predictions have previously been verified for the reaction

at Fermilab and ISR energies,⁹ and in the reaction

at 205 GeV/c.¹⁰ However, it is not possible to fit $\langle n_c \rangle$ for the total inelastic pp reaction

by a $\ln s$ term alone over the whole range of s including ISR energies.

The addition of a term of the form $s^{-1/2}$, predicted by the inclusion of a secondary trajectory in a Mueller type analysis, does result in a satisfactory fit.¹¹ Experimental results for $\langle n_c \rangle$ for the total inelastic $\pi^- p$ reaction

can be fit by a $(\ln s)$ -dependence alone through Fermilab energies.^{2(a),10}

A linear dependence of $\langle n_c \rangle$ on $\ln s$ has also been observed in several weak and electromagnetic processes.¹²

The various models also suggest a dependence of $\langle n_X \rangle$ on t but do not predict a unique functional form.^{7,8} Studies of reaction (2) at 205 GeV/c and ISR energies and of reaction (3) at 205 GeV/c indicated that n_X has a weak or no t -dependence in these reactions.^{9,13}

In Figure 5(a) we present $\langle n_X \rangle$ from reaction (1) as a function of $|t|$ separately for the proton diffractive region ($M_X^2 < 20 \text{ GeV}^2$) and for the

Figure 5

region $M_X^2 > 20 \text{ GeV}^2$. Both distributions show a similar t -dependence; however, at equal $|t|$, $\langle n_X \rangle$ is lower by ~ 2 units for the proton diffractive region than for the higher M_X^2 region. In Figure 5(b), the t -dependence of $\langle n_X \rangle$ is presented for various M_X^2 intervals, and significant increases in $\langle n_X \rangle$ as a function of $|t|$ are observed in all M_X^2 regions. These data can all be fit by a linear dependence on $|t|$ and within our uncertainties the slopes of this dependence are independent of M_X^2 .

The dependence of $\langle n_X \rangle$ on $\ln M_X^2$ for $|t| < 2 \text{ GeV}^2$ is shown in Figure 6(a) and is consistent with the linear behavior that was found previously in reactions (2) and (3)^{9,10} and predicted theoretically.^{7,8} Figure 6(b) gives the dependence of $\langle n_X \rangle$ on $\ln M_X^2$ for different t intervals. These data can also be fit by a linear dependence on $\ln M_X^2$ and within our uncertainties the slopes of this dependence are independent of t .

We have therefore carried out a two-dimensional fit to all data for reaction (1) in the kinematical region $|t| < 2 \text{ GeV}^2$ and $20 < M_X^2 < 140 \text{ GeV}^2$ (the upper limit corresponds to the limit $x > 0.5$ for the fast π^-) of the expression,

$$\langle n_X \rangle = A + B(\ln M_X^2) + C|t|. \quad (6)$$

The best fit yields the parameters: $A = -1.77 \pm 0.61$, $B = 1.43 \pm 0.15$, and $C = 1.06 \pm 0.19$, with a chi-square probability of 26% ($\chi^2 = 42.5$ for 39 degrees of freedom). The solid lines in Figures 5 and 6 are plotted from this fitted function, where, for each $|t|$ or M_X^2 region, the weighted average in that region has been used in the above expression. As one can see, all the data in Figures 5 and 6 are satisfactorily described by this parametrization.

We have also carried out a fit of equation (6) to the data for

Figure 6

reaction (3) from this experiment and obtained the preliminary result for B which is given in Table III. Table III also contains the value of the coefficient of the $\ln M_X^2$ or $\ln s$ term from previous fits to $\langle n_X \rangle$ or $\langle n_c \rangle$, respectively, for reactions (2) - (5). It can be seen that all the values given, including our result for reaction (1), are in good agreement with each other. It should be noted that the $B \ln M_X^2$ ($B \ln s$) term arises theoretically from the assumption of a uniform distribution of particles with respect to rapidity in the central region. Thus, in this region, $\langle n \rangle = CY$, where C is the average number of particles per unit rapidity and Y is the width of the rapidity range. However, since $Y \approx \ln M_X^2$ ($\ln s$) for large Y , this may be written $\langle n \rangle = C \ln M_X^2$ ($\ln s$).¹⁶ In this experiment the value found for C is 1.6 particles per unit rapidity, in good agreement with our value for the coefficient B.

The value of C obtained from our fit of expression (6) to the data for reaction (3) indicates that there is little or no t -dependence of $\langle n_X \rangle$, in agreement with previous results¹³ and contrasting with the significant t -dependence obtained from reaction (1). This difference may be due to dynamical reasons such as different interaction mechanisms for the two reactions or to kinematical reasons such as the Chew-Low boundary ($t_{\min}$) effect.

When we compare absolute values of $\langle n_X \rangle$ and $\langle n_c \rangle$ in $\pi^- p$ and pp inelastic reactions, using the results of our experiment and data from the literature, we find significant differences, at a given value of M_X^2 and s . These differences persist if the data is interpreted in terms of Q , the available energy, although, as previously pointed out,¹ the measured values of $\langle n_c \rangle$ for reactions $ab \rightarrow X$, when plotted as a function of $Q = \sqrt{s} - m_a - m_b$, lie approximately on a universal curve, for pp , $\pi^\pm p$

Table III. Values of the coefficient B obtained from fits to the data for various reactions for the expressions:

- (i) $\langle n_c \rangle = A + B(\ln s)$
(ii) $\langle n_X \rangle = A + B(\ln M_X^2)$
(iii) $\langle n_X \rangle = A + B(\ln M_X^2) + C|t|$

Reaction	Form of Fit	Coefficient B	s or M_X^2 Range (GeV ²)	Ref.
$pp \rightarrow X$	i	1.38 ± 0.02	$26 < s < 386$	14
$\pi^- p \rightarrow X$	i	1.41 ± 0.03	$13 < s < 95$	1
$pp \rightarrow pX$ (205 GeV/c)	ii	1.39 ± 0.09	$20 < M_X^2 < 200$	**
$\pi^- p \rightarrow pX$ (205 GeV/c)	ii	1.3 ± 0.1	$20 < M_X^2 < 180$	13(a)
$\pi^- p \rightarrow pX$ (147 GeV/c)	iii	1.47 ± 0.17	$20 < M_X^2 < 136$	this expt.
$\pi^- p \rightarrow \pi_f^- X$ (147 GeV/c)	iii	1.43 ± 0.15	$20 < M_X^2 < 140$	this expt.

** We have performed this fit with the data from Figure (1a) in Ref. 15.

and $K^{\pm}p$ interactions. Whitmore and Derrick¹⁵ have extended this idea to inclusive reactions of the type $ab \rightarrow cX$, where c is produced in the fragmentation region of the incoming particle a , and have plotted $\langle n_X \rangle$ as a function of Q , where $Q = M_X - m_b$ for this case. They point out that this is equivalent in a standard exchange picture to the reaction $Eb \rightarrow X$, where E is a virtual exchanged object (Pomeron, Reggeon, pion, or any combination of them) (see Figure 7(a)). A roughly universal dependence of $\langle n \rangle$ on $\ln Q^2$ has been obtained for reactions (2), (3), (4) and (5).¹⁵

In Figure 7(b) we compare our results for $\langle n \rangle$ as a function of $\ln Q^2$ for reactions (1) and (3) with published results for reactions (2) and (3) at 205 GeV/c^{9,10} and reactions (4) and (5) at energies corresponding to $Q^2 \leq 180 \text{ GeV}^2$.¹ The values of $\langle n \rangle$ for all of the above lie in a narrow band, except for our results for reaction (1) with $Q^2 > 20 \text{ GeV}^2$ which are significantly lower than this band. In all cases $\langle n \rangle$ grows linearly with $\ln Q^2$.

The difference observed for $\langle n \rangle$ between reaction (1) and reactions (2) - (5) prompted us to examine the dependence of $\langle n \rangle$ on $\ln Q^2$ for these reactions in more detail. Figures 8(a), (b), and (c) show the data for three pairs of reactions: (4) and (5),¹ (2) and (3) at 205 GeV/c,^{9,10} and (1) and (3) at 147 GeV/c, respectively. In all three pairs of reactions, there is a systematic displacement between the two sets of data, such that in each case the member of the pair involving a π^- interaction on a real proton, e.g. ($\pi^- p \rightarrow X$) or on a virtual exchanged object ($\pi^- E \rightarrow X$) has a higher $\langle n \rangle$ than that involving a p interaction on a proton or virtual exchanged entity

Figure 7

Figure 8

($pp \rightarrow X$ or $pE \rightarrow X$). In order to obtain a quantitative estimate of these displacements, we have carried out fits of the expression $\langle n \rangle = A'B'(\ln Q)^{-1}$ to the data for the five reactions of Figure 8 in the region $20 < Q^2 < 180 \text{ GeV}^2$ and over the whole t -range, where the variable Q' is defined by $Q'^2 = Q^2/Q_M^2$ and Q_M^2 is the central value of Q^2 in the fit, so that A' is the equal to $\langle n \rangle$ at the middle point of each fit (note the arrows in Figure 8). The results of these fits are presented in Table IV, and the solid lines drawn in Figures 8(a) - 8(c) have been calculated from the fitted coefficients A' and B' . The slopes of the lines are similar for all three pairs of reactions but in each case the lines are vertically displaced by an amount given by the difference between the two values of A' . These differences, δ' , are given in Table IV and are seen to be significant for all three pairs of reactions.*

Since models usually describe $\langle n \rangle$ in terms of the variables s and M_X^2 rather than Q , we have also performed fits of the dependence of $\langle n \rangle$ on s and M_X^2 for reactions (1-5) in a manner analogous to that described for the Q^2 variable. The results of fits of the expression $\langle n \rangle = A + B \ln s'(M_X'^2)$ (where $s' = s/s_m$, $M_X'^2 = M_X^2/M_m^2$, and s_m and M_m^2 are the central values of s and M_X^2 in each fit) to the data for the five reactions are given in Figures 8(d), (e), and (f) and in Table IV. For all the three pairs of reactions, the systematic displacements δ are larger than those for the Q^2 variable, δ' , as can be seen from the values given in Table IV. Again, a π^- -induced reaction on either a real p or a virtual E , in the description suggested by Figure 7(a),

* A two-standard deviation difference between $\langle n_c \rangle$ for reactions (4) and (5) in the range 40 to 205 GeV/c was reported in footnote 11 of Ref. 2(d).

Table IV. Values of the coefficients from fits of the average charged multiplicity $\langle n \rangle = A + B \ln s' (M_X'^2)$ and $\langle n \rangle = A' + B' \ln Q'^2$, over the whole t region, to the data for the six reactions of Figure 8. $Q'^2 = Q^2/Q_m^2$, $s' = s/s_m$, 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 8). Thus, A and A' are equal to the fitted value of $\langle n \rangle$ at the middle point. δ and δ' are the differences between those points for each pair of reactions.

Reaction	$\langle n \rangle = A + B \ln s' (M_X'^2)$			$\langle n \rangle = A' + B' \ln Q'^2$			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	1 (a)
$pp \rightarrow X$	4.74 ± 0.04	1.40 ± 0.06		5.30 ± 0.04	1.26 ± 0.05		1
(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	10
205 GeV/c							
$pp \rightarrow pX$	5.12 ± 0.07	1.39 ± 0.09		5.37 ± 0.08	1.23 ± 0.12		9
(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	this 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		this exp.

(a) The data of the highest two points (50 and 100 GeV/c) were taken from Refs. 2(b) and 2(c).

seems to produce on the average more hadrons than the corresponding p-induced reaction.

We have attempted to understand the differences observed in our study by a simple model¹⁷ which assumes that for any given reaction $ab \rightarrow X$, the outgoing particles can originate from three distinct regions (Figure 8(g)): a central region, which is independent of particles a and b and where the average multiplicity n_o increases with energy as $B \ln s$, and the fragmentation regions of particles a and b, where the average multiplicities n_a and n_b are presumably energy independent, but may depend on the nature of the fragmented particle. Based on this description one obtains for the average charged multiplicity:

$$\langle n_c \rangle = n_a + n_o + n_b = n_a + B \ln s + n_b \quad (7)$$

$\langle n_X \rangle$ for the single inclusive reaction, $ab \rightarrow cX$, may be described analogously where the process $E_{ac}b \rightarrow X$ replaces $ab \rightarrow X$, as previously discussed. Here, a and c are the particles in the reaction, $ab \rightarrow cX$, which are coupled to the virtual exchanged object, E_{ac} . This is indicated in Figure 8(h), where the fragmentation of the real particle a in Figure 8(g) is replaced by the fragmentation of the virtual object E_{ac} , which makes a contribution of n_{Eac} to the average multiplicity.

Thus:

$$\langle n_X \rangle = n_{Eac} + n_o + n_b = n_{Eac} + B \ln M_X^2 + n_b \quad (8)$$

Due to the virtual nature of E_{ac} , n_{Eac} (unlike n_a or n_b) may depend on the kinematic variables s , M_X^2 and t ; the detailed functional form $n_{Eac} = f(s, M_X^2, t)$ is model-dependent.

Using Equation (7) for reactions (4) and (5), and Equation (8) for reactions (1) - (3), the differences of the average multiplicities

for the three pairs of reactions in Table IV and Figure 8, $\delta(i)$, $\delta(ii)$, and $\delta(iii)$, are found to be:

$$\delta(i) = \delta(ii) = n_{\pi} - n_p \quad (9)$$

$$\delta(iii) = (n_{\pi} - n_p) + (n_{Epp} - n_{E\pi\pi}) \quad (10)$$

Note that for pairs (i) and (ii) the exchanged object, E_{ac} , is coupled to the same particles a and c, and hence, the n_{Eac} terms cancel out. Comparing the experimental results for δ for reaction pairs (i) and (ii) in Table IV, we find that, within errors, $\delta(i) = \delta(ii)$, in agreement with the prediction of (9). The average of their two values is:

$$n_{\pi} - n_p = 0.55 \pm 0.05 \quad (11)$$

A similar result may be obtained from a study¹⁸ of the following pair of reactions:

$$\pi^+ p \rightarrow \Delta^{++} X \quad (12)$$

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

at 100 GeV/c. According to our picture, a subtraction of the values $\langle n_X \rangle$ for reactions (12) and (13), given by expression (8), should be equal to $n_{\pi} - n_p$. The authors of Reference 18 quote the average multiplicity difference to be ~ 0.6 , in excellent agreement with (11). With $n_{\pi} - n_p$ from Equation (11) and the experimental value for $\delta(iii)$ from Table IV, we obtain from Equation (10)

$$n_{Epp} - n_{E\pi\pi} = 0.34 \pm 0.13 \quad (14)$$

The inequality of n_{Epp} and $n_{E\pi\pi}$ can be understood qualitatively since, although both exchange entities can consist of Pomeron and Reggeon (f^0, ρ^0) exchanges, π^- exchange can contribute only to Epp and not to $E_{\pi\pi}$, because of G-parity conservation.

Two short papers presenting these results have recently been submitted for publication to Physics Letters B (Sec. C, References 239 and 240); and a combined paper has been submitted to the XVIII International Conference on High Energy Physics, to be held at Tbilisi, U.S.S.R. (Reference 241). A report of preliminary results for the reactions $\pi^- p \rightarrow pX$ and $\pi^- p \rightarrow \Delta^{++} X$ was presented at the APS Washington meeting (Reference 236). Further analyses of these and other inclusive reactions will be presented in a later, more detailed paper.

(iii) Resonance Production.

The production of Δ^{++} and ρ^0 resonances has been studied both inclusively and exclusively, and considerable work is continuing on this subject. The exclusive production is being studied at present in 4-prong and 6-prong events which make satisfactory constrained fits (in SQUAW) with no neutral particles included. The 4-prong events are discussed in some detail in the following sub-section.

Inclusive production cross sections have been obtained from fits to the invariant mass plots, using appropriate Breit-Wigner shapes for the resonances. The measured cross sections and ρ/π ratios are shown in Table V.

Protons with momenta smaller than 1.4 GeV/c are identified by their ionization in the bubble chamber, and a strong Δ^{++} signal is observed in events with identified protons up through 12 prongs. Invariant mass plots for multiplicities 4 through 12 are drawn in Figure 9. The distribution in the Feynman x variable is shown in Figure 10 for all Δ^{++} events and for those having $|t_{\Delta^{++}}| < 1.0 \text{ (GeV/c)}^2$. The Δ^{++} production

Figure 9

Figure 10

Table V. Inclusive and exclusive resonance production in $\pi^- p$ interactions at 147 GeV/c.

Event Prong Number	$\sigma(\Delta^{++})$ (mb)	$\sigma(\rho^0)$ (mb)	Avg. Number of ρ^0 /event	ρ^0/π^+
2	--	0.04 ± 0.04	--	--
4	0.46 ± 0.06	0.9 ± 0.2	0.21 ± 0.05	0.15 ± 0.03
6	0.48 ± 0.08	1.8 ± 0.4	0.41 ± 0.08	0.16 ± 0.03
8	0.35 ± 0.10	1.6 ± 0.5	0.38 ± 0.11	0.10 ± 0.03
10	0.25 ± 0.09	1.7 ± 0.5	0.54 ± 0.17	0.11 ± 0.04
12-16	0.10 ± 0.09	1.2 ± 1.0	0.39 ± 0.32	0.06 ± 0.05
Total	1.64 ± 0.22	7.3 ± 1.3	0.35 ± 0.06	0.11 ± 0.02

is seen to be concentrated in and near the target fragmentation region. Spin density matrices have been determined from the Δ^{++} decay angular distributions; these are consistent with the predictions of the one-pion-exchange model with absorption, although other processes are probably also involved. Preliminary results on this topic were presented by A. M. Shapiro at the Washington meeting of the APS (Reference 235) and will be presented at the Tbilisi Conference (Reference 243).

Study of ρ^0 production as a function of rapidity shows that the ρ^0 's are produced in the central region, as well as in the beam dissociation region, with a preponderance of ρ^0 's having $Y_{cm} > 0$. The ratio of $\sigma(\rho^0)/\sigma(\pi^+)$ rises to a peak in the very forward direction, indicating that the forward-going pions may relatively often be the products of the decay of ρ^0 mesons produced by beam dissociation.

We have also studied ρ^0 production as a function of transverse

momentum, and have fit the ρ^0 data to the exponential form $d\sigma/dp_T^2 = A \exp(-bp_T^2)$, with $b = 2.7 \pm 0.5 \text{ (GeV/c)}^{-2}$. The non-resonant background in the ρ^0 mass region also fits an exponential with $b = 3.3 \pm 0.1 \text{ (GeV/c)}^{-2}$. The two values of b are consistent within the experimental uncertainty, so the p_T dependence may be a feature of the $\pi^+\pi^-$ system in this mass region, rather than a characteristic of ρ^0 production.

The cross section $d\sigma/dp_T^2$ decreases more slowly with p_T for ρ^0 mesons than for pions, so that the ρ/π ratio approaches a value of 1 for high p_T . This has been observed in other experiments, and has been proposed as part of the explanation for the production of leptons at high p_T observed at Fermilab and the CERN ISR.^{19,20} A preliminary report on ρ^0 production has appeared in Physics Letters B (Section C, Reference 232).

(iv) The Channel $\pi^- p \rightarrow p\pi^+\pi^-\pi^-$ at 147 GeV/c.

The good momentum resolution of the PHS for fast forward going particles, as well as for the slower particles for which the momentum resolution of the bare bubble chamber is satisfactory, allows a reliable use of four-constraint (4C) fits to distinguish events in the channel $\pi^- p \rightarrow p\pi^+\pi^-\pi^-$ from interactions yielding four charged particles together with one or more neutrals. Possible sources of contamination of the 4C sample have been investigated carefully by various means and the overall contamination is estimated to be less than 7%. Monte Carlo studies of the acceptance of the PHS and detailed investigation of single particle inclusive spectra show no geometric or momentum gaps in the system's acceptance.

With all corrections made, the total cross section for the four body interaction is 670 ± 41 microbarns.

Resonance production in this channel is seen in the various invariant mass distributions: Two body distributions show a prominent cross section for ρ^0 production in the forward direction, and an indication of f^0 production, while the $p\pi^+$ mass distribution is dominated by a Δ^{++} peak. Three-pion mass distributions show enhancements in the A_1 , A_2 , and A_3 regions, defined respectively as $1.0 < M_{3\pi} < 1.2$ GeV, $1.2 < M_{3\pi} < 1.4$ GeV, and $1.5 < M_{3\pi} < 1.8$ GeV. The fact that these regions seem to be distinct in our data may be an accident of low statistics. Three-pion mass plots made with the requirement that one of the $\pi^+\pi^-$ pairs be in the ρ^0 or f^0 region show that the A_1 and A_2 regions are predominantly $\rho\pi$ configurations, while there is an indication that the A_3 region contains an f^0 contribution. Cross sections for these regions are given in Table VI, together with data from other experiments at lower momenta.

In Figure 11 we have plotted the Feynman x of the proton, x_p , against the x of the faster π^- , x_{π^-} , in each event. Leading proton and π^- peaks are clearly evident. We define all events where $x_p < -0.96$ and where the invariant mass of the three-pion system $M_{3\pi} < 3.2$ GeV to be pion diffraction dissociation, and all events where $x_{\pi^-} > 0.96$ and where the invariant mass of the other two pions and the proton $M_{p\pi\pi} < 3.3$ GeV to be proton diffraction dissociation. The cross sections for pion dissociation and proton dissociation based on these definitions are given in Table VI and their ratio is seen to be $\frac{\sigma(\pi p \rightarrow \pi^* p)}{\sigma(\pi p \rightarrow \pi p^*)} = 1.67 \pm 0.21$ at 147 GeV/c for this channel. This is somewhat less than the value 2.3 ± 0.5 found at 205 GeV/c.²¹ The reason for this difference can be found in Table VI where we report a somewhat lower cross section for the fragmentation of the pion projectile than the previous work. The momentum resolution obtained by use of our downstream spectrometer might account

χ_p vs. $\chi_{(faster \pi^-)}$
in $\pi^- p \rightarrow p \pi^+ \pi^- \pi^-$

Figure 11

Table VI. Summary of cross sections for the reaction $\pi^- p \rightarrow p \pi^+ \pi^- \pi^-$.

Channel	147 GeV/c σ (μb)	205 GeV/c (Ref. 21) σ (μb)	40 GeV/c (Ref. 22) σ (μb)
$\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$	670 ± 41	635 ± 61	
$\pi^- p \rightarrow \pi^* p \rightarrow 3\pi p$ ($x_p < -0.96, M_{3\pi} < 3.2$ GeV)	$388 \pm 31^\dagger$	416 ± 50	
$\pi^- p \rightarrow \pi^- p^* \rightarrow 3\pi p$ ($x_{\pi^-} > 0.96, M_{p\pi\pi} < 3.3$ GeV)	$232 \pm 23^\dagger$	184 ± 33	
$\pi^- p \rightarrow 3\pi p$ ($1.0 < M_{3\pi} < 1.2$ GeV)	88 ± 15		115 ± 9
$\pi^- p \rightarrow 3\pi p \rightarrow \rho^0 \pi^- p$ ($1.0 < M_{3\pi} < 1.2$ GeV) ($.66 < M_{2\pi} < .86$ GeV)	67 ± 13		97 ± 8
$\pi^- p \rightarrow 3\pi p$ ($1.2 < M_{3\pi} < 1.4$ GeV)	98 ± 15		117 ± 9
$\pi^- p \rightarrow 3\pi p \rightarrow \rho^0 \pi^- p$ ($1.2 < M_{3\pi} < 1.4$ GeV) ($.66 < M_{2\pi} < .86$ GeV)	83 ± 14		95 ± 7
$\pi^- p \rightarrow 3\pi p$ ($1.5 < M_{3\pi} < 1.8$ GeV)	67 ± 13		106 ± 9
$\pi^- p \rightarrow 3\pi p \rightarrow f^0 \pi^- p$ ($1.5 < M_{3\pi} < 1.8$ GeV) ($1.17 < M_{2\pi} < 1.37$ GeV)	33 ± 9		

† Corrected for possible scanning biases and losses.

for this difference. We observe three events which satisfy the definitions for both categories and only $7.5\% \pm 1.5\%$ ($50 \pm 11 \mu\text{b}$) of the total $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$ cross section is not accounted for by the sum of the pion and proton diffraction cross sections.

We have fit the t -dependence of both the pion and proton diffraction differential cross sections with an exponential, Ae^{bt} . We obtain the result $b = 7.3 \pm 1.0 \text{ (GeV/c)}^{-2}$ for pion dissociation which is similar to our result $8.29 \pm 0.32 \text{ (GeV/c)}^{-2}$ for $\pi^- p$ elastic scattering at 147 GeV/c (Section C, Ref. 230). Our result for the exponential slope for the proton dissociation differential cross section is $b = 7.5 \pm 0.9 \text{ (GeV/c)}^{-2}$ which is also similar to the elastic scattering result.

We can test whether our cross sections are consistent with factorization by comparing the ratio of our $\pi p \rightarrow \pi p^*$ cross section (Table VI) and the cross section for $pp \rightarrow pp^*$ at 205 GeV/c,²³ to the ratio between our $\pi^- p$ elastic scattering cross section^{2(a)} and the pp elastic scattering cross section at 205 GeV/c.²³

$$\sigma(\pi^- p \rightarrow \pi^- p^*) / \sigma(pp \rightarrow pp^*) = 0.80 \pm 0.19$$

$$\sigma(\pi^- p \rightarrow \pi^- p) / \sigma(pp \rightarrow pp) = 0.47 \pm 0.04$$

The ratios should be approximately equal if all reactions are mediated by the same exchange and this condition is satisfied within two standard deviations.

A short paper on the analysis of the four-prong four-constraint sample has been submitted to Physics Letters B (Reference 238).

Considerable study has also been made of the six-body four-constraint channel $\pi^- p \rightarrow p \pi^+ \pi^+ \pi^- \pi^-$, and preliminary results were presented in a paper at the APS Washington Meeting (Reference 234). Further work is in progress on the analysis of this interaction.

(v) Other Topics.

Further work is in progress on the correlations among particles produced in π^-p interactions at 147 GeV/c and in particular on the question of charged cluster emission. These studies are particularly sensitive to possible biases arising from loss of some tracks in complex events because of measurement failure, hence a program of remeasurement of lost events is in progress. A report on evidence for charged cluster emission, based on complete measurements of a portion of the data of Experiment 154, was published in Physics Letters (Section C, Ref. 233).

Rescanning and remeasurement of neutral strange particles has been carried out during the past year, and a detailed analysis is being made of strange particle production in π^-p and K^-p interactions.

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

Work on this experiment has been proceeding steadily, but the pace has been slow because we have been especially short-handed this year and the Fermilab experiments have had higher priority. Nevertheless, all the four-prong events and the two-prong events with V^0 's have been measured, including those requiring hand measurement. The predigitizing of the remaining two-prong, six-prong and eight-prong events has been finished, and the events are being measured by PEPR in accordance with a regular schedule. Analysis programs are available, and high statistics studies of quasi-two-body reactions and resonance production will be carried out.

c) 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 purpose of this experiment is primarily to study and to compare the characteristics of high energy interactions as a function of the quantum numbers of the incident projectile particles, the π^+ , p, and π^- .

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

At present, all the two-, four- and six-prong events in the designated fiducial volume of the bubble chamber have been predigitized, and predigitizing of the remaining events is in progress for the

158,000 frame exposure. A number of improvements in the automatic measurement process and in the geometric-reconstruction programs have been initiated as a result of experience gained in Experiment 154, and measurement and analysis of the new data will be carried out when these improvements have been fully implemented. Several automatic measuring facilities will be in operation for this experiment, in addition to the MIT PEPR which was used for Experiment 154.

Approximately 25 percent of all the predigitizing is being done at Brown, and Professor Widgoff has special responsibilities for overseeing the flow of the data analysis for the Consortium as a whole.

II. Experimental Runs in Progress and in Preparation.

- a) A Study of π^+p , pp , and π^-p Interactions in the Proportional Hybrid System (FNAL Experiment 299); Improvements in the Hybrid System.

As mentioned in Section I, 158,000 pictures of the 600,000 - 1,200,000 originally planned have been obtained. Since that exposure in 1975, and while waiting for the next run (now scheduled for this fall), work has been proceeding on two important improvements in the downstream hardware system, as well as the software improvements indicated in Section I (c). The major one is the development of a forward gamma-ray detector (FGD) for the precise measurement of energies and directions of forward-going photons.

As discussed in last year's Renewal Proposal, the FGD is primarily a lead-glass Cerenkov system for precise energy measurement, preceded by scintillator and lead-glass hodoscope arrays for the precise determination of the vertices of the gamma showers. Originally planned to cover a 60 cm x 60 cm area, we now expect to expand this coverage to 75 cm x 75 cm.

As a first step in the construction of the full FGD, a prototype system of area 30 cm x 30 cm has been built and tested this past spring. Brown helped purchase the large lead-glass blocks and we built in our laboratories a small counter telescope for the initial tests. The prototype was installed in the N5 hadron beam line to the 15-foot bubble chamber for testing, and the beam was tuned successively to 30, 60, 75, and 100 GeV/c momentum. The prototype detector was moved to several positions at each momentum, and many runs were made. Martin Heller, a graduate student in our group, worked on all of these test runs at the Fermilab.

The intention of the test was to determine the energy calibration, the resolution, and the discrimination of the prototype, using showers from tagged electrons in the beam. Tagging was done by an upstream Cerenkov counter which was set to differentiate electrons from muons and heavier particles, and a triplet of proportional wire chambers which gave the position of the particles as they entered the shower counter. Data collection from the many photomultipliers made use of fast logic and analog-to-digital-conversion circuits and a CAMAC branch highway which fed data to the experiment's PDP-11 minicomputer. The computer wrote the data onto magnetic tape, and provided online histograms of the detector's performance.

The energy resolution and the discrimination of the prototype is most impressive. Figure 12 shows a typical run of the system with 60 GeV incident electrons. The full-width-half-maximum value is 2 GeV and this should be reduced by about a factor of two when the remaining stabilization features of the system are installed. The final energy resolution will be about $\pm 1\%$.

We plan to use the prototype FGD during our next exposure for Experiment 299 this fall. This will give us the power to analyze the forward photon component earlier than originally expected. The full FGD should be ready later in the winter or in the spring.

The second important PHS improvement is the replacement of the present 30 cm x 30 cm proportional wire chamber which is furthest downstream by a drift chamber of area 70 cm x 150 cm. The solid angle subtended by the improved downstream system will be more than quadrupled. This produces a greatly increased acceptance of the PHS: namely, 95% or more of all particles coming from 147 GeV/c π^-p collisions in the

Nominal Electron Energy - 60 GeV

Figure 12

bubble chamber and having a momentum of 10 GeV/c or more will enter and be measured in the downstream chambers, while at present the 95% limit is true only for secondaries having 40 GeV/c or more momentum.

b) Extension of FNAL Experiment 299;
Last Year's Proposals to the Fermilab.

In last year's Renewal Proposal we discussed five new proposals to the Fermilab (#375, #376, #377, #378, and #393) that various components of an extended PHS Consortium (including Brown) had submitted for a variety of experiments to follow the completion of Experiment 299. Two of these proposals were approved, with modifications to them and to the continuation of Experiment 299.

Proposal 375, "A Study of K^+p Collisions at an Incident Momentum Close to 150 GeV/c," has been approved for the 160,000 pictures requested with an enriched K^+ beam; but it is to be added onto the positive beam (π^+ and p) portion of Experiment 299. Since 342,000 positive-beam pictures remain to be taken in the original #299, the modified Experiment 299 (including 375) will obtain an additional $342,000 + 160,000 = 502,000$ pictures with incident π^+ , p, and K^+ particles. These, together with the 158,000 pictures already taken, will make a total of 660,000 positive pictures in the new #299.

Proposal 393, "A Study of the Properties of the Forward-Going Photon Energy in the Two-Charged-Prong Topology Created in 150 GeV/c π^-p Interactions," has been approved for the 300,000 pictures requested; but it is to be merged with the negative beam (π^-) portion of Experiment 299. Since 100,000 negative-beam pictures remain to be taken in the original #299, the modified experiment (to be called the new #393) will obtain

a total of $300,000 + 100,000 = 400,000$ π^- pictures. In the new Experiment 393, the physics to be studied is also modified to include all aspects of $150 \text{ GeV/c } \pi^- p$ interactions. A small percentage of $K^- p$ collisions will also be seen and probably studied, as in Experiment 154, but that would be a minor part of the program.

The Consortium applied considerable effort this past year to the problem of enriching the percentage of K^+ and K^- mesons in the 30" bubble chamber beam line. K^- enrichment appears exceedingly difficult and has been put aside for the present. K^+ enrichment to a level of about 15% has been achieved and will be used in our run this fall.

The following table will help to clarify the rearranged experiments and the numbers of events expected from each:

Particle	Expt.	Pictures (in 1,000's)	Beam Percent	Equiv. Pictures (in 1,000's)	Events (in 1,000's)
π^+ } p }	299 (old)	158	{ 46% 46%	73 73	
π^+ } p } K^+ }	299 (new)	502	{ 36% 36% 15%	181 181 75	
Total π^+				254	39
Total p				254	66
Total K^+				75	9
π^-	393 (new)	400	95%	380	60
(π^-	154	105	95%	100	16)

c) Further Improvement of the 30" Bubble Chamber Hybrid System.

Following the Bubble Chamber Symposium held at Fermilab in September 1975, there was general agreement that the upgrading of the 30" bubble chamber spectrometer system by the addition of a downstream external particle identifier (EPI) would add significantly to the physics program. Two systems of particle identification have been studied intensively -- a system of segmented Cerenkov counters, and a system using the relativistic rise in ionization with energy.

An EPI workshop was held at FNAL in May 1976 for all physicists interested in the use of the bubble chamber as a target, in order to study and discuss the merits of the two systems. A consensus was quickly reached when it became evident that a combined system containing some elements from each would be simpler, more effective, and less expensive than either system by itself. This comes about because the 50 - 100 GeV/c momentum region can best be covered by a single helium-nitrogen 1-atmosphere multicell threshold Cerenkov counter which uses pulse height analysis to separate kaons from pions above the kaon threshold, while the 5 - 50 GeV/c region can best be covered by three 1-meter³ relativistic-rise ionization-sampling devices. This entire system is relatively simple to design and build, is very flexible and adaptable to different types of experiments, and would cost approximately \$130,000. A proposal that such an EPI be constructed has been submitted to FNAL on behalf of all bubble chamber users.

d) Proposal for a Study of Heavy Particle Production and Dynamics near $x = 0$, as a Function of Incident Particle Quantum Numbers (FNAL Proposal #488).

If the EPI system described briefly above is built, many investigations become feasible which are not possible with the present hybrid spectrometer. The PHS Consortium is particularly interested in studying the production of heavy particles (Λ^0 , K^0 , K^+ , K^- , p , $\bar{p}$) as a function of the nature of the incident projectiles (π^+ , p , K^+ , π^- , and $\bar{p}$). To this end we have submitted Proposal #488 to use the new hybrid system with incident particle beams having a momentum in the neighborhood of 300 GeV/c. A detailed description of the proposed experiment is given in the accompanying Renewal Proposal.

Fermilab has advised us that the construction of the above EPI and our Proposal 488 will both be given careful consideration by the Director and the Program Advisory Committee this summer.

III. Associated Matters.

Dr. David H. Brick joined our program this March, coming to Brown from a two-year research associateship with Professor Fridman in Strasbourg, France. He had the major responsibility for the processing and analysis of several experiments while at Strasbourg, and he also worked closely with physicists at CERN on the development of the next generation of hybrid system analysis programs. His contributions to our program have been of great value in just the few months that he has been here.

Professor Widgoff is entering her second year as a member of the Executive Committee of the Fermilab User's Group. She was also appointed this year to be a member of the Committee on Professional Concerns of the American Institute of Physics.

Professor Shapiro was invited to participate in the XI Rencontre de Moriond at Flaine, France, this March, where he discussed the Fermilab hybrid system experiments. He was also invited to the Third European Symposium in Antinucleon-Nucleon Interactions, to be held at Stockholm, Sweden, this July, and to the XVIII International Conference on High Energy Physics, to be held at Tbilisi, U.S.S.R., during July 15-21, 1976. Because travel funds are very limited, he will attend only the latter.

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

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

C. Papers Published During the Preceding Year and Papers in Press.

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