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PROGRESS REPORT
OF A RESEARCH PROGRAM
IN
EXPERIMENTAL HIGH ENERGY PHYSICS

by

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

1 June 1973

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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 1972 - 31 August 1973). This work has been supported by the U. S. Atomic Energy Commission under Contract AT(11-1)-3130 (Task B - Experimental).

This report is divided into five sections:

- I. Data Analysis in Progress;
- II. Experimental Runs in Progress and in Preparation;
- III. Associated Matters;
- IV. Papers Published During the Preceding Year and Papers in Press;
- V. Scientific Personnel Associated with the Experimental Program.

I. Data Analysis in Progress.

A. The Argonne π^+ p Bubble Chamber Experiment - First Stage.

(Widgoff, Shapiro, Massimo, and Fong)

During the past year some remeasuring and reanalysis of the first 100,000 pictures of 4.1 GeV/c positive pions taken with the ANL 30" liquid hydrogen bubble chamber has been accomplished. Our first efforts on this film were concentrated on the two-prong and four-prong events. The six- and eight-prong events (none with more than eight have been observed) were left for later.

We completed our measurements of all the events in this film this past winter and have completely analysed the single-pion and double-pion "inclusive" spectra. The following three reactions were analyzed in detail:

$$\pi^+ + p \rightarrow \pi^- + X, \quad (1)$$

$$\pi^+ + p \rightarrow \pi^+ + X, \text{ and} \quad (2)$$

$$\pi^+ + p \rightarrow \pi^- + \pi^- + X, \quad (3)$$

where the X in each case represents all the other particles emerging from the interaction. These results are now in press and will appear shortly in the Physical Review (see Section IV, Reference 173).

Various conjectures of limiting behaviour (i.e. the approach of cross sections, properly scaled, to a constant value) as a function of energy have been proposed. Chan Hung-Mo and collaborators¹ have suggested that such behaviour may begin at relatively low energies for reactions of the type $a + b \rightarrow c + X$, where the quantum numbers of the

¹Chan Hung-Mo et al., Phys. Rev. Lett. 26, 672 (1971).

combination (abc) are exotic. For reaction (1), $abc \equiv \pi^+ p \pi^+$, which has baryon number 1, charge +3, and thus is exotic. For reaction (2), $abc \equiv \pi^+ p \pi^-$, which has baryon number 1, charge +1, and is not exotic.

Our results (Ref. 173) agree very well with this prediction over certain ranges of the pertinent variables, when compared with corresponding data taken at other energies: for example, those given by Crennell et al.² at 6 and 22 GeV/c and by Beaupré et al.³ at 8 and 16 GeV/c. In Figures 1(a) and 2(a) the invariant cross sections for reaction (1) are plotted as a function of P_L (target) and P_L (projectile), respectively, where these variables are the longitudinal momenta of particle c in the target and projectile frames of reference. In Figures 3(a) and 4(a) the corresponding cross sections for reaction (2) are plotted. The ratios of the cross sections at 22 GeV/c to those at 4.1 and 6 GeV/c are drawn in the (b) sections of these figures.

It should be noted that in the first two figures the invariant cross sections are practically identical in the region of P_L near zero. These are the fragmentation regions for the target and projectile particles, respectively. In Figures 3 and 4, while the ratios are not far from 1 for larger values of P_L (target) and P_L (projectile), they are distinctly different from 1 in the fragmentation regions. Thus we see that "limiting fragmentation" does occur even at 4.1 GeV/c in the exotic channel, but not in the nonexotic channel, in accordance with the ideas of Chan et al.¹

²D. J. Crennell et al., Phys. Rev. Lett. 28, 643 (1972).

³J. V. Beaupré et al., Phys. Lett. 37B, 432 (1971).

In Figures 5 and 6 the corresponding cross sections for reactions (1) and (2), respectively, are plotted as a function of the Feynman variable $x \equiv 2 P_L^* / \sqrt{s}$, where P_L^* is the longitudinal momentum of particle c in the overall c.m. system and s is the square of the total energy of a and b in the c.m. system. We observe in these plots that some form of scaling seems to occur in the central range of x for the nonexotic channel (reaction (2)), but not near $x = \pm 1$; while for the exotic channel (reaction (1)), the reverse seems to be true. The difference between the two reactions is not yet understood and needs considerable further investigation.

Figure 7 shows our data points for the invariant cross section, evaluated at $x = 0$, together with other published data. Our points are very consistent with the other data and they all agree with a linear variation of the cross sections for both reactions (1) and (2) when plotted as a function of $(p_{\text{incident}})^{-1/2}$. This plot was first presented by Ferbel⁴ and we consulted with him in making a number of corrections to his published drawing.

Our data have been analyzed in detail in terms of the 'rapidity' variable y as well, and interesting conclusions have been reached. A study was also made of two correlation functions for the double-particle reaction (3). These results are presented in Reference 173.

Together with the analysis of the inclusive reactions, a reanalysis of all the four-prong sample was performed this past year. A paper on this sample (Reference 163 in last year's Progress Report) was delayed in order to include this new analysis. The exclusive reaction

$$\pi^+ p \rightarrow \Delta^{++} \omega^0 \rightarrow p \pi^+ \pi^+ \pi^- \pi^0 \quad (4)$$

⁴T. Ferbel, Phys. Rev. Lett. 29, 448 (1972).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Table I

Values of b from Fits of the Experimental Data to $d\sigma/dt = ae^{-b|t|}$, for the Reaction $\pi^+p \rightarrow \Delta^{++}\omega^0$.

Momentum of Incident Pion (GeV/c)	Range of $ t $ (GeV/c) ²	b (GeV/c) ⁻²
4.0 ^{a,b}	0.2 < $ t $ ≤ 0.45	3.8 ± 0.8
	0.2 < $ t $ ≤ 0.60	2.3 ± 0.5
	0.2 < $ t $ ≤ 1.05	2.7 ± 0.3
4.08 ^c	0.2 < $ t $ ≤ 1.2	2.7 ± 0.3
4.09 (This experiment)	0.2 < $ t $ ≤ 0.44	3.4 ± 0.6
	0.2 < $ t $ ≤ 0.60	3.1 ± 0.6
	0.2 < $ t $ ≤ 1.00	3.1 ± 0.2
5.0 ^d	0.15 < $ t' $ ≤ 0.4	4.4 ± 1.0
	0.15 < $ t' $ ≤ 0.6	3.7 ± 0.5
	0.15 < $ t' $ ≤ 1.0	4.3 ± 0.3
5.72 ^e	(0.2) < $ t' $ ≤ 1.0	2.7 ± 1.0
8.0 ^f	0.15 < $ t' $ ≤ 0.4	3.2 ± 1.7
	0.15 < $ t' $ ≤ 0.6	3.9 ± 0.7
	0.15 < $ t' $ ≤ 1.0	4.6 ± 0.5
18.5 ^{b,g}	0.1 < $ t' $ ≤ 0.5	2.8 ± 1.2
	0.1 < $ t' $ ≤ 1.0	3.6 ± 0.8

^aM. Aderholz et al, Nuovo Cimento 35, 659 (1965).

^bThe exponent factor b was not given in the reference, but was determined from data given in the reference.

^cD. Brown et al, Phys. Rev. D1, 3053 (1970).

^dC. L. Pols et al, Nucl. Phys. B25, 109 (1971).

^eF. T. Dao, MIT Thesis, April 1970, unpublished.

^fM. Aderholz et al, Nucl. Phys. B8, 45 (1968).

^gN. N. Biswas et al, Phys. Rev. D2, 2529 (1970).

was particularly restudied. Comparisons of our experimental values of $d\sigma/dt$ as a function of t with the predictions of several theoretical models indicate that the shape of the $d\sigma/dt$ curve is best fit by the Regge exchange model of Fox and Sertorio,⁵ which includes ρ , B , ρ' , and B' exchange.

For $|t| > 0.2 \text{ (GeV/c)}^2$, our data for reaction (4), as well as most other corresponding data, are well fit by an exponential of the form

$$d\sigma/dt = a e^{-b|t|}.$$

It is interesting that no significant variation in the parameter b as a function of the incident momentum is observed in the range from 4.0 up to 18.5 GeV/c, for momentum transfers $|t|$ from 0.2 up to at least 0.6 (GeV/c)^2 . This, and a lack of significant change in the spin density matrix elements with changing incident momentum, are consistent with the assumption that the production mechanism is unchanged over this incident momentum range. Table 1 shows these data from the revised manuscript.

B. Backward Pion Charge Exchange (AGS #416).

(Chen, Massimo, and Lanou)

As we discussed in previous proposals, this is an experiment to measure π^0 and η^0 angular distributions in the backward hemisphere (including 180° point) when produced in π^-p collisions.

The major interest in this experiment arises from its bearing on baryon-exchange processes, Regge-pole models, the determination of some of

⁵G.C. Fox and L. Sertorio, Phys. Rev. 176, 1739 (1968).

the parameters of nucleon resonances, and charge-independence tests at high momentum transfer. The principal data used in this study are the high-statistics angular distributions taken at a sequence of energies. Energy dependent trends can be identified and compared to various models. The energy range involved here covers in detail the very sensitive "**intermediate energy**" region and its highest point overlaps high energy data which exist at isolated points.

The experimental run was concluded in May 1971 at the Brookhaven National Laboratory AGS and last year we reported the completion of all of the analysis programs as well as the final results for the Brown data at two of the momenta.

This data was to be combined with that of our collaborators (Bari (Italy) and M.I.T.) and presented at the XVI International Conference on High Energy Physics held at NAL and the University of Chicago. This was done and the results are contained in Ref. 174 -- the conclusions were unchanged from those reported in our Progress Report last year based on the Brown data alone.

Since then a great deal of progress has been made. We have now completed and combined with our collaborators data at 2.6, 2.85, 3.5, 3.7, 4.3 and 6.0 GeV/c for $\pi^- p \rightarrow \pi^0 N$ and at 3.5 and 6.0 GeV/c for $\pi^- p \rightarrow \eta^0 N$. The angular distributions which result are shown in Figures 8,9, and 10.

Several points are of interest as a consequence of these results.

First consider the charge exchange data. At all momenta, the angular distributions (here plotted as a function of u , the four momentum transfer in the u -channel) exhibit a strong backward peak falling rapidly to a dip whose position depends upon the incident momentum. Experiments on backward elastic scattering of charged pions have shown a similar structure in $\pi^+ p$

FIG. 8

FIG. 9

FIG. 10

U-LOCATION OF N-EXCHANGE DIPS

but the dip is absent in π^-p . These features have been reasonably well dealt with through a reggeized baryon exchange model for the charged elastic data if the N_α regge trajectory is considered to dominate in the exchange. This situation should then result in an angular distribution for charge exchange qualitatively similar to what we find, but quantitatively different from our data. In particular the dip occurs in our data at larger u -values (typically, $\geq 0.25(\frac{\text{GeV}}{c})^2$) than is expected. The extraction of the position and depth of the dip can depend in an important way upon the knowledge and magnitude of the experimental resolution. Our resolution is superior to any similar experiments and at the momentum 6.0 GeV/c, where data exist in common, we find that our dip is further out and shallower but does not depend strongly upon our resolution since it is narrower than the dip width. Consequently we feel confident of our preliminary results. Recent work by Barger, Halzen, and Phillips shows that for π^+p backward elastic data, the dip location appears to depend upon the variable $u(\text{dip}) = (u_{\min} - 0.2)$. Figure 11 shows our dip position which appears to be a different function of momentum. We have another data point at 8.0 GeV/c currently being analyzed which should prove interesting as to the shape of the momentum dependence. Superficially, it would seem that these results present serious difficulty for models of this type, however, a word of caution is in order. Before direct comparisons of backward pion data can be made in a u -dependent way (e.g., comparison of $\pi^\pm$ with π^0 at the same u -value) radiative corrections must be made. This was recently pointed out by M. Sogard in a paper submitted to Physical Review Letters. The correction is substantial ($\sim 20\%$ for π^+) as a result of the low mass of the pion and the largeness of the momentum transfer. We are currently embarked upon the calculation of the radiative corrections for our data.

Turning to the results for $\pi^- p + \eta^0 N$ there are two interesting points. The first relates to the resulting angular distributions which show little or no evidence for a dip. Because this reaction should proceed through $I = 1/2$ exchange (in the reggeized baryon exchange model) then if N_α is dominant one would expect the same kind of dip structure and it can be directly predicted from the observed cross-sections for $\pi^- p$, $\pi^+ p$, and $\eta^0 N$. We have performed this extraction and find rather striking disagreement in the shapes; however, one should keep in mind the proviso that radiative corrections have not yet been made to the pion data.

Secondly, it is possible to extract the ratio of the coupling constant for ηNN , ($g_{NN\eta}$) to that of πNN ($g_{NN\pi}$) via the usual isospin relations and again assuming N_α dominance. We find

$$\frac{g_{NN\eta}^2}{g_{NN\pi}^2} = \frac{\sigma_\eta}{\frac{1}{3}(\sigma^+ + \sigma^0 - \frac{1}{3}\sigma^-)_\pi \sigma_\pi^0} = \frac{\sigma_\eta}{\sigma_\pi^0} = 0.35 \pm .07 \text{ at } 6.0 \text{ GeV/c.}$$

In a pure SU3 description this ratio provides a relation to the parameter α , which gives the fraction of F-type coupling.

$$\frac{g_{NN\eta}^2}{g_{NN\pi}^2} = \frac{1}{3}(4\alpha - 1)^2$$

where $\alpha = F/(F + D) = 0.51 \pm .03$ from our data at 6.0 GeV/c.

Again, the conclusion based upon these preliminary data does not seem to support the idea of N_α dominance down into the "intermediate momentum region."

The above mentioned results were presented in two papers at the 1973 Washington meeting of the APS (Ref. 175 & 176).

The work remaining on all of the data available in this experiment is substantial. We still have slightly more than 1/2 - scanner - year measuring to be done. Radiative corrections must be evaluated and made to all of the data. The remaining energies (which are all scanned) must be processed and energy dependent cross section corrections calculated. Various other checks on the data should be made before final publication.

Interest in this experiment is extensive among theoretical physicists working on phenomenological models; we have honored several requests for preliminary results as reported at NAL and Washington.

C. The Argonne π^+ p Bubble Chamber Experiment - Second Stage.

(Widgoff, Shapiro, and Fong)

In the second stage of the 4.1 GeV/c π^+ p experiment, 395,000 additional good pictures are being analyzed. These have been completely scanned for all the events that they contain within the central fiducial volume, and about 15% have been double scanned in order to check efficiencies.

The total number of events in this film is approximately 90,000 of which 35,000 are of two types: four-pronged, and two-pronged with one or two V^0 decays. The 35,000 events have all been rough-digitized at Brown and then precision measured by Brown personnel using the MIT PEPR system. About half of all the remaining events have also been rough-digitized at Brown this year, and these have also been started through the MIT PEPR system.

Last summer and fall several subtle bugs crept into the PEPR hardware and also the portion of the software that Brown was using. These were not immediately detected and took many months to eliminate. The job of salvaging the affected events turned out to be extremely difficult, and thus it was decided to re-PEPR this group. We have almost completed this processing.

Approximately 15% of the events have one or another measuring problem which makes them essentially unmeasurable by any automatic device. These we are hand-measuring at Brown on our Hermes and Franckenstein machines. We have started our precision hand-measuring and a strong effort will be made to complete it during the coming year.

The four-pronged and two-pronged-with- V^0 events were chosen for initial study in order to make an improved measurement of the branching ratios of the A_2 meson into its main decay modes. The three main modes are known to be roughly in the proportions $\rho\pi: \eta\pi: \bar{K}K \approx 76: 18: 5$, but no systematic study of the ratios has yet been made. Also, the above proportions were determined primarily from A_2^- decays, while we shall be investigating A_2^+ and A_2^0 decays.

There are two principal reactions for A_2 production in this experiment:

$$\pi^+ p \rightarrow p A_2^+,$$

and

$$\pi^+ p \rightarrow (\Delta^{++} \text{ or } p\pi^+) A_2^0.$$

The main decay modes are then

$$\begin{array}{l} A_2^+ \longrightarrow \rho^0 \pi^+, \rho^+ \pi^0 \\ \quad \quad \quad \longrightarrow \eta^0 \pi^+ \\ \quad \quad \quad \longrightarrow K^+ K^0 \end{array}$$

$$\begin{array}{l} A_2^0 \longrightarrow \rho^+ \pi^-, \rho^0 \pi^0, \rho^- \pi^+ \\ \quad \quad \quad \longrightarrow \eta^0 \pi^0 \\ \quad \quad \quad \longrightarrow K^+ K^-, K^0 K^0 \end{array}$$

Most of the final states in the above channels have four prongs or two prongs plus one or two V^0 's. Mr. R. Simard is pursuing this study as part of his doctoral dissertation.

As mentioned above, we are proceeding with the measurement of the remaining two-prong events and of the six-prong and the handful of eight-prong events, so that as much information as possible will be derived from this film. We are particularly interested in extending our investigation of the inclusive reactions discussed in Section IA. The double-particle reaction (3) appears to be very important in this field, and thus the much improved statistics from stage two will be very helpful.

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

(Chen, Massimo and Lanou)

This experiment, which was reported last year as being in its running stage, has moved into scanning and measuring.

The physics of this experiment (and AGS #622, mentioned below) is very closely related to that of our current backward scattering experiment. 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. In this range there are 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. 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.

Preliminary scanning indicates that these data should provide angular distributions containing roughly 900 events each in the channel $\bar{p}p \rightarrow \pi^0 \pi^0$ with a mass resolution of 8 MeV. The mass interval covered is continuous from 2080 MeV to 2580 MeV. 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 $\pi^0 \eta^0$, $\pi^0 \omega^0$, $\pi^0 f^0$, $2\pi^0 \omega^0$, 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.

Our plans for this coming year include intensive scanning, measuring and

computer programming. This will make it imperative that we keep the scanning staff at as high a level as possible. This is discussed further in the accompanying Renewal Proposal.

Mr. R. K. Thornton, who was resident full-time at Brookhaven during the running of this experiment and AGS #622, has returned to Brown and is working on the setting-up of the data analysis procedures to be used. His Ph.D. thesis will contain data from this experiment.

E. Search for $\bar{p}p$ Resonances of Definite G-Parity in the T-Region (AGS #622).

(Chen, Lanou and Massimo)

This very interesting experiment, which was not mentioned in last year's proposal, was run by our group this past spring at the AGS in place of AGS #600 ("A $\bar{p}p \rightarrow$ bosons in the S-region") when it developed that AGS #600 would take 1000 hours of running time.

As was discussed in some detail in last year's Progress Report, AGS #600 required some special techniques in order to obtain adequate fluxes of such low energy anti-protons. We had conducted some preliminary tests which looked promising and on this basis AGS #600 was approved for running as soon as AGS #527 was completed. The apparatus for the two experiments was virtually identical. We then went ahead with the final beam de-grading scheme. The results were very satisfying in terms of the momentum resolution attainable but unfortunately the flux into the available solid angle was roughly a factor 2 less than desired. This indicated that nearly 1000 hours would be needed. Because there were less than 500 hours remaining before the long AGS shutdown this summer and because post-shut down running of this experiment would conflict with BNL's

plans for the A-station as well as our own plans for scientific manpower in that period, we elected to propose AGS #622 to be run in place of AGS #600. The physics of AGS #600 is still of considerable interest and we may at some future time re-propose it.

We then proposed AGS #622 and it was approved for running by the BNL High Energy Advisory Committee. The motivation for AGS #622, comes largely because of its complimentary nature to our AGS #527 and the nature of the current somewhat confused situation in high-mass meson spectroscopy (see recent Proceedings of Experimental Meson Spectroscopy - 1972, A.I.P. Conference Proceedings No. 8, Rosenfeld & Lai, editors). Briefly the situation is that several mesons seen in some types of experiments are not seen in others of a different type (or occasionally even the same type) while some that have been seen via particular decay channels have no unambiguous quantum number assignments. Our AGS #622 is designed to improve the situation in the former while AGS #527 was designed for the latter purpose of unambiguous quantum number assignment.

The principal assumption involved in AGS #622 is 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. AGS #622 then consists 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 should be able to detect energy dependent structure at the 2-3% level above background. A by-product of this work, if we do not run into serious detection efficiency problems with the charged pions, will 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.

The apparatus which consisted of the 4 π , high-Z optical spark chamber system and hydrogen target already in place from AGS #527, required only the removal of several anti-coincidence counters and the addition of three more small counters. The trigger was very simple and took only a short time to de-bug. The data was run off at the AGS during March and April. The data consists of 150K photographs which are divided evenly amongst the collaborators. A minimal amount of measuring is expected to be required on this film. It is essentially a scanning and counting experiment.

Preliminary scanning is just beginning and based on it we expect to be in full production sometime during the summer.

II. Experimental Runs in Progress and in Preparation.

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

(Chen, Cutts, Massimo, and Lanou)

This approved experiment is 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 0 to 1.5 (GeV/c)². It has been described extensively in previous Progress Reports and Renewal Proposals.

The spectrometer is of flexible design and can operate either with 8 μ steradians acceptance and $\pm 0.03\%$ momentum precision up to 200 GeV/c or can be changed to give considerably larger acceptances at lower momenta. It will be equipped with DISC 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 consists of individual physicists from ANL, Bari, CERN, Cornell, MIT, Stanford, and NAL.

This past year, and especially in the last three months, preparations have been moving very rapidly. The spectrometer tunnel is now complete and the bending magnets for the spectrometer are in place but not yet powered. The two Portakamps assigned to NAL #96 are installed adjacent to the spectrometer tunnel. The PDP-11 computer, most of the fast electronics, and much of the auxiliary electronic equipment has been or is being put into operation in the Portakamps. The SPEX (Spectrometer Executive) control program is operational on that PDP-11 and the various utility programs it controls are currently being incorporated into the overall system as they are

de-bugged on-site. During the past week a Digital Equipment Corp. DK-11 high speed disk system, which was purchased with Brown University funds, was added to the operating PDP-11 system. It has increased the capacity and flexibility of the system several fold.

The beam magnets through the first two foci in the M6 beam line (which will deliver beam to our hydrogen target) are in place. The first beam was delivered to this part of the M6 line ten days ago. During these past ten days we have been using the beam for aligning and tuning up through the second focus. This tuning work will continue until the month long shut-down of the accelerator scheduled for 10 June.

One of the differential and one of the threshold Cerenkov counters have been installed in the beam line and tested out successfully with an 80 GeV/c beam, two of the threshold Cerenkov counters are in approximate position in the spectrometer tunnel, nearly all of the multiwire proportional chambers have arrived from Italy, and parts and whole sections of the other detection systems have arrived at the site.

During the shut-down we expect to install more apparatus as well as the remaining M6 beam line and spectrometer magnets. In July, when the accelerator re-commences operations we are scheduled to receive more beam for tuning. In terms of construction and installation the largest problems remaining are the completion of the Meson Building end-station and the powering of the spectrometer magnets. In general, the beam related program is about four months behind the schedule set down a little more than a year ago.

Clearly much work is just beginning particularly in the area of alignment, tuning and making a complex detection system operational. We hope and expect to be receiving some beam into the spectrometer for measurements before

September.

Mr. Lorne Levinson, part of whose thesis will contain data from this experiment, has been resident full-time at NAL since January. He will continue there until the completion of NAL #96. Miss Deborah Fausch, a first year graduate student in physics, will also be resident there for most of the summer. Professor Massimo and Professor Lanou have been traveling back and forth between NAL and Providence. They, together with Professor Cutts and Dr. Chen will do so increasingly in the coming year since the running of this experiment and the data analysis on AGS #527 and #622 are our current major efforts.

B. An Experiment to Study "Inclusive" Reactions Using the NAL Single-Arm Spectrometer (NAL Proposal #118).

(Chen, Cutts, Massimo, and Lanou)

A little more than a year ago we, together with our Bari and MIT collaborators, submitted a new proposal to the Program Committee for NAL. At this writing, no action has been taken by the Program Committee on any of these "second wave" experiments for the spectrometer. We include this partly for completeness but primarily because (as is discussed in our Renewal Proposal) we retain a very keen interest in performing the experiment and/or a modification of it.

We proposed to make an experimental study of the so-called "inclusive reactions" -- they are ones in which some particle 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 plan to make an exploratory investigation of these

processes by measuring the momentum spectra of final state hadrons over a range of production angles and incident energies with the use of the NAL focussing spectrometer which will be constructed for Experiment #96, as mentioned above. 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^+ can be simultaneously measured. The spectra of final state π^- , K^- , and $\bar{p}$ can be simultaneously measured with reverse magnetic fields. With the use of Cerenkov counters in the incident beam as well, reactions resulting from protons, antiprotons, K^+ mesons, and π^+ mesons can be simultaneously measured over the part of the kinematic range to be covered in this experiment in which the incident intensities are about 10^7 particles per pulse or less.

This proposal is one of several submitted by sub-groups of the single-arm-spectrometer collaboration and they will constitute the "second wave" of experiments to be performed using the original facility without major modification to the spectrometer. This should represent a saving in capital equipment costs per experiment. It is hoped that the Program Committee will consider this group of "second wave" experiments at its meeting this August.

C. The Proportional Hybrid System (PHS) Experiment at NAL
(NAL Experiment #154).

(Widgoff, Shapiro, and Fong)

For the past year the ANL-NAL 30" bubble chamber has been running extremely well. During the first eight months of operation (from July 1972 through February 1973) over 180,000 bare-bubble-chamber pictures were taken. Several times this number of pictures could have been obtained if the accelerator had operated more steadily and if the 30" chamber beam had been made fully compatible

with other experiments. Even with this number of pictures, much of the most important physics which has come from NAL up to the present has originated from these exposures.

In approved experiment #154 the PHS collaboration or consortium will use the 30" chamber together with a set of multi-wire proportional chambers and scintillation counters upstream from the bubble chamber and another set of larger proportional chambers downstream.

The upstream section will identify each particle entering the 30" chamber as to its three-dimensional position, its angle (to within $\pm 1.1 \times 10^{-5}$ radians), its momentum (to within $\pm 0.04\%$), and its time order of arrival. Cerenkov counters in the beam further upstream will identify each particle as a π , K, or proton and this information will be incorporated with that from the proportional chambers.

The Brown group designed and constructed the scintillation counters and the associated electronics and logic system for the upstream and downstream sections. The scintillation counter system provides a master gate during which all the wire chamber information is collected and stored. Controlled deadtimes are provided which permit complete storage before new information will be accepted. Together with each master gate a record is kept of all multi-track problems, such as the arrival of additional particles during the master gate and during the following deadtimes.

The upstream section was installed and was working in June of 1972, when the first particles were brought down the 30" beam line. The detailed profile of the beam both horizontally and vertically, proved to be very valuable to the NAL staff in tuning the beam. From that time on, a television camera has been focussed on our display oscilloscope (at our PDP-9 computer on the Building A

mezzanine) and the beam profile picture has been shipped over the entire laboratory monitor hook-up. The proportional wire planes just before the bubble chamber are still used as the principal detecting element for tuning the beam.

During the past year PHS consortium members have operated our system for the benefit of NAL and the bubble chamber users during all the 30" exposures. Since two groups out of the nine-group consortium provided personnel for each run, this meant that a Brown staff member helped operate the system during about one-quarter of all the bubble chamber runs.

Last summer the collaboration selected a small sub-group of its members to act as a software team to develop the final set of analysis programs. Dr. Fong has been one of the principal members of this group. He first developed the main TVGP-like program which takes a particle's positions in the downstream proportional chambers and "swims" the particle back up through the fringe field of the bubble-chamber magnet and then through the full field up to the vertex of the interaction in the bubble chamber. This determines the particle's sign, momentum, and angle of emergence from the interaction, using only the electronic information and a measurement of the vertex. No measurements on the particle's track in the bubble chamber are necessary. Of course, these measurements will be made whenever possible, and the two sets of parameters compared and combined in a fashion consistent with their error matrices. In general, the proportional chamber information will be much more accurate for very fast particles -- the momentum of a 150 GeV/c secondary can be determined to $\pm 10\%$ -- and in many cases bubble chamber measurements will not be possible in the forward cone of high-multiplicity events.

This "swimming" program has been written up as an internal report

(Reference 178) and has been circulated through the consortium. A copy was also requested by and was sent to the wide-gap-spark-chamber hybrid system collaboration. Dr. Fong has also been working with Profs. Ludlam of Yale and Watts of Rutgers to incorporate his work into the complete set of electronic information programs. This work has also been written up for the PHS consortium (Reference 179).

At present the software team is finishing off the overall systems programs which combine the above programs with all the direct bubble chamber analysis and then prepare this information for a SQUAW-like kinematics program.

The large downstream proportional chambers were completed and installed this spring, and are being continuously tested. In June our first 2,000 pictures were obtained using the bubble chamber and our complete hybrid system. These are essentially a test group to make an initial check on how well our system is operating. Many hardware and software bugs are sure to be found. As soon as these are corrected we shall be ready to take the 20,000 pictures which will constitute Phase II of our experiment. So far with the first of the 2,000 pictures, we have been linking up successfully tracks in the upstream chambers with those in the bubble chamber and with secondaries passing through the downstream section.

In previous Progress Reports and Renewal Proposals we have described at length the wide variety of interesting physics that we propose to investigate with our hybrid system. In the accompanying Renewal Proposal some of the main areas are discussed further. The 20,000 pictures of Phase II should be taken approximately near the middle of this summer and will provide a thorough test of how fast and well we can extract the essential information

from our system. If this is successfully done, we expect to begin a Phase III exposure consisting of 500,000 pictures containing incident π^- , π^+ , and protons. The unique capabilities of our hybrid system will then be fully demonstrable.

At the Washington meeting of the American Physical Society this April, a series of eight papers were presented describing the many facets of our PHS hardware and software. The Brown group co-authored two of these papers, on which we had made important contributions (References 180 and 181).

III. Associated Matters.

As was mentioned last year, the Physics Department recommended and the University Administration approved, the appointment of a new assistant professor in experimental particle physics. After a national search the appointment has been made to an outstanding young physicist, Dr. David Cutts. He received his Ph.D. in 1968 from the University of California (Berkeley), he was a post-doctoral appointment at Stony Brook (SUNY), and is currently performing experiments with Group "A" of the Rutherford Laboratory. He has worked in both strong and weak interaction physics; and has had extensive experimental experience in both electronic hardware and on-line computers as well as in data analysis. He will be joining the Department this summer.

In recognition of his excellent work and his remarkable ability, Dr. D. G. Fong has been promoted to the position of Assistant Professor of Physics (Research) as of this coming September. Also, Professor Widgoff has been promoted to the position of full Professor of Physics (Research).

Professor Lanou was invited and participated in the "International Conference on New Results from Experiments on High Energy Particle Collisions" held at Vanderbilt University during March (Ref. 177).

Professor Shapiro has been invited to attend and will participate in the Fifth Hawaii Topical Conference in Particle Physics to be held in Honolulu in August, and the Fifth International Conference on High-Energy Collisions to be held at the State University of New York at Stony Brook also in August.

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

173. D. G. Fong, A. M. Shapiro, and M. Widgoff, "Inclusive Reactions from $\pi^+ p$ at 4.1 GeV/c," Phys. Rev. (in press).
174. G. T. Y. Chen, C. R. Fletcher, J. T. Massimo, R. E. Lanou, Jr., and co-authors, "Backward Pi-Minus Charge Exchange at Intermediate Energies," Proceedings of XVI International Conference on High Energy Physics, Chicago, Illinois, 1972.
175. G. T. Y. Chen, C. R. Fletcher, J. T. Massimo, R. E. Lanou, Jr., and co-authors, "Differential Cross Sections for $\pi^- p$ Backward Charge Exchange Scattering at Intermediate Momenta," A. P. S. Bulletin, Washington meeting, April 1973.
176. G. T. Y. Chen, C. R. Fletcher, J. T. Massimo, R. E. Lanou, Jr., and co-authors, "A Measurement of Backward Process $\pi^- p \rightarrow N\eta^0$ at 3.5 and 6.0 GeV," A. P. S. Bulletin, Washington meeting, April 1973.
177. R. E. Lanou, Jr., "An Informal Report on the Vanderbilt Conference," Internal Report #127, April 1973.
178. D. G. Fong, "A 'Swimming' Program for the Proportional Hybrid System Experiment," Internal Report #128, April 1973.
179. D. G. Fong, T. W. Ludlam, and T. L. Watts, "Secondary Tracks in Multi-wire Proportional Counters at the NAL 30" Bubble Chamber," Internal Report #129, May 1973.
180. D. G. Fong, A. M. Shapiro, M. Widgoff, and co-authors, "Particle Tagging for the NAL 30" Bubble Chamber Beam," A. P. S. Bulletin, Washington meeting, April 1973.

181. D. G. Fong and co-authors, "Secondary Track Measurement Using Multi-wire Proportional Counters with the NAL 30" Bubble Chamber," A. P. S. Bulletin, Washington meeting, April 1973.
182. Anatole M. Shapiro and Robert E. Lanou, Jr., "Progress Report of a Research Program in Experimental High Energy Physics," June 1973.

V. Scientific Personnel Associated with the Experimental Program.

A. M. Shapiro	--	Professor
R. E. Lanou, Jr.	--	Professor
M. Widgoff	--	Professor (Research)
J. T. Massimo	--	Associate Professor
D. Cutts	--	Assistant Professor
D. G. Fong	--	Assistant Professor (Research)
G. T. Y. Chen	--	Research Associate
D. Fausch ¹	--	Graduate Research Assistant
M. Heller	--	Graduate Research Assistant
L. J. Levinson	--	Graduate Research Assistant
R. Simard	--	Graduate Research Assistant
R. K. Thornton	--	Graduate Research Assistant

1. During summer of 1973.