PROGRESS REPORT OF A RESEARCH PROGRAM
IN EXPERIMENTAL HIGH ENERGY PHYSICS

MASTER

Task C
Progress Report
for Period January 1, 1979 to December 31, 1979

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ABSTRACT

An experimental program in strong and weak interaction physics of elementary particles is being carried out using electronic detection techniques. Experiments have been performed or have been proposed utilizing the accelerators of the laboratories at Brookhaven, Fermilab, LAMPF, and SLAC.

The experiments described in this report by the Electronic Detector Group include the following: (1) an analysis of resonances in the proton-antiproton system, (2) a study of inclusive scattering in hadron reactions of the form $a + p(n) \rightarrow b + X$, where "a" and "b" can be π^+ , K^+ , p^+ in any combination at incident momenta up to 175 GeV/c, (3) an experiment to measure neutrino-electron and other neutral current phenomena at the BNL-AGS, and (4) development of a muon polarimeter and proposals for its use in further experiments.

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 of the Electronic Detector Group during the present contract period (1 January 1979 - 31 December 1979). This work has been supported by the U.S. Department of Energy under contract EY-76-C-02-3130.A003 (Task C - Experimental).

This report is divided as follows:

- I. Data Analysis in Progress
- II. Experiments in Progress and in Preparation
- III. Associated Matters
- IV. Scientific Personnel
- V. Papers Published During the Preceeding Year and Papers in Press

I. Data Analysis In Progress

a) An Analysis of $\bar{P}P \rightarrow \pi^0 \pi^0$ and $\pi^0 \eta^0$:

Although this is an old experiment in the sense that data reduction, analysis and publication^{1,2} occurred some time ago (and have been duly reported in previous Progress Reports) it continues as a lively subject of wide interest due to its relation to possible multiquark states and in particular, baryonium.

Consequently, we have continued some analytical work on this problem principally as it relates to its inclusion in analyses with other $\bar{P}P \rightarrow$ (two mesons) experiments and the widely known discrepancy between analyses based upon $\pi^0 \pi^0$ and $\pi^+ \pi^-$ experiments separately. During the past year we have shed some light on this problem by checking on consistency of data sets and tracing inconsistencies into the $I=0$ and 1 interference terms. The problem is almost certainly associated with the "complex zeroes" technique used by the group of Carter et al in their application to the $\pi^+ \pi^-$ case under conditions where there were more than a single dominant angular momentum state. Other recent analyses such as that of Martin and Pennington have independently come to a similar conclusion; they carried out a more exhaustive version of the same technique but in an energy independent manner.

We have also pushed the analysis further for the $\pi^0 \eta^0$ channel. We have indications of a possible resonance at 2.15 GeV in $J=2$. This is particularly interesting since it is at the same approximate mass as our $\pi^0 \pi^0$, $J=2$ resonance; however, $\pi^0 \pi^0$ is $I=0$ but $\pi^0 \eta^0$ is $I=1$ and hence we would seem to have evidence for isopin degenerate resonances: both in the

mass region of the T-meson.

We reported³ on the above results in a workshop at Orsay this past June. They were received with considerable interest and had important bearing on several models; in particular, the model of Chan and Hoagasen was unable to accommodate this degeneracy.

b) Inclusive Hadron Scattering at FNAL Energies:

One of the "second round" of experiments to be run using the FNAL Single Arm Spectrometer (SAS) is E-118. It is the work of a collaboration of physicists from Brown University, Bari University (Italy), CERN, FNAL, and MIT. The goal of the experiment is to study inclusive hadron scattering for all of the "long-lived", charged hadrons via

$$a + b \rightarrow c + X$$

where (a) and (c) can be any combination of π^+ , K^+ , proton and antiproton. The incident hadrons (a) are produced by 400 GeV protons in the target of the FNAL Meson Laboratory. Hadron (a) is then directed onto a target - for purposes of E-118 this is a hydrogen target; however, a later phase (E-451) had nuclear targets - and the scattering product (c) is detected in SAS. This M6-SAS combination has been discussed extensively in previous reports and published literature so we repeat only the parameters important for these measurements. The M6-SAS combination permitted the study of particles with momenta up to $180 \frac{\text{GeV}}{c}$. Both beam line and spectrometer were instrumented with four Cerenkov counters each, thus permitting independent particle identification in either or both. Magnet polarities were also easily changeable thus permitting (++) , (+-), (-+), and (--) combinations for (M6-SAS). These two features thus permitted a combination of 36 different reactions to be studied - many of them simultaneously. For the studies in E-118 a multiplicity detector was installed at the target region to allow the measurement of associated multiplicities for each reaction.

The kinematic variables for data taken in this experiment are $p_a = +70, +100, +175 \frac{\text{GeV}}{c}$ while for particle (c) we had Feynman - x ,

$$0.1 < x < 1.0 \text{ and } 0.1 < p_T(c) < 1.5 \frac{\text{GeV}}{c}.$$

Although for many years there had been high statistic data on $pp \rightarrow \pi^+ X$ (mainly from internal targets and storage rings) as well as low statistics (and poor particle identification) bubble chamber experiments on $\pi p \rightarrow \pi X$ there was little or no knowledge of reactions such as $\pi^- p \rightarrow K^+ X$ or $\bar{p} p \rightarrow K^+ X$. Every model for hadronic strong interactions must either confront or make use of such data. Because many of the reactions involve multiple quantum number exchanges (or production for the unseen particle X) the cross sections range over several orders of magnitude and allow the possibility for discovery of rare processes.

All of the data has now been processed at least to the level of cross sections for each kinematic point. Analyses are proceeding on many areas of these data. Some have already appeared in print⁴, some are just appearing⁵, and others are in preparation.

We briefly summarize the results appearing recently:

A) It has long been known for the more easily accessed reactions such as $pp \rightarrow \pi^+ X$ that the invariant cross sections, $E \frac{d\sigma^3}{dp^3}$, had a power law dependence upon x via $(1-x)^n$ where n was found experimentally to be about 3; further there was some evidence that when more quantum number changes were present between (a) and (c) (such as $pp \rightarrow K^- X$) that higher values of n were indicated. Recently, models based upon application of quark-parton ideas to low - p_T hadron interactions have appeared. Of particular interest has been a model of Brodsky and Gunion⁶ which introduces the concept of two processes mediating the low - p_T inclusive scattering of hadrons: (1) quark exchange or annihilation or (2) gluon exchange. The inclusive, in-

variant cross section should factorize

$$E \frac{d^3\sigma}{dp^3} = f(p_a, p_T) \cdot (1-x)^{2n_s-1}$$

and n_s refers to the number of spectator quarks to the production of particle (c). For any given particle combination (a) $\rightarrow$ (c) gluon exchange should have a value of n_s one lower than for quark exchange. We have tested our data against this model. Figure 1 shows a sample of data for several π^+ initiated reactions. In Figure 2 is illustrated the success of the p_1 and x factorization using $\pi^+ + K^-$ as an example. In Figure 3 are summarized the results for the n_s - power. The solid line gives the Brodsky - Gunion prediction for quark exchange (or annihilation) and the dashed for gluon exchange. In the right hand margin of the figure are given the n_s values for the reactions indicated in the left margin. It is clear that the $(1-x)$ powers measured in our experiment fall into hierarchies which roughly follow the quark predictions, but are in clear disagreement with the minimum value predicted for gluon exchange. However, all the meson $\rightarrow$ meson channels with double charge exchange have exponents more than two units less than the quark exchange predictions, $n_s = 5$. It is in these channels that the data of high - x are enhanced by the production and decay of meson resonances⁴. The experimental evidence, therefore, suggests that the underlying constituents of hadrons are important in describing fragmentation processes at low $-p_T$ and that quark exchange is closest to being the dominant mechanism for these processes.

B) While these quark parton ideas are very suggestive, Regge pole

theory as a description of scattering amplitudes for two body scattering reactions, has had a number of successes, which at least are part of the truth if only to the extent of a useful parameterization. For inclusive processes, the Regge model has been extended by Mueller and de Tar et al⁷ into what is known as triple Regge theory. From $pp \rightarrow pX$ it is known⁸ that this is still a useful way to parameterize data and within the model to suggest similarities and differences to other, previously untested reactions such as we have measured here. Referring to Figure 4 which diagrams the triple Regge amplitude the invariant cross section for our process $a + p \rightarrow c + X$ is given by

$$E \frac{d^3\sigma}{dp^3} = \sum_{ijk} G_{ijk}(t) (1-x)^{\alpha_k(0) - \alpha_i(t) - \alpha_j(t)} [s]^{\alpha_k(0)-1}$$

where $G_{ijk}(t)$ is proportional to the residue function and measures the coupling at each of the four vertices. $\alpha_{i,j,k}$ are the respective Regge trajectories for the i,j,k - exchanges. The lower vertex is related through the optical theorem to the total cross section of particle $i=j$ on protons. For the cross sections we have measured i and j can be P (pomeron), R (reggeon, e.g., ρ or f), π , K^* , n or Δ and the k - trajectory may be either P or R.

For input to the data we have used

	trajectory	J^P	I^G
P-pomeron	$1 + \alpha'_p t$	0^+	
R-reggeon	$1/2 + t$		
ρ		1^-	1^+
f		2^+	0^+
ω		1^-	0^-
A_2		2^+	1^-
π	$0 + t$	0^-	1^-
$K^*(892)$	$.2043 + t$	1^-	$1/2$
n	$-.3828 + t$	$1/2^+$	$1/2$
$\Delta(1232)$	$-.0178 + t$	$3/2^+$	$3/2$

The appropriateness of triple Regge formalism is for $\frac{s}{m^2} \rightarrow \infty$ and $m^2/m_p^2 \rightarrow \infty$; for the incident energies we are dealing with this implies $0.75 < x < 0.97$. For a given reaction all data points are fit at once. In general good fits are obtained with a Pomeron slope, $\alpha'_p = -0.06 \pm 0.05$. Note that scaling (cross sections are a function of p_T and x but not s) will occur except for terms such as $PPR = ijk$. Tables 1 and 2 summarize the results of these fits. Very briefly the implications from the fits to these data are that, on the whole, the triple Regge formalism allows a faithful parameterization of the data within the kinematic region used. Some of the more prominent successes and failures are:

- 1) Scaling: $\pi^+ p \rightarrow \pi^+ X$ and $pp \rightarrow pX$ cross sections change by less than 2% from 70 to 175 GeV/c; $\pi^- p \rightarrow pX$ changes by less than 3%; within our statistics for $K^+ p \rightarrow K^+ X$, $K^- p \rightarrow K^- X$ and $\bar{p}p \rightarrow \bar{p}X$ we cannot distinguish

complete scaling with s and a moderate $1/\sqrt{s}$ contribution.

2) Regge dependence on t and p_T . We find the triple Regge approach successfully gives the general kinematic dependence for the x and t regions used in the fits; however, if the fits are extended to large values of $|t|$ more complicated trajectories are needed.

3) Comparison of line reversed reactions such as $ap \rightarrow aX$ and $\bar{a}p \rightarrow \bar{a}X$ allow checks on the possible existence of interference terms such as PRR which is the only term changing sign under a change of beam polarity. Table 3 shows this comparison in the right hand column. At the 2 standard deviation level there is roughly a 5% contribution for $p^\pm$ and $\pi^\pm$ and a 13% contribution for $K^\pm$. Although this term violates scaling, it is small enough to be consistent with our comments above.

4) Particle exchange comparisons: $ap \rightarrow cX$, $a \neq c$. If we look at reactions where the t channel exchanges (i and j) are line reversed; e.g., $\pi^+p \rightarrow pX$ and $pp \rightarrow \pi^+X$ then we exchange a nucleon, n , and an anti-nucleon, $\bar{n}$, respectively. Since for such reactions the lower portion of the triple Regge diagram represents $ip \rightarrow ip$ scattering at $t=0$ and $(\text{energy})^2 = m_x^2$, we expect the inclusive cross section to be proportional to the total ip cross section at energy $= \sqrt{m_x^2}$. For the above mentioned reaction we would then expect from our cross section formulas integrated over t to give

$$\frac{\sigma(np)}{\sigma(\bar{n}p)} = \frac{39\text{mb}}{48\text{mb}} = 0.81 = \frac{\int_0^t E \frac{d^3\sigma}{dp^3} (\pi^+p)}{\int_0^t E \frac{d^3\sigma}{dp^3} (p\pi^+)}$$

however, we find 0.31 ± 0.06 .

Better agreement is found for reactions involving K^* and $\bar{K}^*$ exchanges:

$$\frac{\int_0^t E \frac{d^3\sigma}{dp^3} (\pi^+ K^+)}{\int_0^t E \frac{d^3\sigma}{dp^3} (\pi^- K^-)} = 0.73 \pm 0.13 \text{ while } \frac{(K^+ p)}{(K^- p)} = 0.63.$$

5) Factorization. Many of the reactions share a common vertex and hence if ratios are formed to isolate the common term we should find equality. For example using measured total cross sections and the PPP(t=0) terms from our fits for our combined $a p \rightarrow a x$ we form the ratios:

$$R = \frac{\text{PPP}_{ap \rightarrow ax}}{[\sigma_{\text{tot}}(ap)]^2} \propto \frac{G_{\text{PPP}}(0)}{G_{pp^p}(0)}$$

and we find:

$$\left. \begin{array}{l} p, p \\ - \\ p, p \end{array} \right\} R = 0.74 \pm 0.05 \times 10^{-3} \text{ mb}^{-1} \text{ GeV}^{-2}$$

$$\left. \begin{array}{l} \pi^+, \pi^+ \\ - \\ \pi^-, \pi^- \end{array} \right\} R = 0.81 \pm 0.05 \times 10^{-3}$$

$$\left. \begin{array}{l} K^+, K^+ \\ - \\ K^-, K^- \end{array} \right\} R = 0.80 \pm 0.05 \times 10^{-3}$$

Thus we find that factorization is well satisfied.

C) From the point of view of short-range order in high energy hadronic interactions, the associated multiplicity in inclusive reactions is of great interest. It can be related to the same type of parameterization

as is done in total cross section multiplicities - $\langle n_c \rangle \approx A + B \ln s$ - in many many models. In particular if M_X is the missing mass in the reaction $a + p \rightarrow c + X$ then it is expected that $\langle n_c \rangle = A' + B' \ln M_X^2 + C(t)$. For our data, C is usually very small; however, the general form gives an excellent fit to all of the data. The $\ln (\text{energy})^2$ term is common to nearly all models; however, the nature and size of B (the strength of the contribution from the central rapidity region) is a point of some interest. The reactions $p+p \rightarrow p+X$ and $\pi^- + p \rightarrow \pi^- X$ have been studied before; our values agree with the world average. It is interesting that the parameters we find for $\pi^+ + p \rightarrow \pi^+ X$ and $K^+ p \rightarrow K^+ X$ are very similar. This similarity suggests that charged particle production in this inclusive reactions is dominated by pomeron-proton interactions producing the observed associated multiplicity. We have also compared our results for the coefficients of $\ln M_X^2$ to the $\ln s$ coefficients obtained by fitting the world data for total inelastic multiplicity. We find for incident positive particle induced reactions excellent agreement exists between coefficients. Our results for the $\pi^- p \rightarrow \pi^- X$ are also in good agreement with our positive beam results. However, the agreement between total and associated $\ln (\text{energy})^2$ coefficient is poor for all other negative beam reactions. Typically our results are about one standard deviation lower than the total inelastic results. The results are summarized in the tables of Figures 5-8.

FIG. 1

FIG. 2

FIG. 3

TABLE I

$d\sigma/dm^2$ (10^{-2} nb/GeV 2)

t integrated from $-.1$ to -1.0 GeV/c 2

		$x = .8$	.84	.88	.92	.96
Reaction	Term					
$P \rightarrow P$	PPP	$1.191 \pm .08$	$1.485 \pm .11$	$1.970 \pm .16$	$2.920 \pm .25$	$5.618 \pm .50$
	RRP	$1.804 \pm .18$	$1.524 \pm .10$	$1.246 \pm .05$	$.961 \pm .02$	$.652 \pm .004$
$\pi^+ \rightarrow \pi^+$	PPP	$.721 \pm .05$	$.901 \pm .07$	$1.199 \pm .09$	$1.796 \pm .13$	$3.580 \pm .26$
	RRP	$.984 \pm .05$	$.853 \pm .03$	$.718 \pm .02$	$.574 \pm .006$	$.409 \pm .001$
$K^+ \rightarrow K^+$	PPP	$.717 \pm .03$	$.896 \pm .04$	$1.195 \pm .05$	$1.792 \pm .07$	
	RRP	$.312 \pm .06$	$.273 \pm .06$	$.232 \pm .05$	$.188 \pm .04$	
$\bar{P} \rightarrow \bar{P}$	PPP	$1.188 \pm .08$	$1.486 \pm .11$	$1.981 \pm .14$	$2.971 \pm .21$	
	RRP	$1.284 \pm .22$	$1.085 \pm .18$	$.886 \pm .15$	$.682 \pm .12$	
$\pi^- \rightarrow \pi^-$	PPP	$.962 \pm .06$	$1.120 \pm .07$	$1.367 \pm .08$	$1.818 \pm .11$	$2.944 \pm .18$
	RRP	$.658 \pm .04$	$.591 \pm .04$	$.517 \pm .03$	$.433 \pm .03$	$.325 \pm .02$
$K^- \rightarrow K^-$	PPP	$.491 \pm .04$	$.614 \pm .05$	$.819 \pm .06$	$1.228 \pm .10$	
	RRP	$.666 \pm .27$	$.544 \pm .20$	$.427 \pm .11$	$.312 \pm .05$	

t-Slope and Intercept for Particle Changing

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Reactions at $x = .8$

Reaction	Term	t-Slope	Intercept (mb/GeV ²)	$d\sigma/dm^2$ (10 ⁻² mb/GeV ²)
$\pi^+ \rightarrow K^+$	K^*K^*R	$2.77 \pm .12$	$.31 \pm .015$	$.187 \pm .01$
$K^+ \rightarrow \pi^+$	K^*K^*R	$2.80 \pm .72$	$.35 \pm .085$	$.209 \pm .06$
$\pi^- \rightarrow K^-$	K^*K^*R	$2.89 \pm .20$	$.235 \pm .018$	$.135 \pm .01$
$K^- \rightarrow \pi^-$	K^*K^*R	5.06 ± 1.29	$.71 \pm .20$	$.234 \pm .07$
$\pi^+ \rightarrow p$	$\bar{n} \bar{n} R$	$1.82 \pm .15$	$.117 \pm .011$	$.107 \pm .01$
$p \rightarrow \pi^+$	nnR	$2.76 \pm .29$	$.052 \pm .005$	$.032 \pm .004$
$\pi^- \rightarrow \bar{p}$	nnR	$1.89 \pm .43$	$.041 \pm .010$	$.037 \pm .01$
$\bar{p} \rightarrow \pi^-$	$\bar{n} \bar{n} R$	2.88 ± 2.15	$.152 \pm .066$	$.089 \pm .04$
$\pi^+ \rightarrow \bar{p} \& p \rightarrow \pi^-$	$\Delta\Delta P$	3.26 Set	$.0116 \pm .0033$	$.007 \pm .002$
$\pi^- \rightarrow p \& \bar{p} \rightarrow \pi^+$	$\bar{\Delta} \bar{\Delta} P$	3.26 Set	$.0424 \pm .0091$	$.022 \pm .007$

TABLE 3

 $d\sigma/dm^2$ (10⁻² mb/GeV²) for $a^\pm p \rightarrow a^\pm x$ at $x = .88$

Both Polarities Fitted Simultaneously

 t integrated from $-.1$ to -1.0 (GeV/c)²

	PPP	RRP	PRR
$p^\pm p \rightarrow p^\pm x$	$2.04 \pm .16$	$1.11 \pm .05$	$.11 \pm .08$
$\pi^\pm p \rightarrow \pi^\pm x$	$1.15 \pm .09$	$.71 \pm .02$	$.06 \pm .02$
$K^\pm p \rightarrow K^\pm x$	$1.03 \pm .05$	$.30 \pm .05$	$.13 \pm .06$

Table V.1
Total Cross Sections (mb)

Beam Momentum = 100 GeV/c

	π^+p	K^+p	pp	π^-p	K^-p	$\bar{p}p$
<u>Measured</u>						
σ	22.1±.9	17.7±1.6	38.7±1.3	23.1±.7	20.2±1.1	38.1±1.1
<u>Corrections</u>						
σ^{elastic}	.7±.2	.5±.1	1.7±.3	.7±.1	.6±.2	2.0±.4
$\sigma^{\text{inelastic}}$	.1±.1	.1±.1	.3±.1	.1±.1	.1±.1	.3±.1
<u>Corrected Results</u>						
σ^{total}	23.4±.9	18.4±1.7	38.7±1.3	23.9±.7	20.8±1.2	40.4±1.2
<u>World Data</u>						
σ^{total}	23.3±.1	18.9±.1	38.4±.1	24.0±.1	20.4±.1	42.0±.2
σ^{elastic}	3.3±.2	2.5±.1	7.1±.4	3.3±.1	2.5±.1	7.8±.6

* Ref. V.13
** Ref. V.1
*** Ref. V.7

Fig. 5

Table V.1

Beam Momentum = 175 GeV/c

<u>Measured</u>						
σ	20.9±1.1	16.9±1.6	23.9±1.0	21.3±.8	20.7±1.0	36.2±1.6
<u>Corrections</u>						
σ^{elastic}	1.6±.2	1.1±.2	3.7±.3	1.7±.2	1.1±.2	4.0±.6
$\sigma^{\text{inelastic}}$	.6±.1	.2±.1	1.0±.2	.4±.2	.3±.1	1.0±.3
<u>Corrected Results</u>						
σ^{total}	22.9±1.2	18.2±1.8	29.6±1.1	23.4±.8	21.4±1.1	41.2±1.7
<u>World Data</u>						
σ^{total}	23.6±.1	19.6±.1	38.8±.1	24.2±.1	20.7±.1	41.6±.5
σ^{elastic}	3.4±.1	2.5±.1	7.1±.3	3.4±.1	2.6±.1	7.3±.5

* Ref. V.13
** Ref. V.1
*** Ref. V.7

Table V.3

Inelastic Charged Topology Cross Section Comparisons

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Charged Prong	100 π^+p		Reaction		100 π^-p		100 $\bar{p}p$	
	Ours (mb)	Ref. V.2 (mb)	Ours (mb)	Ref. V.2 (mb)	Ours (mb)	Ref. V.3 (mb)	Ours (mb)	Ref. V.5 (mb)
2	2.5 $\pm$.9	2.4 $\pm$.2	3.7 $\pm$.9	4.9 $\pm$.3	1.9 $\pm$.6	2.0 $\pm$.3	4.6 $\pm$.6	3.6 $\pm$.3
4	4.2 $\pm$.5	4.7 $\pm$.2	8.9 $\pm$.9	7.3 $\pm$.3	4.8 $\pm$.4	4.8 $\pm$.1	8.0 $\pm$.7	8.1 $\pm$.2
6	4.4 $\pm$.6	4.8 $\pm$.2	7.0 $\pm$.9	7.0 $\pm$.3	5.0 $\pm$.5	5.2 $\pm$.1	8.3 $\pm$.9	8.3 $\pm$.2
8	4.0 $\pm$.8	3.6 $\pm$.2	4.3 $\pm$ 1.0	5.6 $\pm$.2	3.9 $\pm$.6	4.3 $\pm$.1	4.9 $\pm$ 1.1	6.9 $\pm$.2
10	2.5 $\pm$.8	2.6 $\pm$.2	4.4 $\pm$.8	3.7 $\pm$.2	2.8 $\pm$.6	2.5 $\pm$.1	4.4 $\pm$ 1.1	4.1 $\pm$.1
12	1.6 $\pm$.5	1.3 $\pm$.1	1.7 $\pm$.2	1.7 $\pm$.1	1.7 $\pm$.4	1.4 $\pm$.1	3.0 $\pm$.7	2.2 $\pm$.1
14	.9 $\pm$.1	.6 $\pm$.1	.7 $\pm$.2	.8 $\pm$.1	.5 $\pm$.1	.6 $\pm$.04	.8 $\pm$.4	.9 $\pm$.1
16	.2 $\pm$.1	.13 $\pm$.03	.3 $\pm$.1	.2 $\pm$.04	.12 $\pm$.07	.13 $\pm$.03	.2 $\pm$.1	.4 $\pm$.04
18	.1 $\pm$.1	.04 $\pm$.02	.1 $\pm$.05	.1 $\pm$.02	.03 $\pm$.01	.05 $\pm$.01	.06 $\pm$.06	.18 $\pm$.02
20	-----	.02 $\pm$.01	-----	.1 $\pm$.1	-----	.01 $\pm$.006	-----	.04 $\pm$.01
	20.0 $\pm$.9	20.2 $\pm$.2	31.3 $\pm$ 1.2	31.4 $\pm$.2	20.7 $\pm$.7	21.0 $\pm$.2	34.2 $\pm$ 1.1	35.6 $\pm$.6

Table V.4

Inelastic Charged Topology Cross Section (mbarns)

Charged Prong	+100		-100		+175		-175		-175	
	π^+p (mb)	π^-p (mb)	π^+p (mb)	π^-p (mb)	π^+p (mb)	π^-p (mb)	π^+p (mb)	π^-p (mb)	$\bar{p}p$ (mb)	$\bar{p}p$ (mb)
2	1.7 $\pm$.9	2.1 $\pm$.5	1.9 $\pm$.8	2.1 $\pm$.6	3.7 $\pm$.8	2.2 $\pm$.5	1.5 $\pm$ 1.0	4.0 $\pm$ 2.0		
4	3.5 $\pm$.5	3.8 $\pm$.5	3.7 $\pm$.7	2.6 $\pm$.9	5.4 $\pm$.8	3.7 $\pm$.4	3.7 $\pm$.5	6.8 $\pm$ 1.2		
6	3.8 $\pm$.6	4.9 $\pm$.7	4.2 $\pm$.9	3.4 $\pm$ 1.1	6.5 $\pm$ 1.0	3.6 $\pm$.5	3.4 $\pm$.7	6.9 $\pm$ 1.7		
8	3.2 $\pm$.6	2.9 $\pm$.7	3.6 $\pm$ 1.0	3.6 $\pm$ 1.3	5.9 $\pm$ 1.0	3.7 $\pm$.8	3.7 $\pm$.8	7.0 $\pm$ 2.3		
10	2.3 $\pm$.5	2.8 $\pm$.7	2.9 $\pm$ 1.0	2.3 $\pm$ 1.2	4.2 $\pm$ 1.0	2.9 $\pm$.4	2.7 $\pm$.5	3.5 $\pm$ 1.5		
12	1.1 $\pm$.5	1.3 $\pm$.4	2.7 $\pm$.7	7.5 $\pm$.7	3.7 $\pm$.8	1.7 $\pm$.3	1.6 $\pm$.3	3.3 $\pm$ 1.5		
14	.5 $\pm$.1	.4 $\pm$.2	1.0 $\pm$.5	.5 $\pm$.5	1.5 $\pm$.2	1.0 $\pm$.3	.8 $\pm$.3	1.7 $\pm$.5		
16	.2 $\pm$.1	.1 $\pm$.1	.4 $\pm$.3	-----	.6 $\pm$.2	.6 $\pm$.2	.5 $\pm$.2	.9 $\pm$.3		
18	.1 $\pm$.1	.05 $\pm$.05	.1 $\pm$.1	-----	.3 $\pm$.1	.4 $\pm$.1	.2 $\pm$.1	.5 $\pm$.3		
20	-----	-----	-----	-----	.1 $\pm$.06	.2 $\pm$.1	.1 $\pm$.1	.3 $\pm$.2		
22	-----	-----	-----	-----	-----	.13 $\pm$.07	-----	-----		

Total Inelastic
Cross Section :16.4 $\pm$ 1.6 18.4 $\pm$ 1.1 20.2 $\pm$ 1.1 17.1 $\pm$ 1.7 33.7 $\pm$ 1.0 19.9 $\pm$.7 18.1 $\pm$ 1.1 34.9 $\pm$ 1.6

FIG. 6

Table V.2
Mean Inelastic Charged Multiplicity

Reaction	Incident Beam Momentum (GeV/c)	This Experiment		No. of Events			Ref.
		Mean	D		Mean	D	
π^+p	100	$6.75 \pm .16$	$3.33 \pm .12$	2106 ± 116	$6.62 \pm .07$	$3.19 \pm .05$	V.2
π^-p	100	$6.79 \pm .11$	$3.15 \pm .08$	3461 ± 140	$6.79 \pm .08$	$3.39 \pm .04$	V.3
π^+p	175	$7.55 \pm .21$	$3.67 \pm .14$	1210 ± 72			
π^-p	175	$7.83 \pm .14$	$3.81 \pm .10$	2013 ± 80			
K^+p	100	$6.95 \pm .25$	$3.33 \pm .16$	967 ± 62	$6.65 \pm .31$	$3.34 \pm .19$	V.4
K^-p	100	$6.76 \pm .18$	$3.17 \pm .10$	2247 ± 152			
K^+p	175	$7.61 \pm .37$	$3.85 \pm .21$	665 ± 74			
K^-p	175	$7.56 \pm .18$	$3.63 \pm .17$	1787 ± 100	$7.33 \pm .21$	$3.51 \pm .15$	V.6*
pp	100	$6.44 \pm .17$	$3.24 \pm .13$	1712 ± 113	$6.37 \pm .06$	$3.26 \pm .06$	V.2
$\bar{p}p$	100	$6.92 \pm .11$	$3.13 \pm .09$	2482 ± 93	$6.74 \pm .06$	$3.26 \pm .05$	V.5
pp	175	$7.54 \pm .15$	$3.71 \pm .10$	2739 ± 130			
$\bar{p}p$	175	$7.36 \pm .24$	$3.81 \pm .17$	1083 ± 80			

*Results at 147 GeV/c

Table VI.1

Fit Parameters

$$\langle n \rangle_A = A + B \ln A^2 + C|t|$$

180 GeV/c Reactions
(Positive Incident Beam Particles)

Reaction*	A	B	C	χ^2/OF
$\pi^+ \rightarrow \pi^+$	$-.71 \pm .15$	$1.34 \pm .04$	$.33 \pm .11$	85/32
$\pi^+ \rightarrow \pi^-$	$.61 \pm .89$	$1.06 \pm .22$	$-.46 \pm .93$	7/6
$\pi^+ \rightarrow K^+$	$-.39 \pm .53$	$1.24 \pm .14$	$.41 \pm .27$	47/32
$\pi^+ \rightarrow K^-$	$.83 \pm 1.70$	$1.04 \pm .91$	1.00 ± 1.32	9/5
$\pi^+ \rightarrow p$	$.82 \pm 1.31$	$1.01 \pm .36$	$.08 \pm .31$	26/17
$K^+ \rightarrow \pi^+$	-2.42 ± 2.05	$1.74 \pm .60$	$.10 \pm 1.22$	3/7
$K^+ \rightarrow K^+$	$-.42 \pm .46$	$1.29 \pm .13$	$.19 \pm .37$	48/27
$p \rightarrow \pi^+$	-4.86 ± 1.96	$1.98 \pm .42$	$.68 \pm .51$	37/16
$p \rightarrow p$	$-.78 \pm .16$	$1.36 \pm .05$	$.42 \pm .10$	98/36

Kinematic Region fitted

$$.2 < |t| < 2. \text{ GeV}^2$$

$$10 < M_A^2 < 130 \text{ GeV}^2$$

*All reactions are on proton targets. For instance $\pi^+ \rightarrow \pi^+$ is shorthand for $\pi^+p \rightarrow \pi^+p$.

FIG. 7

Table VI.2

Fit Parameters

$$\langle \sigma \rangle_x = A + B \ln M_x^2 + C|t|$$

175 GeV/c Reactions
(Positive Incident Beam Particles)

Reaction ^a	A	B	C	χ^2/DF
$\pi^+ \rightarrow \pi^+$	-0.38 ± 0.26	1.27 ± 0.06	0.25 ± 0.14	47/25
$\pi^+ \rightarrow \pi^0$	-4.8 ± 3.90	2.03 ± 0.80	0.78 ± 1.16	16/6
$\pi^+ \rightarrow K^+$	-0.31 ± 0.50	1.31 ± 0.12	0.17 ± 0.27	23/25
$\pi^+ \rightarrow K^0$	-9.40 ± 4.60	2.98 ± 0.99	1.40 ± 1.40	2/6
$\pi^+ \rightarrow p$	-0.80 ± 0.62	1.45 ± 0.19	-0.00 ± 0.36	28/10
$K^+ \rightarrow \pi^+$	-1.23 ± 1.04	1.38 ± 0.26	1.46 ± 0.62	10/15
$K^+ \rightarrow K^0$	0.70 ± 0.46	1.04 ± 0.12	0.08 ± 0.31	37/23
$p \rightarrow \pi^+$	-4.50 ± 1.42	1.91 ± 0.28	0.68 ± 0.22	30/16
$p \rightarrow p$	-0.80 ± 0.27	1.38 ± 0.07	0.56 ± 0.14	51/24

Kinematic Region Fitted

$$.2 < |t| < 2. \text{ GeV}^2$$

$$15 < M_x^2 < 250 \text{ GeV}^2$$

^aAll reactions are on proton targets. For instance $\pi^+ \rightarrow \pi^0$ is shorthand for $\pi^+ p \rightarrow \pi^0 X$.

Table VI.3

Fit Parameters

$$\langle \sigma \rangle_x = A + B \ln M_x^2 + C|t|$$

100 GeV/c Reactions
(Negative Incident Beam Particles)

Reaction ^a	A	B	C	χ^2/DF
$\pi^- \rightarrow \pi^-$	-0.11 ± 0.16	1.20 ± 0.05	0.39 ± 0.10	61/23
$\pi^- \rightarrow \pi^0$	-2.37 ± 0.52	1.66 ± 0.13	-0.41 ± 0.38	8/6
$\pi^- \rightarrow K^-$	-0.30 ± 0.62	1.19 ± 0.15	0.61 ± 0.22	22/25
$\pi^- \rightarrow K^0$	1.42 ± 1.83	0.71 ± 0.40	1.15 ± 0.64	8/6
$\pi^- \rightarrow \bar{p}$	-0.93 ± 1.60	1.20 ± 0.41	0.46 ± 0.29	20/14
$\pi^- \rightarrow p$	-3.46 ± 1.60	2.25 ± 0.50	-0.58 ± 0.56	7/9
$K^- \rightarrow \pi^-$	-6.16 ± 3.10	2.50 ± 0.70	0.20 ± 0.90	4/9
$K^- \rightarrow K^0$	1.63 ± 0.62	0.94 ± 0.16	0.64 ± 0.40	39/21
$p \rightarrow \pi^-$	-1.02 ± 0.80	1.47 ± 0.88	-2.01 ± 1.26	11/9
$p \rightarrow p$	1.62 ± 0.46	0.94 ± 0.12	0.60 ± 0.20	41/25

Kinematic Region Fitted

$$.2 < |t| < 2. \text{ GeV}^2$$

$$10 < M_x^2 < 130 \text{ GeV}^2$$

^aAll reactions are on proton targets. For instance $\pi^- \rightarrow \pi^0$ is shorthand for $\pi^- p \rightarrow \pi^0 X$.

FIG. 8

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II. Experiments in Progress and in Preparation.

a) An Experiment to Study Neutrino Interactions.

Final approval for this experiment was received in January from the BNL Directorate. Conditional approval had been given the previous September.

The experiment is designed to study a variety of neutral current phenomena induced by neutrinos. It is to be performed at the Brookhaven National Laboratory A.G.S. by a collaborative group of physicists from BNL, Brown University, and the University of Pennsylvania, and K.E.K. (Japan).

Although the background, need for, and nature of this experiment were discussed in our Renewal Proposal, we reproduce some of that text here before going on with our plans for 1980.

"The weak neutral current was discovered¹ in 1973 in experiments studying the interaction of neutrinos on nuclei. Since that time a very extensive body of experimental evidence has accumulated on a variety of neutral current phenomena ranging from neutrino (and anti-neutrino) scattering on hydrogen and nuclei, through neutrino-electron scattering, to polarized electron-deuterium scattering and observations of parity violation in heavy atoms². Attempts to interpret the combination of all of these data to see if a coherent picture emerges for the mediation of the weak neutral current in the mutual interactions of leptons and quarks have recently appeared³. These have been carried out in both a model independent way and in the spirit of specific models such as that of Weinberg-Salam and incorporating the quark-parton model. While the details of the different analyses differ a rather striking picture is

emerging: a) the space-time structure of the neutrino-quark interaction appears to favor an interaction involving both V and A with (V-A) dominant, b) for the neutrino-electron interaction a solution favoring $g_V \approx 0$ and $g_A \approx -\frac{1}{2}$; c) a value of $\sin^2 \theta_w = 0.23 \pm 0.02$ is deduced from

a "world average" of all experiments; and d) a parameter $\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_w}$

which is related to the ratio of the fermi coupling constant determined from neutral current phenomena to that from charged current is $0.98 \pm .02$; the closeness of the ratio to unity suggests a limit on the Higgs multiplicity in gauge theories. The fact that a consistent value of $\sin^2 \theta_w$ fits all of the experiments is very striking and suggestive of the possible correctness of the Weinberg-Salam model; however, as Bjorken⁴, Sakurai and Hung⁵ have pointed out that model is not a unique description. Additional points should be made: a) although a 10% error appears on the "world average" for $\sin^2 \theta_w$ the individual experiments have quoted errors ranging up to 40% and many have systematic errors at the same level; b) reactions such as $\nu_\mu e^- \rightarrow \nu_\mu e^-$ are included for which the largest number of events after background is 8 and for $\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$ where the number of events is 6 and all other experiments have 1 or 0; c) these latter reactions then must compare $\frac{\sigma(\bar{\nu}e)}{E} = 1.3 \pm 0.6$ to $\frac{\sigma(\nu e)}{E} = 1.6 \pm 0.4$ where their difference determines the important quantity (g_V, g_A) . Figures 1, 2, and 3 tabulate and illustrate the synthesis of the above mentioned analyses. In Figure 2 it can be seen that the right-handed sector is not well determined - clearly much better data is needed on $\nu(\bar{\nu})p \rightarrow \nu(\bar{\nu})p$. As another example, Figure 3

(and the comments above on the number of events available to date on $\bar{\nu}e^-$) illustrates that a precise measurement of $\bar{\nu}e^- \rightarrow \bar{\nu}e^-$ could reveal some surprises. Langacker et al.³ have also studied the systematic errors inherent in the theoretical models and have concluded that they are small. What is clearly indicated by the above considerations and the importance of a precise understanding of the weak neutral current is a "second generation" experiment of high statistical significance and low systematic error. Our experiment E-734 is designed to fill that need.

The experiment we are performing is designed to measure simultaneously the following reactions:

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^- \quad (1)$$

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^- \quad (2)$$

$$\nu_\mu + p \rightarrow \nu_\mu + p \quad (3)$$

$$\bar{\nu}_\mu + p \rightarrow \bar{\nu}_\mu + p \quad (4)$$

and in order to properly understand these reactions we also measure:

$$\nu_\mu + n \rightarrow \mu^- + p \quad (5)$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n \quad (6)$$

$$\nu_\mu + N \rightarrow \nu_\mu + N' + \pi \quad (7)$$

$$\bar{\nu}_{\mu} + N \rightarrow \bar{\nu}_{\mu} + N' + \pi \quad (8)$$

$$\nu_e + n \rightarrow e^{-} + p \quad (9)$$

$$\bar{\nu}_e + p \rightarrow e^{+} + n \quad (10)$$

These reactions are of course also valuable in their own right for studying the neutral current and its relation to the charged current as well as the question $e-\mu$ universality. The experiment is performed at the relatively low energy of the A.G.S. for several reasons, principal among them being: a) $\nu(\bar{\nu})p$ cross sections are nearly independent of energy, b) while $\nu(\bar{\nu})e$ cross sections do depend upon the incident neutrino energy the combination of high intensity and high pulse repetition rate make the event rate per ton per day favorable in comparison to CERN and FNAL, and c) the backgrounds most troublesome for these reactions are measured, well understood, and more manageable at A.G.S. energies. The unique overall features of the detector which make it ideal for the processes we wish to study are a) its large active volume (roughly 160 tons of visible liquid scintillator); b) its fine granularity and multiple hit capacity in dead-time-less operation; c) good multiple dE/dx (65% FW) measurements; and d) good tracking with excellent angular resolution $(\frac{9mr}{\sqrt{E}})$.

The detector, which is shown schematically in Fig. 4 and 5 consists of 128 4m x 4m x 7.5cm slabs of liquid scintillator each of which is

followed by 2 ~ 4 planes of track detector (also 4m x 4m). The scintillator slabs are segmented into 16 4m x 7.5cm x 25cm cells viewed at each end by photomultipliers. Total charge and timing information from each photomultiplier yield the energy deposited and position of energy deposition along the cell.

Liquid scintillator has been chosen for the target for several reasons:

1) so that the detector is entirely active, i.e., all energy depositions as low as 5 MeV are detected, thus providing maximum sensitivity to entering and exiting neutral particles, 2) the p/n ratio equals 1.3 thus enhancing the signal to background for $\nu_p + \nu_p$, 3) the number of electrons/radiation length, an important parameter for $\nu_\mu e + \nu_\mu e$, is approximately twice as large as that for other commonly available substances (i.e. aluminum, concrete, liquid argon), and 4) the presence of additional tracks at the vertex, important for selection of both $\nu_p + \nu_p$ and $\nu_\mu e + \nu_\mu e$ may be detected for energies as low as 15 MeV; this is comparable even to the sensitivity of a bubble chamber (≈ 8 MeV).

Proportional drift tubes have been chosen as the track detector since (1) they provide good position resolution ($< 1\text{mm}$) and dE/dx information (65% FWHM) at a low cost and (2) they are modular, easy to construct, and rugged. The high density of dE/dx measurements in the scintillator and proportional drift tubes (16 measurements/ radiation length or interaction length) provides excellent p/π identification and γ/e separation.

The small mass of the target electron in the reaction $\nu_\mu e + \nu_\mu e$ ($\bar{\nu}_\mu e + \bar{\nu}_\mu e$) results in a potentially very clean signature - a single, unaccompanied electron produced at an angle of $1 - 2^\circ$ to the beam direction - but also in a very low cross section; we assume for computational

purposes $\sigma(\nu_\mu e + \bar{\nu}_\mu e) \approx 1.4 E_\nu (\text{GeV}) \times 10^{-42} \text{ cm}^2/\text{electron}$ which is the value in the $SU(2) \times U(1)$ model for $\sin^2 \theta_W = 0.25$. It is therefore necessary that the detector have a large mass, and at the same time be able to identify single recoil electrons and measure their angle with excellent resolution in order to distinguish the signal from other ν interactions which occur approximately 8,000 times more frequently.

A recoil electron will be identified in the proposed detector as a single, minimum-ionizing track, originating in the liquid scintillator, and developing in a fashion characteristic of an electromagnetic shower. Three X,Y coordinates and 6 dE/dx measurements in the first 40% of a radiation length will measure the angle of the electron to a precision of $\sim 9\text{mr}/\sqrt{E}$ and will verify that the track is minimum ionizing. Photon conversions, $\gamma \rightarrow e^+e^-$, which in general are characterized by an energy deposition that is twice minimum ionizing will be rejected by a factor of 4 : 1. Sixteen (fourteen) samples per radiation length of the longitudinal (transverse) development of the shower will identify the particle as an electron rather than a hadron.

We have estimated the production rate for $\nu_\mu e + \bar{\nu}_\mu e$ ($\bar{\nu}_\mu e + \nu_\mu e$) based on the measured event rates in two independent experiments at BNL. Based on previous experience, the AGS has an average intensity of 9×10^{12} protons/pulse and can run at a 1.3 sec repetition rate 20 hours/day. This would produce 3 - 4 ($\nu_\mu e + \bar{\nu}_\mu e$) events/day or 300 events/calendar year given the present mode of AGS operation. The event rate for $\bar{\nu}_\mu e$ should be approximately one half that, i.e., 1.5-2 events/day or 150 events/calendar year. Hence in only three calendar years, one would produce 900 $\nu_\mu e + \bar{\nu}_\mu e$ events or 300 $\nu_\mu e + \bar{\nu}_\mu e$ and 300 $\bar{\nu}_\mu e + \nu_\mu e$ depending upon the

ratio of $\nu/\bar{\nu}$ running.

It has been determined by measurement, in two independent experiments at the CERN PS, that the dominant backgrounds to $\nu_\mu e \rightarrow \nu_\mu e$ ($\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$) are (1) $\nu_e n + e^- p \rightarrow \bar{\nu}_e p + e^+ n$ and (2) $\nu_\mu n + \nu_\mu n \pi^0$ ($\bar{\nu}_\mu n + \bar{\nu}_\mu n \pi^0$) where one photon from the π^0 decay is detected in the forward direction, and the other γ and the n are unobserved. Background from (1) is largely eliminated by selecting only those events which satisfy $\nu_\mu e \rightarrow \nu_\mu e$ kinematics, specifically $\theta_e^2 \leq \frac{4m_e}{E_e}$. A Monte Carlo calculation generating $\nu_e n + e^- p$ events and assuming $\nu_e/\nu_\mu \approx 4 \times 10^{-3}$ yields an estimated background of 12%. A careful determination of this background by the Aachen-Padova group concludes that it is even smaller, $< 3\%$.

Background from the neutral current reaction $\nu_\mu n + \nu_\mu n \pi^0$ is also suppressed primarily by the kinematic cut $\theta_e^2 E_e < 4m_e$. A Monte Carlo calculation using data on charged current single pion production in the BNL 7'BC indicates that in the absence of any γ/e discrimination or n detection the background from $\nu_\mu n + \nu_\mu n \pi^0$ is 35%. Including an additional rejection factor of 6 from γ/e discrimination and detection of the neutron yields a background 6%. This may be further decreased by improving the detection efficiency of the second γ ; we are considering placing thin lead sheets next to the proportional tubes within 50cm of the edges of the detector.

We feel that this experiment has a number of significant advantages compared to others intending to study $\nu_\mu e \rightarrow \nu_\mu e$ (all of which use high energy neutrinos).

- (1) The event rate/ton/sec at Brookhaven, as measured in two independent experiments, equals or exceeds that at Fermilab. This benefit is further enhanced by the electron/nucleon ratio of .57 in our detector

compared to approximately .50 for other detectors. Hence the production rate for $\nu_\mu e + \bar{\nu}_\mu e$ ($\bar{\nu}_\mu e + \nu_\mu e$) is comparable to or exceeds that for any other experiment: ≈ 3 events/day or 300 events/year.

- (2) Our proposed detector is the only counter experiment with significant photon rejection. It has been demonstrated both by the GGM and 15'BC experiments studying $\nu_\mu e + \bar{\nu}_\mu e$ that background from single photons is large and photon rejection is critical.
- (3) Backgrounds at low energy have been measured in a counter experiment at CERN, and indicate that with a photon rejection of $\approx 4 : 1$, a total background $< 20\%$ may be obtained. By way of contrast, no (counter) experiment or proposal has demonstrated adequate separation of electrons and hadronic showers at high energies.
- (4) The ratio of the electron angular resolution to the mean scattering angle for $\nu_\mu e + \bar{\nu}_\mu e$ is a smaller fraction than for any other experiment except the 15'BC.

Finally, while there exist experiments intending to study $\nu_\mu e + \bar{\nu}_\mu e$ at high energies, an experiment at low energies, with completely different systematic errors would be very useful.

The elastic scattering reactions $\nu_\mu p + \bar{\nu}_\mu p$ and $\bar{\nu}_\mu p + \nu_\mu p$ will be identified by observation of a single recoil proton, with no accompanying particles. The entirely active detector is sensitive to the existence of additional neutrons, photons and charged particles with energies as small as 10 MeV. The event rate is estimated to be 140 $\nu p + \bar{\nu} p$ events/day and 30 $\bar{\nu} p + \nu p$ events/day for $0.3 < q^2 < 0.9$ (GeV/c)² after all cuts and selection criteria. Hence, we will obtain ≈ 4000 $\nu p + \bar{\nu} p$ and 2000 $\bar{\nu} p + \nu p$

events/calendar year.

The calculation of event rates and backgrounds is based directly on measurements made in a previous experiment (BNL Exp. 613) carried out by several of the members of this collaboration. That experiment observed 217 $\nu p \rightarrow \nu p$ and 66 $\bar{\nu} p \rightarrow \bar{\nu} p$ events in a similar but much smaller and less sophisticated detector than the one proposed here. The experiment was notably successful in measuring

$$R_V^{el} = \sigma(\nu p \rightarrow \nu p) / \sigma(\nu n \rightarrow \bar{\mu} p)$$

and $R_V^{el} = \sigma(\bar{\nu} p \rightarrow \bar{\nu} p) / \sigma(\bar{\nu} p \rightarrow \mu^+ n)$ ($0.4 < q^2 < 0.9(\text{GeV}/c)^2$) to an accuracy of 20 - 25% statistical error with a systematic error of approximately and in obtaining crude differential cross sections. However, a number of fundamental weaknesses prevented precise measurements:

(1) Background:

While neutron-induced background was virtually eliminated, background from other neutral current channels was not small, 38% for ν and 42% for $\bar{\nu}$.

(2) Particle identification:

Below 175-200 MeV, the range of the proton was comparable to the detector cell size (20cm x 20cm) and it became increasingly difficult to distinguish protons from pions (15 - 20%). This was aggravated by the lack of track detectors in 60% of the detector.

(3) Normalization:

Because of the lack of track detectors in the bulk of the detector,

it was difficult to reconstruct quasi-elastic events, $\nu n + \mu^- p$, at moderate q^2 . For a reliable measurement of $d\sigma/dq^2(\nu p + \nu p)$, it is desirable to compare the elastic and quasi-elastic reactions bin by bin in q^2 .

Each of the above difficulties arises from the lack of sufficient granularity, both in terms of track detectors and calorimeter cell size, to adequately distinguish single track from two track events. Further, the number of independent dE/dx measurements was limited.

The experiment proposed here remedies these problems by decreasing the cell size and adding a high density of track chambers, which measure dE/dx as well as position. Table I compares the information which will be obtained in the proposed experiment to that obtained from Experiment 613 for elastic scatters as a function of q^2 .

Table I. Comparison of number of dE/dx measurements and X-Y position measurements for proposed experiment with Exp. 613.

q^2 (GeV/c) ²	Proposed Detector				Exp. 613		
	Modules Traversed	dE/dx PDT	dE/dx Calor	X,Y Position Meas.	dE/dx Calor	X-Y Position Measurements Front (60%)	Back (40%)
0.2	1	2-4	0	1-2	0	0	2
0.4	2	6	1	3	0	0	2
0.6	3	8-10	2	4-5	1	0	2
0.8	6	18	5	9	3	0	4

The high density of dE/dx measurements will reduce ambiguities in particle identification to negligible levels, and the smaller cell size and addition of track chambers will greatly reduce other background. Specifically, improved γ detection will reduce the background from $\nu p \rightarrow \nu p \pi^0$ and $\nu n \rightarrow \nu n \pi^0$, and the sensitivity to additional charged tracks with as little as 20 MeV greatly reduces the background from $\nu p \rightarrow \nu \pi^+ p$ and $\nu n \rightarrow \mu^- p$. Table II compares the background anticipated in the new experiment with that present in the previous experiment.

Table II. Estimated Backgrounds

	Previous experiment	Proposed experiment
$\nu p \rightarrow \nu p \pi^0$	13%	2%
$\nu n \rightarrow \nu n \pi^0$	3%	< 1%
$\nu n \rightarrow \nu p \pi$	16%	< 4%
$\nu n \rightarrow \mu^- p + \chi$	28%	4%

Nuclear corrections have been shown to be relatively small. Background from $\nu n \rightarrow \nu n^- p$ and $\nu p \rightarrow \nu p \pi^0$ due to pion absorption is less than 5%, and the loss of $\nu p \rightarrow \nu p$ due to proton interactions in the nucleus (12%) is almost cancelled by the increase in events (13%) from $\nu n \rightarrow \nu n$ followed by the charge exchange reaction $np \rightarrow np$. In summary, we anticipate that the total background will be less than 15%. It is our experience in the previous experiment that the backgrounds can be determined to an accuracy of at least 30%. Hence, the net uncertainty in the rate for $\nu p \rightarrow \nu p$ ($\bar{\nu} p \rightarrow \bar{\nu} p$) will be $< 10\%$.

Similarly, for quasi-elastic events, Table III shows the angle of the muon and the number of XY measurements in the new detector as a function of q^2 .

Table III.

Angle of muon and number of X-Y position measurements for $\nu n \rightarrow \mu^- p$ events ($E = 1$ GeV) in the proposed detector. The vertex of the event is assumed to be on beam axis.

q^2	θ_μ	X-Y Meas.
—	—	—
0.2	28°	51
0.4	41°	30
0.6	55°	18
0.8	70°	9

It is clear from Tables I & II that quasi-elastic events can be reconstructed over a q^2 range of at least $0.3 - 0.8$ (GeV/c) 2 . This will enable the elastic reaction $\nu p \rightarrow \nu p$ to be normalized bin-by-bin as a function of q^2 . Note that most systematic effects such as nuclear effects, p reconstruction efficiency, etc., occur equally for $\nu p \rightarrow \nu p$ and $\nu n \rightarrow \mu^- p$ and hence drop out in the ratio of these reactions.

In conclusion, we feel that the proposed experiment is of fundamental importance and is unique, both in the physics it addresses and in the proposed technique. The estimated rates and backgrounds for $\nu_\mu e \rightarrow \nu_\mu e$ and $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$ are competitive with, if not better than, any other proposed experiment. In addition, it has two fundamental advantages: (1) it is the only proposed experiment with significant γ/e discrimination - a feature which has been deemed of crucial importance by all existing bubble chamber studies; (2) It would provide a measurement of $\langle \bar{\nu}_\mu \rangle_p \rightarrow \langle \bar{\nu}_\mu \rangle_e$ with an entirely different set of systematic errors than experiments performed at high energies assuming that the latter are indeed successful.

The proposed measurements of $\langle \bar{\nu}_\mu \rangle_p + \langle \bar{\nu}_\mu \rangle_e$, which certainly rank in importance with deep inelastic ν -scattering, would be unique. There exists no other experiment in the world which intends to measure these reactions with comparable statistical and systematic precision.

Measurements of neutral current single pion production, important for determining the isospin of the weak neutral current, and for understanding the production mechanisms, would be obtained with high statistics for at least several of the reactions."

Much of the effort of the past year has been devoted to completion of the design of the components and systems for this experiment, the performance of tests on prototypes, and preparations for the massive construction effort which now must follow.

The Brown group has principal responsibility for several major portions of the experiment. Among these are the on-line software for the PDP-11/34 in its new environment of microprocessors and PDP-10's. In addi-

tion, to the above we are coordinating and taking a large responsibility for an area called "low level computing" for purposes of this experiment but which might be more appropriately described as fast logic and interfacing in a more conventional, hard-wired electronic experiment. This task consists of the overall handling of the data after it has been passed through the detector front-ends and into the extensive system of scanners and microprocessors and through their links with the PDP-11/34 and PDP-10.

We also have major responsibilities for the design, construction, and operation of the calorimeter portion of the detector.

Taking each of these areas in turn, the progress this year can be summarized as follows.

Because extensive use will be made in this experiment of micro-processors (LSI-11's) a system was needed to give us experience with the hardware and also serve as a device in which we could do software development for the experiment. We have constructed such a system incorporating an LSI-11-03, disks (new and old) and a printer. It is operating very well and is in use almost constantly in software development and testing of other hardware associated with data collection (e.g., fast data links between microprocessors and the PDP 11/34). A major software effort has been in the area of conversion of the SPEX system for use in this experiment. SPEX is the acronym for Spectrometer Executive, a computer executive system which enabled us to satisfy the rather extensive and complicated data handling needs of our previous FNAL Single Arm Spectrometer experiments (E-96, E-118, E-451, E-469) in a rather modest computer - a PDP-11/45. For our neutrino experiment rather extensive and detailed changes must be made

to SPEX for it to operate in the PDP-11/34 available and in conjunction with the LSI-11's (which have their own system, RT-11). Dealing with multiple microprocessors as well as CAMAC is also a complication. Much of this work has been completed but much remains before we have a final system for the full detector; however, in the meantime, it is useful to have various partial functions completed. For example, in order to test and operate test modules of calorimeters and proportional drift tubes we need the portion which operates CAMAC on the floor at BNL; a temporary solution has been provided and current PDT and calorimeters are operating under CAMAC control and a more permanent one is near completion. Professors Massimo and Dulude have been responsible for the above work.

At the same time, selection and ordering of microprocessors and associated equipment has been going ahead. Professor Cutts has been in charge of that area as well as designing data handling schemes for the microprocessors and working with the electronics team in developing logical means for reading the data from detectors into the microprocessors using homemade hardware scanners capable of selecting or skipping data or originating test events - all under microprocessor control.

Work associated with our calorimeter responsibilities has recently been centered on three fronts: i) phototube testing, ii) calorimeter module testing, and iii) design and testing of a fiber optics calibration system. In order to test (measure gain, quantum efficiency, and light-tightness) the 4000 photomultipliers to be used in the calorimeters, we have developed a microprocessor based, semi-automatic system which is now working well and has tested ~200 tubes so far. Besides its intrinsic importance as a "pro-

duction line", it also provided us with valuable experience in the use and programming of microprocessors. Professor Dulude provided us with a complete microprocessor system which automatically measures the gain of these tubes 32 at a time.

Among the tests on calorimeter prototypes were beam and cosmic ray measurements to establish light attenuation lengths in the liquid and container combination. These tests enabled us to select an inexpensive acrylic rectangular cylinder which resulted in a 2 meter attenuation length for an individual module. Many other tests with the photomultipliers selected (Amperex 2212) indicate that a minimum of 6 photoelectrons (at 9 mv per photoelectron) is readily obtainable for a minimum ionizing track traversing the module 13 feet away from the photomultiplier. Checks were also made of the intrinsic timing resolution which is about 2 nanosec. Now under construction is a complete "wall" of 16 calorimeters. This will be a fully instrumented plane; its construction is serving to shakedown our assembly line procedures. After assembly we will test with beam, cosmic rays, and pulser the operation under computer control.

We have designed a fiber optics light pulser system to be used in calibrating and monitoring the 4000 photomultipliers when they are installed in the full detector. It will also be used to establish the timing constants as well as to measure the stability and equality of tube response. We have built a prototype fiber and pulser (spark gap) and tested it with fibers inserted into opposite ends of a filled calorimeter. The test was very promising in that the light intensity is such that a range is available downward from at least two times that from minimum ionizing 1 foot away from the

phototube. Pulse shape is also very similar to that from organic scintillator. Mr. Hughlock, Dr. Suzuki, and Professor Lanou have been the principals in the Brown calorimeter effort.

All of the above mentioned programs are continuing at an accelerating pace and our plans for the coming year are outlined in the accompanying Renewal Proposal.

Process	Comparison with theory
1 Purely leptonic $\nu_\mu + e \rightarrow \nu_\mu + e^-$ $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$ $\nu_e + e^- \rightarrow \nu_e + e^-$	Very clean (no hadrons involved)
2 Elastic scattering $\nu_\mu + p \rightarrow \nu_\mu + p$ $\bar{\nu}_\mu + p \rightarrow \bar{\nu}_\mu + p$	Relatively straightforward, some uncertainty due to proton form factors (M_A)
3 Single pion production $\nu_\mu + N \rightarrow \nu_\mu + N' + \pi$ $\bar{\nu}_\mu + N \rightarrow \bar{\nu}_\mu + N' + \pi$	Model-dependent due to hadronic vertex, also nuclear physics corrections
4 Inclusive $\nu_\mu + N \rightarrow \nu_\mu +$ $\bar{\nu}_\mu + N \rightarrow \bar{\nu}_\mu +$	Dependent on quark-parton model
5 Atomic physics $e + Bi \rightarrow e^- + Bi$	Large uncertainties due to atomic-physics calculations
6 Electron scattering $\bar{e} + d \rightarrow e^- +$	Dependent on quark-parton model

Experimental results and W-S model predictions for neutral currents

Process	Experimental results	$\sin^2 \theta$	W-S prediction with $\sin^2 \theta = 0.23$
1 Purely leptonic			
$\nu_e + e \rightarrow \nu_e + e^-$	$(5.7 \pm 1.2) \times 10^{-42} \text{ cm}^2$	0.29 ± 0.05	0.50
$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$	$(1.7 \pm 0.5) \times 10^{-42} \text{ cm}^2$	$0.21 \begin{cases} -0.09 \\ -0.06 \end{cases}$	1.5
$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$	$(1.8 \pm 0.9) \times 10^{-42} \text{ cm}^2$	$0.30 \begin{cases} -0.10 \\ -0.30 \end{cases}$	1.3
2 Elastic scattering			
$\nu_\mu + p \rightarrow \nu_\mu + p$	$(0.11 \pm 0.02) \times \sigma(\nu_\mu + n \rightarrow \mu^- + p)$	0.26 ± 0.06	0.12
$\bar{\nu}_\mu + p \rightarrow \bar{\nu}_\mu + p$	$(0.19 \pm 0.08) \times \sigma(\bar{\nu}_\mu + p \rightarrow \mu^+ + n)$	~ 0.5	0.13
3 Single-pion production			
$\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0$	$(0.45 \pm 0.08) \times \sigma(\nu_\mu + N \rightarrow \mu^- + N + \pi^0)$	0.22 ± 0.09	0.43
$\bar{\nu}_\mu + N \rightarrow \bar{\nu}_\mu + N + \pi^0$	$(0.57 \pm 0.11) \times \sigma(\bar{\nu}_\mu + N \rightarrow \mu^+ + N + \pi^0)$	$0.15 - 0.52$	0.60
4 Inclusive			
$\nu_\mu + N \rightarrow \nu_\mu +$	$(0.29 \pm 0.03) \times \sigma(\nu_\mu + N \rightarrow \mu^- +)$	0.24 ± 0.02	0.30
$\bar{\nu}_\mu + N \rightarrow \bar{\nu}_\mu +$	$(0.35 \pm 0.025) \times \sigma(\bar{\nu}_\mu + N \rightarrow \mu^+ +)$	0.30 ± 0.10	0.38

FIG. 1

Summary of the weak-neutral-current couplings

Coupling constant	Value in unique solution ^a	Weinberg-Salam	
		with $\sin^2 \theta = 1/4$	in terms of $\sin^2 \theta$
g_V	0.0 ± 0.1	0.0	$-1/2 + 2\sin^2 \theta$
g_A	-0.55 ± 0.1	-0.5	-1/2
u_L	0.35 ± 0.07^b	0.33	$1/2 - (2/3)\sin^2 \theta$
d_L	-0.40 ± 0.07^b	-0.42	$-1/2 + (1/3)\sin^2 \theta$
u_R	-0.19 ± 0.06^b	-0.17	$-(2/3)\sin^2 \theta$
d_R	0.0 ± 0.11^b	0.08	$(1/3)\sin^2 \theta$

Fig. 1: Allowed domain of neutrino-quark neutral current couplings.

FIG. 3

FIG. 4

FIG. 5

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b) Experiments to Measure Muon Polarization and the Development of the Muon Polarimeter.

In last year's Renewal Proposal we discussed in detail our proposal to test weak-electromagnetic interference effects in $e^+e^- \rightarrow \mu^+\mu^-$ by measurement of the muon polarization. Also part of the experiment involved looking for inclusive muon polarization from new states formed in e^+e^- . The proposal was submitted to the PEP Program advisory committee and was designated PEP-16.

The response of the Advisory Committee was favorable toward PEP-16 though their decision was to "defer decision" until a later time for three general reasons. The Committee recognized that the experiment needed good statistics for a polarization measurement of a few percent accuracy and correspondingly required the operation of the machine at its design luminosity. Since PEP performance was unknown (and still is), the Committee felt it prudent to wait until after the needed luminosity was achieved or at least reasonably expected. A second consideration of the Committee in deferring action was the observation that the effect we sought to measure (the interference in the reaction $e^+e^- \rightarrow \mu^+\mu^-$ of the photon and z^0 exchanges) was very small, so that the resultant determination of the Weinberg angle θ_w might not be competitive by the time the measurement could be made. The third concern the Committee expressed centered about our proposed detector. Although "intrigued by the novelty" of the polarimeter designed, the Committee wanted its performance reasonably well established before approving its use.

We have subsequently discussed these matters with the SLAC Director (W. K. Panofsky) and he emphatically urged us to pursue the polarimeter

development.

In the time since the initial formation of the PEP-16 proposal, we have had a continuing interest in the development of the polarimeter, as we envisage it could become a unique tool for a large number of high energy physics experiments. Muon polarization measurements are an important probe of weak interactions, more difficult than the usual energy spectra determinations, but also more sensitive to the basic weak interaction structure and less affected by systematic uncertainties. At the accelerators now under construction (PEP, CESR, ISABELLE) weak interaction physics will be of prime importance, and muon polarization measurements could make a major contribution. However, at the high energies of these machines the thickness of degrader needed to slow muons taken together with the low interaction rate (at PEP or CESR), requires the polarimeter be very large - in area, to have a large solid angle, and in thickness, because of range straggling. Polarimeters of the conventional design, alternating layers of detector and degrader would be difficult and expensive to deploy. We have proposed instead that the polarimeter be made of large tanks of clear fluid in which the muons stop. The Cerenkov light from the decay electron is detected with waveshifter sheets outside the six transparent walls, and the decay electron's direction is inferred from the relative amount of light collected by each sheet. (See 1978 Renewal Proposal for a more extensive description of the polarimeter.) With our design one could inexpensively cover a large area, yet because one measures the total electron energy in the muon decay (from the summed pulse height) one has a device with improved analyzing power, compared to the standard design. For these reasons,

the polarimeter may be well matched to the physics opportunities at the new accelerators.

Our specific interest with the PEP-16 proposal was a study of the interference between the single photon exchange and Z^0 exchange diagrams (a and b) in the process $e^+e^- \rightarrow \mu^+\mu^-$. As stated above,

this measurement requires the highest luminosity planned for PEP. The presence of a third diagram, specifically one involving a resonance of quark-antiquarks of new flavor would provide both an enhanced data rate at the appropriate energy as well as an excellent physics opportunity - the determination of the weak coupling of the new quark. In addition to data taking at a specific energy, measurements spanning a range of machine energies would give the polarization of the inclusive muon spectrum, important results in studying the properties or existence of new heavy leptons. (These later physics interests could also be pursued at CESR.)

The timetable at PEP calls for the completion of the machine this fall, with serious data-taking not to begin until sometime in 1980. Clearly the appropriate time for a polarimeter experiment would not be until 1981 - 82, at which time good luminosity should be reliably available. The initial survey experiments by then will have fulfilled their design functions (much of the physics is already being obtained at DESY) and there will be a need for second generation experiments. This new round will certainly

include upgraded versions of current detectors but - especially at PEP - it will be important to include one-of-a-kind, special purpose devices to probe the physics questions in unique ways. We think a polarimeter experiment at this time could make a real contribution to the PEP physics program.

With SLAC and our own continuing interest in the physics potential of the polarimeter, we have maintained a development program geared toward a demonstration of the device. As described in last year's Progress Report, we first built a rectangular box of dimensions 20" x 12", and 6" deep. The box was mounted with respect to the axis of a scintillation counter cosmic ray telescope as shown:

the angle of tilt of the box could be varied, effectively changing the angle of the Cerenkov light cone made by a cosmic ray muon as it passes through fluid filling the box. Two waveshifter sheets, made of Pilot 425, served as the bottom and one side of the box, the other sides being aluminum. With these sheets, coupled to photomultiplier tubes, we detected the Cerenkov light; and in particular, we measured the variation in the relative amount of light collected on the two sides with the orientation of the Cerenkov cone given by the box tilt angle. Under the direction of Professor Cutts, Mr. Bronislaw Dichter reviewed these measurements this last spring as part of his Senior Honors thesis project. The data taken with the box did show a dependence of relative light with tilt angle, but not as sharp or clean

as expected. In addition to the poor event statistics resulting from a narrow cosmic ray cone, the pulse heights observed suffered from a low number of photons collected. Studies of the various materials involved in the device have since shown that the waveshifter used was not suitable. This plastic should absorb low wavelength light, while being transparent to the wavelengths at which the light is reradiated. In this way a wave shifter sheet can cover a large area, absorbing most of the light incident, and transmitting by multiple internal reflections to its edges the reemitted light. Unfortunately, the Pilot 425 emission spectrum peaks in the blue, and it is correspondingly transparent to light above 450 nm. Since both water and 1-1-1 trichloroethane (the two fluids tested in the device) absorb strongly in the u.v., only a very small slice of the Cerenkov light spectrum was not absorbed in the fluid yet was of sufficiently low wavelength to be captured in the waveshifter sheet. The data reflected the correspondingly poor photon statistics, with the pulse height spectra being broad and (because of low event statistics) poorly defined.

Despite these problems, the tests with the rectangular box succeeded in demonstrating the validity of our technique: the determination of particle's direction by measuring relative amounts of Cerenkov light collected on orthogonal surfaces. Note that internal reflection (sensitive to the incident angle of the Cerenkov light rays) is the key feature in this device. Altogether, the test device demonstrated clearly that directional information can be measured, with a sensitivity in good agreement with our calculations.

These first tests of the polarimeter design concept showed that we could with just a few counters measure a charged particle direction to an accuracy

of $10\text{--}20^\circ$ over a wide range of angles. This accuracy is fully adequate for a polarimeter, where the electron angular direction in the μ -e decay is not a strong function of the μ polarization. One fits the distribution of electron directions from many decays spread over 180° , to find $\hat{\sigma}_\mu$, so a 20° measuring accuracy in individual decays has little systematic effect. Further, higher accuracy would not be appropriate, as the direction is already smeared by multiple scattering.

Our next step in the development of the polarimeter was to design and build a prototype, incorporating our first ideas in all aspects of the detector but of about $1/2$ the scale as envisaged for PEP-16. The prototype was very simply made by welding 2 ft. lengths of angle iron to make the sides of a cube. The inside was lined with $3/8$ " plate glass, with fill and drainage pipes provided in corners. For light collection we obtained $2' \times 2'$ sheets of acrylic doped with the waveshifter chemical "BBQ". In order to keep the area of one side of the waveshifter sheet material to the sensitive area of a 2" photomultiplier tube, we chose an acrylic thickness of $1/8$ ". The waveshifters, backed by aluminum foil, were laid on sheets of plywood together with attached adiabatic light guide and PMT. One of each of these packages was fastened to each of the 6 sides of the polarimeter with each window (22" on a side) then covered by a waveshifter sheet. This basic design - a glass-walled cube of fluid viewed by sheets of waveshifter - proved straight-forward to build and generally successful in operation.

During last spring we finished building the polarimeter prototype and moved it together with associated electronics to the G10 test beam area of the AGS, at Brookhaven National Laboratory. Our intention was to verify in

full the operation of the polarimeter, specifically that it could be used to detect electrons from the decay of muons stopping in its fluid, and that from this data one could accurately determine the polarization of the muons. Taking part in this test at different times were Professors Cutts, Dulude, and Lanou, together with Mr. Dichter, for whom this work was part of a Senior Project. We were joined for this run by Professors Grannis and Kirz, from S.U.N.Y., Stony Brook, our collaborators on the PEP-16 proposal. From Stony Brook we obtained lightguides for the wave shifters, additional electronics, plus the use of a computer already in place in the test beam area.

To obtain μ^+ stopping in the polarimeter, we placed the device in the test beam, setup to give π^+ of momenta variable between 0.5 and 1.5 GeV/c. It's well known that μ 's from π decay are fully longitudinally polarized in the π center of-mass; however, the μ 's will have zero polarization in the lab because of integration over the isotropic center of mass decay angle. In order to have polarized μ 's we needed to select a small range of center of mass decay angles. The muon's lab momentum depends uniquely on this angle, and varies from half to nearly the full π momentum. Since the thickness of the polarimeter was small compared to the muon's typical range, with appropriate degrader and setting of the beam (π) momentum we could select a small range of cm decay angles and obtain polarized muons stopping in the detector.

For the tests at Brookhaven we installed a number of scintillation counters in the beam to define particles penetrating the degrader (typically 12"-24" Pb) and entering the polarimeter. Additionally, a large counter behind the polarimeter, labelled T4 in Fig. 1 was used in anticoincidence to signal a stopping particle; a similar counter mounted in front of the device

helped to veto events with particles scattering into the polarimeter. The electronic logic was designed to trigger on a μ -e decay events: we required a stopping signal followed by a signal due to Cerenkov light within the polarimeter fluid. The decay electron (typical range $\approx 6''$) stayed usually within the module, so the light collected by the waveshifter sheets (whose pulse height we wanted to accurately measure) had to serve also as an essential element of the trigger. For the measurement of the electron direction we wanted to measure the six pulse heights separately, yet it was important also to mix the pulse heights, so the "decay" signal used in the trigger had no bias as to the electron direction. The trigger had to be as efficient for events with all the Cerenkov are absorbed in one wall as it was when the same amount of light was collected by several waveshifter sheets. For this reason our first test data was taken in special runs to standardize the responses of each of the waveshifter sheets. In these runs a single waveshifter sheet was mounted, in the downstream face of the polarimeter; with a simple trigger requiring a beam particle completely penetrating the module we determined the average pulse height from the waveshifter as a function of the high voltage on its photomultiplier. Similar data from every waveshifter module then provided the calibrations needed to select appropriate voltages for uniform response.

We split the signals from each waveshifter to provide input for the trigger while preserving part of the initial pulse for digitization with a CAMAC ADC. A further split of these signals allowed us to record, using a CAMAC TDC, the time of arrival of the waveshifter signal, relative to the time of the initial stopping signal. In addition to the times associated with

each waveshifter, we also digitized the time that the summed waveshifter outputs completed the trigger. The electronic logic required that for a valid trigger this " μ -e decay" signal occur between 0.8 and 5 μ sec following the coincidence of a " μ -stop". We expected the distribution in time of the triggers to follow an exponential falloff characteristic of μ -e decays, with a lifetime of 2.2 μ sec. Indeed, as shown in Fig. 2, this distribution for some data runs did verify the logic of our trigger. Also, the comparison of the trigger time with times recorded separately for each waveshifter allowed us to ignore pulse heights from channels out of time with the trigger. Generally, there was excellent agreement between the trigger time and the time recorded for those waveshifter channels with ADC readings above pedestal.

The handling of the signals from the waveshifter, the design of the trigger logic, and the combination of times and pulse heights recorded via CAMAC was a major accomplishment of the test beam run. Our final arrangement evolved through a number of stages with our experience as we perfected signal splitting, gating and clearing, vetoing of secondary particles, and other features of the logic. The live time with the beam, learning to handle exactly the same signals as from a full scale detector, was extremely valuable.

Beyond the development of data handling techniques, we hoped in the test beam run to determine the analyzing power of our device by measuring the polarization of appropriately selected samples of μ^+ 's. With our detector we were certainly sensitive to μ -e decays, as shown by the time distributions of delayed signals from the waveshifters. However, these

time distributions also indicated a severe background problem in data taken at higher beam intensities. The test beam had poor momentum definition and spot size compounded by scattering caused by other user's equipment in the beam upstream of us. Further, the reliance on an open decay space meant that only a small fraction of the $\pi \rightarrow \mu$ decays could give μ 's within the small cone defined by our beam telescope. For π 's decaying a given distance from the detector, only those at a specific angle to the beam could give acceptable μ 's - as our range bite defined μ 's with fixed lab angles relative to the π direction. A beam designed to produce μ 's (such as at LAMPF) has a decay region filled with quadrangle magnets to keep the μ 's focussed; an excellent π/μ separation and μ momentum selection (determining the polarization) is then achieved with a bending magnet and collimators. In our runs at the BNL test beam we had a low μ/π ratio (typically 1%), with momentum selection and π/μ separation only via degrader. Typical running conditions were a beam to "stopping" signal ratio of 1000/1 or worse, and accidental monitors $\sim 1/1$ compared to triggers. Background in our data samples at all but very low beam intensity was typically 40 - 60%, as indicated by fits to the time distributions of "decays" with a two term function - one term independent of the "stop" time in addition to an expected term that falls with the muon lifetime. The poor statistics and high background have made it impossible to derive correlations between the measured waveshifter pulse height distributions and the μ^+ polarization selected by the range criterion.

Despite the poor beam quality several tests suggested that the polarimeter prototype was performing as designed. An important feature of the

detector is the relative independence of the pulse heights from the waveshifters to the μ^+ stopping position (the origin of the e^+ Cerenkov cone). The light collected on each side should depend only on its angle to the side; and with an internal reflection angle $\sim 45^\circ$, light in a given direction should be transmitted through the same side regardless of its origin. To test this feature we displaced the polarimeter so that the beam axis passed within 6" of one side or within 6" of the other side, rather than its normal position 12" from both sides. In these two extreme cases, the ratio of the relative amounts of light collected on the two sides was 0.8 ± 0.1 , certainly an encouraging result. We made a further test of the optical properties of our design by counting the number of events for which the pattern of waveshifters collecting light included two on opposite sides. Internal reflections off one face should always be transmitted through the next face; with both the Cerenkov cone angle and the internal reflection angle $\sim 45^\circ$, no light should penetrate opposite walls of the cube. Data at low beam intensity showed that these patterns were indeed rare ($<10\%$), confirming the design. High statistics data included 30-50% of these "bad optics" events, just at the level expected. Background particles gave a second Cerenkov cone, almost always destroying the "good optics" pattern.

At the test beam we tested an additional feature of the polarimeter: its ability to give a rough measure of the momentum of the muon entering the module. For much of its residual range in the polarimeter fluid, the muon would emit Cerenkov light; studies by Mr. Dichter predicted the amount of light expected from the waveshifters in prompt coincidence with a "stopping μ " signal. Our data agreed well with these calculations and with the

FIG. 1

Number of events

FIG. 2

general muon momentum selected by the range bite.

Overall, the studies of the first prototype polarimeter in the Brookhaven test beam provided valuable experience with the device. The aspects of the design which we could probe, given the limitations of the beam, proved to be satisfactory. A complete demonstration of the device, the determination of the ability to accurately measure polarization, was not possible given the nature of the test beam available at BNL. It is important to point out that this lack of success was under flux conditions radically different from any expected in situations where the polarimeter might be used for physics. In all of the possible applications at PEP, CESR, or ISABELLE the extent of degrader needed to slow the μ 's of interest will protect the device from the background problems we found at Brookhaven.

Since the Spring we have reassembled the detector and electronics at Brown, and are undertaking a number of small projects related to improving the apparatus. These include coating the polarimeter iron framework with an epoxy paint, making further tests of the waveshifters, using cosmic rays, and developing an LED-based system for calibrating and maintaining the uniformity of response of the wave shifter sheets. As described in our Renewal Proposal, we expect this series of improvements to be completed by the spring. We have already contacted LAMPF with regard to using their high purity polarized muon beam and have been promised some running time. Our goals for this run, discussed in the Renewal Proposal, point toward the complete demonstration of the polarimeter. Following this run we expect to be able to make more concrete proposals for its deployment.

III. Associated Matters:

There are a small number of topics which either cut across the individual topics discussed in the Report or are of a nature requiring only a brief comment. We include them here.

Effective July 1, 1979, Prof. Cutts was promoted to Associate Professor with tenure. We are gratified by the University's recognition of Professor Cutts' contributions and interest in the continuity of the high energy program at Brown.

Also on 1 July, Dr. Dulude was promoted from Research Associate to Assistant Professor (Research).

In May of this past year, we were joined by Dr. Y. Suzuki as a Research Associate. Dr. Suzuki has been working on experiments at K.E.K. in Japan and recently recieved his Ph.D. from Kyoto University. His work with us is an important contribution to the effectiveness of E-734 at the A.G.S.

Professor Cutts continues to serve on the Willis Committee at BNL which considers proposals for ISABELLE-related detector development.

This year completed the first of a three year term on the BNL High Energy Advisory Committee (the program committee for the A.G.S.) for Professor Lanou.

Also, Professor Lanou was elected to a term on the Executive Committee the A.P.S.'s Division of Particles and Fields.

Professor Cutts and Lanou received invitations to and attended the International Conference on Leptons and Photons held at Fermilab in late August this year.

In June, Professor Lanou participated in a pre-conference workshop and presented an invited paper on our antiproton work at a conference held

in Orsay (France) on Baryonium and Other Unusual Hadron States.

We have been fortunate in having Dr. William Toy (Bell Labs) join us as a part-time collaborator. Dr. Toy received his Ph.D. from MIT last year and previously worked with us through the Brown-MIT collaboration at Fermilab. Dr. Toy has been assisting us in some of the on-line computer work associated with the neutrino experiment.

Mr. B. Dichter (a Brown senior who did his Senior Honors thesis with our group by making measurements related to detection of muon polarization) was graduated from Brown and is attending graduate school at Yale where he intends to pursue further work in particle physics.

IV. Scientific Personnel Involved With This Research Program

R. E. Lanou, Jr.	Professor
J. T. Massimo	Professor
D. Cutts	Associate Professor
R. S. Dulude	Assistant Professor (Research)
Y. Suzuki	Research Associate
B. W. Hughlock	Graduate Research Assistant

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

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2. R. E. Lanou, "How Well Do We Know the Quantum Numbers of $\bar{P}P + M_1 M_2$ States?", *Proceedings of Workshop on Baryonium and Multiquark States* (in press) Orsay, France (1979).
3. D. Cutts et al, "Triggering at ISABELLE", *Proceedings of 1978 ISABELLE Workshop*, BNL-50885, p. 64-75 (1979).
4. D. Cutts et al, "Data Handling for Lepton Detector", *ibid*, p. 357-366.
5. V. Ashford et al, "Cerenkov Counters at ISABELLE", *ibid*, p. 96-119.
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7. S. Aronson et al, "Comments on Design of Four and Twelve O'Clock Experimental Areas," *ibid*, p. 226-234.
8. S. Aronson et al, "Comments on Two O'Clock Experimental Area", *ibid*, p. 235-238.
9. B. Dichter, "Muon Spin Polarization Measurements Using Cerenkov-Radiation", Sc.B. Senior Honors thesis, Brown University High Energy Group Internal Report #C79-1 (1979).
10. R. E. Lanou, "Progress Report of a Research Program in Experimental High Energy Physics (Electronic Detector Group)" October 1979.