22/75
LA-6041-T

Thesis

DL-1714

UC-34c

Reporting Date: July 1975

Issued: September 1975

Proton-Proton Analyzing Power Measurements at 16 MeV

by

P. A. Lovoi*

MASTER

*Guest Scientist. Permanent address: ILC Technology Incorporated,
164 Commercial Street, Sunnyvale, CA 94086

los alamos
scientific laboratory

of the University of California

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National Technical Information Service
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Springfield, VA 22151
Price: Printed Copy \$5.45 Microfiche \$2.25

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Proton-Proton Analyzing Power Measurements at 16 MeV

Paul Anthony Lovo

ABSTRACT

Few attempts have been made to measure accurately the proton-proton analyzing powers at low energies. With the advent of polarized particle beams the measurement can now be made with high accuracy. Analyzing powers were measured at nine scattering angles from 10° to 35° in the laboratory system. As a check on systematic errors, analyzing power measurements were also made by scattering protons from ^4He . In the $\vec{p}$ -p case the measured values are in very good agreement with the phase shift predictions. The $\vec{p}$ - ^4He measurements, while giving the same form and sign as the phase shift predictions, differ from the predictions by as much as 11 standard deviations. The $\vec{p}$ -p analyzing powers had a maximum value of -0.0043 ± 0.0004 at 10° (laboratory) and decreased to zero near 25° .

A new technique to measure analyzing powers without symmetric detectors is explained. This technique preserves the advantages of the symmetric arm method in that current integration, target density, detector efficiencies, and geometry are cancelled from the final expressions.

A new scattering chamber, named the Supercube, is described. The Supercube was designed primarily to perform scattering experiments with a polarized beam. It contains both left-right and up-down detectors for use with both spin-1/2 and spin-1 measurements. The Supercube was designed to make analyzing power measurements to an accuracy of 0.001 routine.

The Supercube has proved to have low systematic errors and to perform as expected. The systematic errors were found to be equal to or less than 0.0002.

Chapter I

INTRODUCTION

Experimental Background

Most low energy pre-1967 $\vec{p}$ -p analyzing power measurements were not accurate enough to dispute or confirm the phase shift solutions.^{1,2} In 1967, R. J. Slobodrian, et al., measured the $\vec{p}$ -p analyzing powers at three energies, 9.6 MeV, 15.6 MeV, and 19.7 MeV.³ These measurements were incorporated into the then recently completed p-p phase shift analysis by Malcolm H. MacGregor, et al.^{4,5} The conclusion reached in MacGregor's paper was that the Slobodrian data were in contradiction with other data at similar energies. With this problem in mind, P. Catillon, et al., at Saclay performed a set of measurements of the $\vec{p}$ -p analyzing powers at 20.0 MeV.⁶ These measurements were in disagreement with the Slobodrian data and in agreement with the phase shift predictions.

The Saclay data were the most recent (1968) and accurate data available. With the exception of one of the data points all the data were consistent with a zero analyzing power. This is not unexpected since all the measurements were in the angular range of 17.3° to 45° (laboratory). In this angular range the phase shift solutions predict a maximum value for the analyzing power of only -0.001 at 17° . No forward angle measurements had been made which could check the phase shift solutions near the predicted analyzing power maximum of 8° .

Recent accurate differential cross-section measurements have been scaled to fit the phase shift solutions.⁷ A scaling of over 7 standard deviations were needed to bring these data into good agreement

with the phase shift solutions.⁸ This disagreement with the phase shifts lead us to undertake a precise analyzing power measurement at 16 MeV. The purpose of the experiment was to see if a gross difference would be found between the phase shift predictions and our measurements. Since the maximum expected value was near a 0.5% effect the accuracy of our experiment needed to be 0.1% or better.

In the summer of 1973, it was decided to measure the $\vec{p}$ - p analyzing powers to the best accuracy which could be obtained from the yet unfinished Supercube scattering chamber. It was felt that the accuracy needed was well within range (0.001 absolute or better) and that the experiment would provide a good test of the Supercube's capabilities.

A left-right detector pair (not in coincidence) was used to measure the asymmetry. A single surface barrier detector was used in each detector arm. The detector signals were digitized and processed by the on-line data acquisition computer.

The tandem Van de Graaff accelerator operated by the Los Alamos Scientific Laboratory (LASL) has an energy range of 3 to 18 MeV for singly charged particles.⁹ The polarized ion source is a Lamb-shift source which produces a negatively charged beam of hydrogen with a nuclear polarization of near 90% and a beam current of 0.4 μ A DC.¹⁰ The entire system transmission efficiency was between 25% and 33% giving routinely over 0.1 μ A at the Supercube.

As a check for systematic errors, a scattering system for which the phase shift predictions were believed to be fairly well understood was sought. The $\vec{p}$ - ^4He system has the above qualities as well as being a standard for polarized beam calibrations.¹¹

Supercube General Structure

The Supercube is a cubical 61-cm scattering chamber designed primarily for polarized beam analyzing power measurements (see Figs. 1 and 2). The Appendix gives a brief history of the Supercube design and development.

The Supercube is supported by a 20.32-cm diameter stainless steel tube which contains two sets of collimator slits. The stainless steel tube is supported by two roller bearings which are mounted in an adjustable stand. A stationary aluminum "tee" connects the diffusion pump and beam pipe to the rotating stainless steel tube by a dual "O" ring seal. The stainless steel tube is driven by a stepping motor via a worm and gear.

Left, right, up, and down are defined by a rider on the beam, aligned with the spin, entering the Supercube through the stainless steel tube. There is four-fold symmetry about the axis of the Supercube defined by the beam. Left-right detectors were used for measurements with spin-1/2 beams. When spin-1 beams are used all four detector arms are needed. The position of each arm is read out via an optical shaft encoder. Each arm has an electronics package consisting of three preamplifier channels contained in one extruded aluminum box. The signals, high voltages, and test inputs to the preamplifier are routed through the wall by means of semirigid coaxial cables soft soldered through 1/8-in. tapered pipe thread plugs (see Fig. 3) designed by the author. Male Microdot cable connectors form the electrical connections to the preamplifier heads and the outside cabling. Each arm may contain up to three silicon surface barrier detectors which are mounted in good thermal contact to a thermoelectric cooler. This allows the

Figure 1. Supercube Main Scattering Chamber
Detector arms for only one side are shown

Figure 2. Supercube with Support Frame

Figure 3. Coaxial Vacuum Feedthrough
93 Ω impedance coaxial signal feedthrough designed by the author

detectors to be cooled when the experimental constraints dictate an increase in the resolution.

A gas target cell may be suspended in the center of the Supercube by a stainless steel tube attached to the front of the Supercube. The cell is filled by a gas fill line which feeds through the Supercube wall to the outside. Solid targets may also be attached to the same target support system.

The entire rear wall of the Supercube opens as a large door giving access to the detectors and target. A Faraday cup and polarimeter chamber are mounted on the door.

The Faraday cup is 10.1 cm in diameter and split into three sections. The last section contains a slit assembly and an air plunger which can slide a tantalum cover over the exit hole. When this cover is in place the Faraday cup section acts as a Faraday cup and collects all the charge. When the cover is removed the beam can enter the polarimeter chamber which is filled with ^4He gas (see Fig. 4).

The polarimeter chamber has a left, right, up, down detector arm assembly with the same orientation as the Supercube. Each arm angle can be set with a compass and vernier. Thus, when the Faraday cup air plunger is retracted, the chamber may be used to monitor the polarization of the unscattered beam. The polarimeter may also be isolated from ground potential and used as a Faraday cup.

¹Karl W. Brockman, Jr., "Proton Polarization Measurements near 18 MeV," Phys. Rev., 110 (1958).

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- ⁸Based on personal correspondence between Dr. Nelson Jarmie, Staff Member at the Los Alamos Scientific Laboratory, and the author, 4 April 1974.
- ⁹R. Woods, J. L. McKibben, R. L. Henkel, "The Los Alamos Three-Stage Van de Graaff Facility," Nucl. Instr. and Meth., 122 (1964), 81-97.
- ¹⁰G. P. Lawrence, G. G. Ohlsen, J. L. McKibben, "Source of Polarized Negative Hydrogen and Deuterium Ions," Phys. Letts., 28B (1969), 594-596.
- ¹¹Gerald G. Ohlsen et al., "Precise Proton-Polarization Standards Determined with a Lamb-Shift Ion Source Incorporating a Nuclear Spin Filter," Phys. Rev. Letts., 27 (1971), 599-602.

FIGURE 4. FARADAY CUP AND POLARIMETER.

Cross-section of faraday cup and polarimeter with beam entering from the upper right.

Chapter II

EXPERIMENTAL EQUIPMENT

Supercube

The vacuum system for the Supercube is provided on the Supercube stand by a 15.24-cm (6-in.) Veeco¹ diffusion pump. The pump is attached to an integrated liquid nitrogen cold trap and chilled water cooled anti-backstreaming baffles. Above the combined trap is a compressed air operated vacuum valve. This assembly hangs on the main Supercube stand and is attached to the beam line by a large aluminum "tee." This tee has a 10.16-cm High Voltage Engineering² type beam tube flange on the upstream side and a dual "O" ring seal to the main Supercube support tube on the downstream end. The bottom of the tee has a 20.32-cm quick release champ fitting (see Fig. 5).

A liquid nitrogen cold trap is located 2.6 m upstream of the Supercube and provides pumping to the tube when the Supercube is disconnected from it. Vacuum readout is provided by a thermocouple gauge and ion gauge located on one of the view ports of the Supercube. An ion gauge below the vacuum valve reads the pressure directly into the diffusion pump body. On the beam tube an ion gauge and thermocouple gauge read the condition of the beam tube upstream of the Supercube (see Figs. 5 and 6). Typical pressures in the Supercube were 2×10^{-6} Torr in the chamber and 1×10^{-7} Torr directly above the main diffusion pump.

Each detector arm of the Supercube, of which there are four, contains numerous electrical and mechanical feedthroughs. Coaxial signal cables must provide high voltage bias to the silicon surface barrier detectors, test pulses to the preamplifier heads, and output signals from the

Figure 5. Supercube

Figure 6. Supercube and Support Frame
Beam enters Supercube from the left side of picture

preamplifier heads for each of the three possible detectors. Power for the preamplifier and for the thermoelectric cooler is brought through the walls by means of soldered-on ceramic-glass vacuum feedthroughs. Chilled cooling water to cool the heat sink side of the thermoelectric coolers and the return for the water is provided by copper tubing sweated into "O" ring sealed feedthroughs.

Both the main and auxiliary arm mounting plates are vacuum sealed by dual "O" rings. The space between the "O" rings is pumped out to the roughing system by feedthroughs identical to the ones used for the chilled water supply.

Compressed air is provided for both the air plunger on the Faraday cup and the air-operated vacuum valve. Both devices are operated by means of electrically-powered compressed-air valves. The air plunger is controlled locally or by remote control in the tandem control room.

Each main detector arm is driven by a stepping motor. The motor is controlled by an electronic package interfaced to the XDS-930 data acquisition computer. Two hundred steps are required for each revolution of the stepping motors. The gear ratio between the stepping motors and the arms is 327.68:1. This results in 2^{16} or 65,536 steps for 1 revolution of the arm. The position of the main detector arm is read out by a 14-bit binary encoded optical shaft encoder. The four encoder outputs are multiplexed by electronics on the Supercube and then routed to the computer interface electronics.

The main detector arm mounting plate is constructed with 8 mounting slots 45° apart. One of these is designated as the main slot (see Fig. 7). The auxiliary arm mounting plate has only one mounting slot.

Figure 7. Detector Arm Assembly
Two surface barrier detectors in mount connected to triple preamplifier package

The target assembly mounts on a bolt pattern about the upstream opening to the Supercube. Several gas targets have been constructed and are discussed in a later section. The cell is filled by a gas fill line which feeds through to the outside of the Supercube. The entire Supercube could be filled with gas, such as hydrogen or ^4He , but several constraints made this unattractive. For high pressures the beam would be multiple scattered beyond acceptable limits. Lower pressures would not cause as severe a multiple scattering problem but would reduce the count rate. Surface barrier detectors will not function in a hydrogen environment and would require enclosures to protect them. For these reasons no provisions were designed into the Supercube to allow for gas filling of the entire volume.

Faraday Cup

The Faraday cup is an integral part of the Supercube assembly. It attaches directly to the rear door of the chamber. Teflon rings support the three-section internal cup away from the outer wall as well as the separation between sections. The first and second sections were biased to contain secondary emission which must be collected in the third section. Electrical connections to the three sections are provided by BNC vacuum feedthroughs (see Fig. 4).

In the third section four tantalum slits provide collimation as well as beam steering feedback signals. These slits are driven from outside by 1-in.-travel micrometers. The micrometer shafts pass to the outside through teflon supports. The micrometers have electrostatic shields on the outside to remove unwanted electrical noise from the beam steering signals. The tantalum slits are covered on the

upstream side by a tantalum disk with a centered 19-mm hole. This assures that nonconducting materials are not exposed to direct beam.

An air plunger feeds through the wall in a similar fashion to the slits. It has attached to it a large tantalum slit which, when in place, covers a 22.23-mm opening left by the four-way tantalum slits. When the air plunger is retracted, the beam may continue into the polarimeter chamber which follows.

Polarimeter

The polarimeter attaches directly to the rear of the Faraday cup. It is electrically isolated from the Faraday cup by a ceramic ring and bolted through insulated washers. Four detector arms are mounted through the wall with "O" ring vacuum seals. Each arm has a compass and vernier which allows the arm to be positioned to 0.1° . Zero degrees is defined when the detector is positioned directly into the incoming beam. Each arm can hold one silicon surface barrier detector and a collimator snout. The rear cover holds a tantalum disk which acts as a beam stop. The entrance to the polarimeter is equipped to hold an entrance foil in a dual "O" ring assembly. The entire chamber may be filled with gas by means of a valve through the rear cover. Current may be collected by the polarimeter body and act as a Faraday cup where this option is desirable (see Fig. 4).

Detector Arms and Snouts

The main Supercube detector arms bolt to the main detector mounting plate. The preamplifier package screws to the arms upright support placing the input to the preamplifier about 10 cm from the detectors. The detector holder is mounted separately from the snout and is thermally isolated from the arm. This isolation prevents the thermoelectric coolers from cooling the entire arm and snout assembly. The heads are aligned to the arms by means of precisely machined holds and pinned in place. Each detector head can hold one, two, or three surface barrier detectors. The detectors in use consist of 150-mm² and 200-mm² detectors. The collimator snouts can have 1-1/2°, 1°, or 1/2° angular resolution slits as well as two antiscatter slits.

The arm positions are readable to $\pm 0.0118^\circ$ or ± 0.19 milliradian and the arms are positionable to $\pm 0.0027^\circ$ or ± 48 microradians.

The thermoelectric coolers mount directly on the detector head with good thermal contact (see Figs. 8, 10, and 11). A chilled water-cooled heat sink mounts on the opposite side of the cooler. The detectors gain the most in resolution when the temperature drops from room temperature to around 0°C. Little resolution is gained by reducing the temperature below 0°C.

Each detector snout consists of a tapered stainless steel truncated cone 190.5-mm long. The wall thickness is 3.2 mm and the front of the snout is 19-mm diameter. The rear of the snout is 38.0 mm in diameter and the wall is thicker in this region to provide mounting support. Four square slots were machined into the cone to provide alignment, support, and spacing to the two main slits and two antiscatter slits (see Figs. 9 and 10). This arrangement allowed for rapid interchange

Figure 8. Detector and Collimator Snout Assembly
Thermoelectric cooler shown on far side

of slits without removal of the snouts. The antiscatter slits were designed to accomodate main slits which provide $1\text{--}1/2^\circ$ or smaller angular resolution. The main slit width for $1\text{--}1/2^\circ$ angular resolution was 5.00 mm, for 1° resolution 3.33 mm, and for $1/2^\circ$ resolution 1.68 mm.

Selection of the cone angle, cone length, and slit spacing, and the optimum number of antiscatter slits was constrained by several criteria.

Overall length was determined by the target diameter, number and thickness of detectors, and clearance of adjacent auxiliary arm mounting support. Three silicon surface barrier detectors were chosen as the maximum detector thickness. With nominal clearance for the rear of the detector, the only other major factor was target size. The larger the target, the smaller the angle which could be obtained with a given slit size. Also, the larger the target the harder the target foil became to install. As the target became larger, the main slits were brought closer together and must be made narrower for the same angular acceptance. Given a minimum slit angular acceptance of $1/2^\circ$ and a scattering angle of 6° , a target diameter was arrived upon by graphic methods. The criteria used made a target and angle unacceptable if the detector, through the slit assembly, could have viewed any part of the target structure which was illuminated by the main particle beam. This problem occurs only for far forward and far backward angles. Since the angles of most interest in the present experiment were forward, another improvement was made. A snout was attached to the target and the entrance window was installed upstream of the main target diameter. This then moved upstream the illuminated entrance foil and decreased the minimum angle the detectors may be set to (see Fig. 15). Since the detector

Figure 9. Collimator Snout Cross-Section

Figure 10. Exploded View of Detector Arm Assembly

slit assembly (at forward angles) will view the side wall of the target snout, two antiscatter apertures were installed in this snout to reduce the illumination of the snout side wall.

Once the target diameter was picked the final design of the detector snouts and slits was straightforward. The front slit was placed as close to the target as possible and the rear slit as close to the detectors as possible. With this geometry established the slit width was determined for each angular acceptance. In the final design the front slit was 5.1 cm from the target center. The front and rear slits were 19 cm apart leaving the rear slit 24.1 cm from target center. The diameter of the snout front is determined by two constraints.

The first constraint was the required minimum total included angle for which the two detectors may be set. Interference between the snout tips was by far the major constraint on this angle (see Fig. 11). The second constraint was the number of antiscatter slits. The smaller the snout tip, the more antiscatter slits that were needed. Since the number of antiscatter slits was somewhat arbitrary, a number of two was chosen and the snout tips were reduced to a minimum diameter consistent with this choice. This resulted in a minimum total included angle of 23° (see Fig. 11).

The position and width for the antiscatter slits were determined using the criteria that no particle could single scatter from the walls into the detector. The width to accommodate up to $1\text{-}1/2^\circ$ main slits proved to be 7.62 mm. The first antiscatter slit was 34.3 mm from the front slit and the second antiscatter slit was 97.8 mm from the front slit.

The slit heights were determined by the detector active area. The target was designed around detectors of 150 mm^2 which gave a diameter

Figure 11. Target-Detector Assembly
300° circular target with detectors at the minimum forward angle

of 13.8 mm. Putting in a safety factor of approximately 10%, 11.4 mm was chosen as the rear slit height. The other slit heights were then checked to assure that they do not restrict the rear slits' view of the interaction region.

All four of the slits were machined from 2.54-mm thick nickel material. Around each of the slits a recess was machined to reduce the slit edge exposed to the scattered beam. The thickness was optimized to the particle and energy being detected by reducing the slit thickness to a value only slightly thicker than the range of the scattered particle.

The recessed face of the slit was positioned so that it faced the target. This was done to eliminate the possibility that particles could pass through the slit and scatter from the full thickness edge into the detector. As noted above, the amount of slit edge scattering seen at the detector is proportional to the slit edge thickness. To reduce this slit edge scattering, which contributes to the background, the slits are machined to near the minimum thickness needed to stop unwanted particles. This optimum thickness will vary with beam energy and scattering angle.

During the first data runs a low energy hump appeared in the spectrum of one detector arm at forward angles (see Fig. 12). Much checking was involved before it was discovered that the front and rear slits in arm 0 were too thin. The optimal thickness was 0.607 mm, but the slits had been accidentally machined to a thickness of only 0.508 mm. This thickness permitted transmission, with degraded energy, of particles in the elastic peak. When a new set of slits were machined and installed, the noted effect disappeared.

Figure 12. Raw Data Spectrum $\vec{p}$ -p 16 MeV 11.5°
 Upper spectrum is from arm 0, lower spectrum is from arm 2

Gas Targets

The first target designed for the Supercube was an up-down, left-right target with four panels of 2.5- μ m Havar foil.³ This was the first target design since it is a general purpose target (see Fig. 13). The maximum pressure with which it was used was 125 Torr, and the angular range over which it could be used was 18° to 162° . Since our work was to be at more forward angles this target design was soon abandoned for a semi-circular target (see Fig. 14) which was more suited to the present experiment.

The major feature of this target was the continuous forward angle foil. Also, the single exit foil, rather than the five exit foils, would take much less time to install. This target proved to work well up to 400 Torr but had major drawbacks. The higher pressures could only be reached with thicker foils, i.e., 200 Torr with 2.5- μ m Havar, 400 Torr with 6.4- μ m Havar. Thus these foil thicknesses were not being used to advantage, since at the target radius used, 2.5- μ m Havar was calculated to hold 760 Torr of gas pressure, assuming a shear stress of 330,000 psi for Havar. The conclusion was reached that the glue seal was failing rather than the foil. Exit foil thickness is important because particles scattered from other than the desired angle to the exit foil directly in front of the detector may be scattered by the foil into the detector. The thicker the exit foil the higher the probability that this process will occur. Particles which follow this course add to the background. The background has a much higher asymmetry than the proton peak, so that errors in subtracting the background lead to false asymmetries. It is desirable to eliminate or reduce the mechanisms which increase the background.

Figure 13. Tetragonal Gas Target

Figure 14. Semicircular Gas Target

The job of gluing the foil to the target proved to be both time consuming and many times unsuccessful, but still was considerably less work than the tetragonal target. The second major drawback for the semi-circular target was the large wall area very near the target interaction region. At far forward angles the detector slit system would view large areas of wall which proved to be a large source of low energy scattered particles. This occurred despite the precautions taken with the target scraper apertures. Even with its many limitations, this target allowed measurements to be made at forward angles. The asymmetric arm technique was tested and showed reproducible results. With the requirements for an improved target better understood, the final target was designed.

The final target design was a full circular target to remove the wall from the interaction region. This increased the complexity of foil installation and thus a new design was used (see Fig. 15). Both the top and bottom of the target were removable allowing the foil to be glued from the inside. The foil was then forced against, rather than away from, the seal by the target gas. Using 2.5- μm Havar, the target was used to 350 Torr. Another advantage with the circular target was the ability to view the target at 112° . At this angle with ^4He in the target, $\vec{p}\text{-}^4\text{He}$ has an analyzing power of nearly 1.0.⁴ This fact was used several times during the data taking runs to calibrate the polarized beam and to test for systematic errors.

Beam Steering Feedback

The energy of the tandem Van de Graaff accelerator is regulated by means of a slit feedback system. The feedback signal is obtained from

Figure 15. 300° Circular Gas Target

a slit set, called the regulation slits, after a momentum analyzing magnet. If the machine energy is too high, the momentum analyzing magnet does not bend the beam through as large an angle. In this case the left slit collects more beam and a signal is sent to the accelerator to reduce the energy. For a beam with too low an energy the opposite is true. This feedback system produces left-right variations at the regulation slits. Many sets of slits separate the analyzing magnet from the Supercube. These slits somewhat reduced the positional variation and replaced it by a beam current variation. The resulting beam on target was both position and intensity modulated.

A solution, that was attempted, was to install a fast feedback beam steering system. Several unsuccessful attempts were tried before a system began to function at all. The first Supercube slits (see Fig. 16) were used as the control signal source. The left-right current signal was converted to a voltage signal by a LASL-designed electronics unit. This error signal was routed by a control unit, also built by LASL, to a Kepco bipolar operational power supply. This power supply drove a beam steering coil mounted in a metal free coil form and beam pipe section. The avoidance of metal improved the frequency response of the beam steerer.

The original design called for two steering feedback systems. The first steerer was as described above. The second was to correct small angular positional variations nearer the target. This second steerer was to receive its control signals from the slits incorporated into the Faraday cup. This phase of the system was delayed due to lack of success with the first steerer.

Figure 16. Supercube Beamline Plan
 Note that the plan is not to scale

Several tests of the system were conducted during accelerator runs. Unexplainably, the system performed as designed for periods of time and then would not control during other periods. Beam conditions and the spectrum of noise impressed on the beam might be possible factors of the failure of the system. When the system appeared to work it was used to stabilize the beam, but the error feedback signal was always monitored. This was to provide indications when the feedback signal broke into oscillations, thus indicating unstable operation.

Since asymmetries are sensitive to beam position, any improvement in beam stability would reduce possible false asymmetries. At present the positional variations are believed to be random so that false asymmetries produced would average out, but with improved stability less chance exists for a possible systematic error to appear.

¹Veeco Instruments, Inc., Terminal Drive, Plainview, New York 11803.

²High Voltage Engineering Corporation, Burlington, Massachusetts 01803.

³Hamilton Watch Company, Lancaster, Pennsylvania 17604.

⁴Gerald G. Ohlsen et al., "Precise Proton-Polarization Standards Determined with a Lamb-Shift Ion Source Incorporating a Nuclear Spin Filter," Phys. Rev. Letts., 27 (1971), 599-602.

Chapter III

DATA ACQUISITION AND ELECTRONICS

Normal Spin Reversal

Measurements of asymmetries, using spin-1/2 particle beams, are relatively easy experiments, in principle. If an unpolarized particle beam and an unpolarized target are used, the polarization will appear as a difference in the number of particles with spin up vs spin down at a given angle θ . That is, for no polarization, there would be an equal number of particles with spin up and spin down. By convention, where all the particles on the left (at angle θ) are spin up, the asymmetry is equal to plus one.¹ Measurements of the spin state of the outgoing particles is a somewhat difficult and cumbersome task. With the advent of polarized beams a much easier experiment is possible.

Using a polarized beam the asymmetry measurement becomes a task of measuring the number of particles scattered left and right, but not the spin of those particles. The difference between the left and right yields gives a relative measure of the asymmetry, but is not normalized to the yield or counting rate. If the left-right difference is divided by the total left-right counts, then this ratio defines the asymmetry:

$$\epsilon = \frac{L-R}{L+R} \quad (1)$$

where L and R are the number of counts in the left and right detectors, respectively.

For a given analyzing power a higher beam polarization would give a higher asymmetry. The analyzing power is a measure of the asymmetry independent of beam polarization. For measurements made with both left

and right detectors the asymmetry is equal to pA_y , where p is the beam polarization and A_y is the analyzing power. For an analyzing power of plus one, a measurement of the asymmetry is equivalent to measuring the beam polarization.

Several experimental advantages result from using Eq. (1) to measure A_y . The expression for the yield in the left detector is

$$Y_L = \eta N E_L \Omega_L I_0(\theta) (1 + p A_y(\theta)) , \quad (2)$$

where η is the beam flux, N is the target gas density, E_L is the efficiency of the left detector, Ω_L is a geometry factor for the left detector, $I_0(\theta)$ is the unpolarized cross section at angle θ , and p and $A_y(\theta)$ are as above. The yield for the right detector is

$$Y_R = \eta N E_R \Omega_R I_0(\theta) (1 - p A_y(\theta)) . \quad (3)$$

The sign of $p A_y(\theta)$ is in accordance with the standard (Basel) convention.² If the ratio $(L-R)/(L+R)$ is formed using Eqs. (2) and (3), the result requires knowledge of E_L , E_R , Ω_L , Ω_R , but not of η , N , or $I_0(\theta)$, since the latter 3 variables cancel from each term. If the asymmetry measurement is made first with the beam spin in the up state and then the measurement is repeated with the spin in the down state, additional factors cancel from Eq. (1). This can be seen by writing down the four expressions:

$$L_1 = Y_{\uparrow L} = \eta N E_L \Omega_L I_o(\theta) (1 + pA_y(\theta)) \quad (4)$$

$$R_1 = Y_{\uparrow R} = \eta N E_R \Omega_R I_o(\theta) (1 - pA_y(\theta)) \quad (5)$$

$$R_2 = Y_{\downarrow L} = \eta' N' E_L \Omega_L I_o(\theta) (1 - pA_y(\theta)) \quad (6)$$

$$L_2 = Y_{\downarrow R} = \eta' N' E_R \Omega_R I_o(\theta) (1 + pA_y(\theta)) \quad (7)$$

The signs interchange on the spin-down case because the fixed detectors appear to have rotated 180° about the particle beam, as viewed by a rider oriented with the spin. η and N are assumed different in the spin-up case than in the spin-down case since they correspond to measurements made at different times.

If the geometric means are taken using L_1 and L_2 as one pair and R_1 and R_2 as the other, the following expressions are obtained:

$$\sqrt{L_1 L_2} = \sqrt{\eta \eta' N N' E_L E_R \Omega_L \Omega_R} I_o(\theta) (1 + pA_y(\theta)) \quad (8)$$

and

$$\sqrt{R_1 R_2} = \sqrt{\eta \eta' N N' E_L E_R \Omega_L \Omega_R} I_o(\theta) (1 - pA_y(\theta)) \quad (9)$$

If Eq. (8) is set equal to L and Eq. (9) is set equal to R and these are substituted into Eq. (1), the resulting asymmetry is independent of η , η' , N , N' , E_L , E_R , Ω_L , Ω_R , and $I_o(\theta)$, since these terms are a common factor and cancel. This gives $\epsilon = pA_y$ which was stated without derivation earlier.

For a geometric mean, the statistical error in the count rate is³

$$\Delta L = \frac{1}{2} \sqrt{L_1 + L_2} \quad (10)$$

and

$$\Delta R = \frac{1}{2} \sqrt{R_1 + R_2} \quad (11)$$

The error in the asymmetry ϵ is⁴

$$\Delta \epsilon = \frac{1}{L+R} \sqrt{(1-\epsilon)^2 (\Delta L)^2 + (1+\epsilon)^2 (\Delta R)^2} \quad (12)$$

To obtain the analyzing power A_y , the asymmetry is divided by the beam polarization

$$A_y = \frac{\epsilon}{p} \quad (13)$$

The error for A_y is formed by standard error calculations to be⁵

$$\Delta A_y = \frac{1}{p} \sqrt{(\Delta \epsilon)^2 + \left(\frac{\epsilon \Delta p}{p}\right)^2} \quad (14)$$

Another possible approach to data acquisition which eliminates the same variables is to rotate the scattering chamber 180° about the beam axis. Since the Supercube is designed for just such a rotation, data may be obtained using this method as well as the one described above. The four yields are essentially identical to those of Eq. (4)-(7), and may be used to eliminate additional systematic errors.

When the Supercube is rotated from $\phi = 0^\circ$ to $\phi = 180^\circ$, certain conditions must be met for what is called a "proper" flip.⁶ When the Supercube is rotated the relative position of the beam must remain fixed

with respect to the target and detectors. This is done by requiring that the beam current on each slit remain the same even though the slits rotate with the Supercube. If this is not the case, false asymmetries result.

Rapid Spin Reversal

During the evolution of the experimental data-taking procedure, a new method became available. This new method, which flipped the spin state at between 500 and 1000 Hz, showed promise of eliminating suspected false asymmetry due to beam-position instabilities.

Several problems were encountered with rapid reversal which had to be understood before the method was to become viable. Some of these were known beforehand and some were to be discovered in the first data which were taken.

One problem which was known was that the quench ratio (see discussion in Beam Polarization Section) would no longer give a correct measurement of the beam polarization. That is, of the polarizable portion of the beam, in rapid reversal mode only $\sim 80\%$ polarization was obtained. The reason for this loss in polarization will be discussed further on. Also there was the possibility that the polarization of the two spin states would not be the same. The only reliable method for determining the beam polarization was to use a scattering with a known analyzing power. As will be discussed later, $\vec{p}$ - ^4He has a large analyzing power in this energy range.⁷ Where the detectors were not obstructing the unscattered beam the polarimeter could be used. The polarimeter was filled with 800 Torr of helium gas and the detector arms were set at 112° . Using the Supercube, 5 data points were taken at 112° with ^4He

in the 300° circular gas target. Using this calibration point the beam polarization could be determined for the rapid reversal runs.

The comparison of the polarization in each spin state was made by making a run with the Supercube at $\phi = 0^\circ$ and a run with the Supercube at $\phi = 180^\circ$ using $\vec{p}\text{-}^4\text{He}$ scattering at 112° . ϕ is the azimuthal angle about which the Supercube rotates and when the Supercube is in its normal configuration $\phi = 0^\circ$. Increasing ϕ is in a clockwise direction when viewed from upstream. Using left-right detectors, data were taken with the Supercube at $\phi = 0^\circ$ and $\phi = 180^\circ$. Combining measurements with only one spin state, geometric means for left and right may be formed.

$$\frac{L-R}{L+R} = \epsilon = p A_y(112^\circ) , \quad (15)$$

where L and R are the left and right geometric means, respectively.

From the $\vec{p}\text{-}^4\text{He}$ calibration data (see Systematic Error, Chap. IV), $A_y(112^\circ) = 0.9936 \pm 0.0040$. Solving Eq. (15) for p gives

$$p = \frac{\epsilon}{A_y(112^\circ)} = \frac{0.6915}{0.9936} = 0.6960 , \quad (16)$$

and the error in p is

$$\Delta p = \frac{1}{A_y(112^\circ)} \sqrt{(\Delta \epsilon)^2 + \left(\frac{\epsilon \Delta A_y}{A_y}\right)^2} = 0.0049 , \quad (17)$$

where $\Delta \epsilon = 0.0021$ from Eq. (12).

Repeating the above for the spin-down measurement gives $p = 0.7052$ and $\Delta p = 0.0049$. These polarizations agree to within their error bars. Since polarization errors do not significantly affect (see Discussion, p. 49) the analyzing power errors, the two spin state

polarizations may be assumed identical.

An unforeseen problem arose in the labeling of events for the computer. Two additional bits of information were supplied to the computer via the interface. The first bit told the computer which spin state the polarized ion source was in; the second bit blocked the acceptance of an event under certain conditions.

When the ADC's had completed the digitization of an event the computer checked the status of the spin direction bit. Since the event had occurred some time before the ADC was finished, the spin state may have changed status and in this case the event must be blocked. The second bit was present during the time an event could cross from one spin state to another. For the first testing of the rapid reversal system this blocking time was too short and events labeled with the wrong spin state were accepted. Once this problem was detected, the blocking time was extended to cover the worst case (200 μ sec), the data were mostly labeled correctly. A few cases still existed where delays in the acceptance of an event caused a mislabel to occur. For the subsequent use of rapid reversal a new method of labeling the spin state and blocking signals was devised. In this method, the extra information was accepted simultaneously with the ADC linear gate. This then eliminated the spin state mislabeling.

Another potential source of possible trouble with rapid reversal was that a beam position shift, correlated with the spin state, could occur. This would lead to a false asymmetry. The reason to suspect such an occurrence is intrinsic to the nature of the rapid reversal mechanism in the ion source (see Polarized Ion Source, Chap. III).

To measure any remaining false asymmetry due to spin state correlation of beam position, a beam with $\beta = 0^\circ$ was employed. β is the angle between the spin axis and the beam direction. Thus, a $\beta = 0^\circ$ beam is one for which the spin axis is along the beam axis. Since only a transverse-polarized beam can produce an asymmetry, any effect observed with these conditions would either be due to false asymmetries in the Supercube or to positional shifts due to the rapid reversal field changes. The false asymmetries were checked with normal spin reversal techniques, also using a $\beta = 0^\circ$ beam. After verifying that no noticeable effect appeared with normal reversal, the rapid reversal data were taken. Using both phases of rapid reversal and the Supercube at $\phi = 0^\circ$ and $\phi = 180^\circ$, 4 data sets were taken. The observed total false asymmetry was equal to $+0.00028 \pm 0.00031$. As this number is consistent with zero, it was concluded that there is no beam position shift correlated with spin direction.

Since the data taken with rapid reversal were not usable when the blocking signal was incorrect, only a small amount of the rapid reversal data was included with the final set.

While the rapid reversal method promises to be a powerful tool in polarization measurements, the conclusion reached for the present experiment was that it was interesting and workable but not necessary to achieve the desired results.

Asymmetric Arm Measurements

The minimum scattering angle for which both detector arms could be symmetrically set was 11.5° (see Fig. 11). For measurements at smaller laboratory angles a new technique was developed.

Two problems existed which had to be overcome by any new measurement technique; first, the left and right measurement periods would be at different times, and, second, the small angle measurement would make any beam current integration measurement completely meaningless, since the snout intercepted much or all of the beam.

The resulting technique depends on the analyzing power being known at a chosen point. This was called θ_1 , and the measurement sequence was as follows: (The fixed arm numbers are used here, rather than the left-right designation, to avoid confusions with Supercube rotations and spin state changes.)

1. Arm 0 is set at θ_1 angle.
2. Arm 2 is set at the angle to be measured, θ_2 .
3. Data are taken first with spin up and then spin down.
4. Arm 0 is set at θ_2 .
5. Arm 2 is set at θ_1 .
6. Data are again taken with spin up and spin down.

With the proper algebra this fourfold data sequence will produce an analyzing power for θ_2 , as will be discussed below. To complete the possible measurements the Supercube is rotated to the $\phi = 180^\circ$ position and the above data sequence is repeated. This will yield another measurement for $A_y(\theta_2)$. Besides the $\phi = 0^\circ$ and $\phi = 180^\circ$ measurements, two more combinations of the data are possible. By combining the data from arm 0 with the Supercube at both $\phi = 0^\circ$ and $\phi = 180^\circ$ and likewise for arm 2, two independent values for $A_y(\theta_2)$ result. Since these two values are not statistically independent, the overall error is not reduced when they are averaged.

This 8-fold sequence produces 16 numbers, the yield expressions for which are shown in Table 1.

Geometric means were taken between runs with the same angle. An example would be numbers 1 and 11, which are both left-type runs at angle θ_1 . Table 2 lists the 4 data types and the sequence numbers used to produce the correct geometric means.

In the first case of Table 2, the geometric means are

$$\sqrt{L_1 L_7} = \sqrt{\eta_1 \eta_7 N_1 N_7 E_0 E_2 \Omega_0 \Omega_2} I_0(\theta_2) (1 + p_{A_y}(\theta_2)) \quad (18)$$

$$\sqrt{R_3 R_5} = \sqrt{\eta_3 \eta_5 N_3 N_5 E_0 E_2 \Omega_0 \Omega_2} I_0(\theta_2) (1 - p_{A_y}(\theta_2)) \quad (19)$$

Forming the asymmetry and cancelling common terms gives

$$\epsilon_{\theta_1} = \frac{\sqrt{\eta_1 \eta_7 N_1 N_7} (1 + p_{A_y}(\theta_2)) - \sqrt{\eta_3 \eta_5 N_3 N_5} (1 - p_{A_y}(\theta_2))}{\sqrt{\eta_1 \eta_7 N_1 N_7} (1 + p_{A_y}(\theta_2)) + \sqrt{\eta_3 \eta_5 N_3 N_5} (1 - p_{A_y}(\theta_2))} \quad (20)$$

Dividing both numerator and denominator of Eq. (20) by $\sqrt{\eta_3 \eta_5 N_3 N_5}$ and setting

$$k = \sqrt{\frac{\eta_1 \eta_7 N_1 N_7}{\eta_3 \eta_5 N_3 N_5}} \quad (21)$$

gives

$$\epsilon_{\theta_2} = \frac{k(1 + p_{A_y}(\theta_2)) - (1 - p_{A_y}(\theta_2))}{k(1 + p_{A_y}(\theta_2)) + (1 - p_{A_y}(\theta_2))} \quad (22)$$

Table 1

Yield Expressions for Asymmetric Arm Measurements of A_y

Sequence Number	Arm	Scatter- ing Angle	Beam Spin State	Super- cube Angle	Data Acqui- sition Pair	Yield Expression
L ₁	0	θ_2^*	↑	0°	1	$\eta_1 N_1 E_0 \Omega_0 I_0(\theta_2)(1+pA_y(\theta_2))$
R ₂	0	θ_2	↑	180°	2	$\eta_2 N_2 E_0 \Omega_0 I_0(\theta_2)(1-pA_y(\theta_2))$
R ₃	0	θ_2	↓	0°	3	$\eta_3 N_3 E_0 \Omega_0 I_0(\theta_2)(1-pA_y(\theta_2))$
L ₄	0	θ_2	↓	180°	4	$\eta_4 N_4 E_0 \Omega_0 I_0(\theta_2)(1+pA_y(\theta_2))$
L ₅	0	$\theta_1^\dagger$	↑	0°	5	$\eta_5 N_5 E_0 \Omega_0 I_0(\theta_1)(1+pA_y(\theta_1))$
R ₆	0	θ_1	↑	180°	6	$\eta_6 N_6 E_0 \Omega_0 I_0(\theta_1)(1-pA_y(\theta_1))$
R ₇	0	θ_1	↓	0°	7	$\eta_7 N_7 E_0 \Omega_0 I_0(\theta_1)(1-pA_y(\theta_1))$
L ₈	0	θ_1	↓	180°	8	$\eta_8 N_8 E_0 \Omega_0 I_0(\theta_1)(1+pA_y(\theta_1))$
R ₉	2	θ_2	↑	0°	5	$\eta_5 N_5 E_2 \Omega_2 I_0(\theta_2)(1-pA_y(\theta_2))$
L ₁₀	2	θ_2	↑	180°	6	$\eta_6 N_6 E_2 \Omega_2 I_0(\theta_2)(1+pA_y(\theta_2))$
L ₁₁	2	θ_2	↓	0°	7	$\eta_7 N_7 E_2 \Omega_2 I_0(\theta_2)(1+pA_y(\theta_2))$
R ₁₂	2	θ_2	↓	180°	8	$\eta_8 N_8 E_2 \Omega_2 I_0(\theta_2)(1-pA_y(\theta_2))$
R ₁₃	2	θ_1	↑	0°	1	$\eta_1 N_1 E_2 \Omega_2 I_0(\theta_1)(1-pA_y(\theta_1))$
L ₁₄	2	θ_1	↑	180°	2	$\eta_2 N_2 E_2 \Omega_2 I_0(\theta_1)(1+pA_y(\theta_1))$
L ₁₅	2	θ_1	↓	0°	3	$\eta_3 N_3 E_2 \Omega_2 I_0(\theta_1)(1+pA_y(\theta_1))$
R ₁₆	2	θ_1	↓	180°	4	$\eta_4 N_4 E_2 \Omega_2 I_0(\theta_1)(1-pA_y(\theta_1))$

* θ_2 refers to the angle for which the analyzing power is unknown. $^\dagger \theta_1$ refers to the larger angle where the analyzing power is known.

Table 2

Data Sequence Combinations for Asymmetric

Arm Measurements of A_y

<u>Data Type</u>	<u>Angle</u>		<u>Procedure</u>		
	θ_2	θ_1			
L	1,11	5,15	Supercube Normal		
R	3, 9	7,13			
L	1, 4	14,15	Supercube Normal and Reversed	}	Arm 0 θ_1
R	2, 3	12,16			Arm 2 θ_2
L	10,11	5, 8	Supercube Normal and Reversed	}	Arm 0 θ_2
R	9,12	6, 7			Arm 2 θ_1
L	4,10	8,14	Supercube Normal		
R	2,12	6,16			

Using the geometric mean for the known analyzing power angle, θ_2 , gives an equation analogous to Eq. (22), but with different sequence numbers. This new equation is

$$\epsilon_{\theta_2} = \frac{\sqrt{\eta_5 \eta_3 N_5 N_3} (1 + p_{A_y}(\theta_1)) - \sqrt{\eta_7 \eta_1 N_7 N_1} (1 - p_{A_y}(\theta_1))}{\sqrt{\eta_5 \eta_3 N_5 N_3} (1 + p_{A_y}(\theta_1)) + \sqrt{\eta_7 \eta_1 N_7 N_1} (1 + p_{A_y}(\theta_1))} . \quad (23)$$

Dividing both numerator and denominator of Eq. (23) by $\sqrt{\eta_7 \eta_1 N_7 N_1}$ and setting

$$k' = \sqrt{\frac{\eta_5 \eta_3 N_5 N_3}{\eta_7 \eta_1 N_7 N_1}} , \quad (24)$$

gives

$$\epsilon_{\theta_1} = \frac{k' (1 + p_{A_y}(\theta_1)) - (1 - p_{A_y}(\theta_1))}{k' (1 + p_{A_y}(\theta_1)) + (1 - p_{A_y}(\theta_1))} . \quad (25)$$

The data sequence of 16 points was taken in 8 pairs of both left and right detectors for each set. For those pair η and N are equal, and k' is seen to be equal to the reciprocal of Eq. (21). Using the above fact in Eq. (25) leads to

$$\epsilon_{\theta_1} = \frac{1/k (1 + p_{A_y}(\theta_1)) - (1 - p_{A_y}(\theta_1))}{1/k (1 + p_{A_y}(\theta_1)) + (1 - p_{A_y}(\theta_1))} . \quad (26)$$

Since the beam polarization is known, the analyzing power $A_y(\theta_1)$ was assumed known and ϵ is the quantity which was measured, k is the only known in Eq. (26), which when solved for k gives

$$k = \frac{(1-\epsilon_{\theta_1})(1+pA_y(\theta_1))}{(1+\epsilon_{\theta_1})(1-pA_y(\theta_1))} . \quad (27)$$

Solving Eq. (22) for $A_y(\theta_2)$ yields

$$pA_y(\theta_2) = \frac{k(1-\epsilon_{\theta_2}) - (1+\epsilon_{\theta_2})}{k(1-\epsilon_{\theta_2}) + (1+\epsilon_{\theta_2})} , \quad (28)$$

where ϵ_{θ_2} and p are measured quantities and k is derived from Eq. (27). The error for $pA_y(\theta_1)$ can be derived from the standard error equation,

$$\Delta v = \sqrt{\left(\frac{\partial v}{\partial x}\right)^2 (\Delta x)^2 + \left(\frac{\partial v}{\partial y}\right)^2 (\Delta y)^2} , \quad (29)$$

where v is replaced by $pA_y(\theta_2)$, x by k , and y by ϵ_{θ_2} . The error on $pA_y(\theta_2)$ is computed first to reduce the complexity of the resulting expression. The error then becomes

$$\Delta(pA_y(\theta_2)) = \sqrt{\left[\frac{\partial(pA_y(\theta_2))}{\partial k}\right]^2 (\Delta k)^2 + \left[\frac{\partial(pA_y(\theta_2))}{\partial \epsilon_{\theta_2}}\right]^2 (\Delta \epsilon_{\theta_2})^2} . \quad (30)$$

The first term under the square root is equal to

$$\frac{\partial(pA_y(\theta_2))}{\partial k} = - \frac{(1-\epsilon_{\theta_2})}{k(1-\epsilon_{\theta_2}) + (1+\epsilon_{\theta_2})} \{1-pA_y(\theta_2)\}. \quad (31)$$

The second partial derivitave under the square root is equal to

$$\frac{\partial(pA_y(\theta_2))}{\partial \epsilon_{\theta_2}} = \frac{\left[k(1-\epsilon_{\theta_2}) + (1+\epsilon_{\theta_2}) \right] + \left[(1+k) + k(1-\epsilon_{\theta_2}) - (1+\epsilon_{\theta_2}) \right] (1-k)}{\left[k(1-\epsilon_{\theta_2}) + (1+\epsilon_{\theta_2}) \right]^2}. \quad (32)$$

Δk also must be derived using standard error techniques with v replaced by k , x replaced by $A_y(\theta_1)$, and y replaced by ϵ_{θ_1} . Taking the required partial derivatives gives

$$\Delta k = \sqrt{\left[\frac{\partial k}{\partial A_y(\theta_1)} \right]^2 (\Delta A_y(\theta_1))^2 + \left[\frac{\partial k}{\partial \epsilon_{\theta_1}} \right]^2 (\Delta \epsilon_{\theta_1})^2}, \quad (33)$$

where

$$\frac{\partial k}{\partial A_y(\theta_1)} = \frac{(1-\epsilon_{\theta_1})}{(1+\epsilon_{\theta_1})} \frac{2}{(1-pA_y(\theta_1))^2}, \quad (34)$$

$$\frac{\partial k}{\partial \epsilon_{\theta_1}} = - \frac{pA_y(\theta_1)(1+k)}{(1-pA_y(\theta_1))(1+\epsilon_{\theta_1})}. \quad (35)$$

$\Delta A_y(\theta_1)$ is the stated error in the known analyzing power measurement and $\Delta \epsilon_{\theta_1}$ is the counting error in the measured asymmetry. The last term under the square root in Eq. (30) is $\Delta \epsilon_{\theta_2}$ or the counting error in the measured unknown angle asymmetry. This gives an expression for the

error in $pA_y(\theta_2)$ which leaves the error in $A_y(\theta_2)$ to be determined by Eq. (14). Once the geometric means are made using Table 2, the expressions for $A_y(\theta_2)$ and $\Delta A_y(\theta_2)$ are formally identical with the results derived above.

Several assumptions were made in the above derivation. One such assumption is that the beam polarization does not change between runs. A look at Table 10 shows that the variation in beam polarization is within the limits quoted for the quench ratio method of beam polarization measurements. Since the $\vec{p}$ -p asymmetries are less than 0.01 and $p = 0.90$ and $\Delta p = 0.01$, the contribution to ΔA_y from the polarization uncertainty is at most, from Eq. (22),

$$\frac{(0.01)(0.01)}{(0.9)^2} = 0.0001 \quad . \quad (36)$$

A second assumption which was made was that angles δ_1 and δ_2 are set equal for arm 0 and arm 2 when each is at a given angle. The zero angle setting techniques described in that section lends strength to the argument that the absolute arm position was good to better than 1.1 mR. An error in angle setting, for small errors, gives to first order

$$A_y(\theta) = \frac{1}{2}(A_y(\delta_1) + A_y(\delta_2)) \quad , \quad (37)$$

where δ_1 and δ_2 are the true angles of the left and right detectors and $\theta = \frac{1}{2}(\delta_1 + \delta_2)$, where θ is the true average angle. The true average angle and the indicated angle were believed different by less than 0.04° .

Beam Polarization

The quench ratio method for beam polarization measurements involves changing the fields in the polarized ion source.⁸ The polarized beam contains both a polarized component and an unpolarized component. Each component is produced by a different mechanism in the source. When the spin filter fields are adjusted so that no spin state is transmitted, the polarized component of the beam is removed and the source is then in the quenched state. The ratio of the quenched beam to the normal beam gives the fraction of the beam which is not polarized. Subtracting this ratio from unity gives the beam polarization.

Beam polarization measurements have always been a problem at the scattering chamber. The reason for this is the phenomenon of polarization enhancement by beam slit scraping. The emittance of the polarized ion source is such that the center of the beam is of higher polarization than the edge. Since at each slit the edge of the beam is stripped away, the beam polarization tends to improve closer to the target. The standard method of beam polarization measurement is to use a Faraday cup and measure the polarized beam current and then the quenched beam current.⁹ The polarization of the beam is usually of the order of 0.88. The ideal place to measure this current would then be directly in front of the gas target. Unfortunately, the beam position stability is such that accurate measurements of the beam current at the Supercube have not been possible.

Another way to measure the beam polarization is to use a polarimeter chamber after the main scattering chamber. For angle measurements where the unscattered beam is not intercepted, the Supercube polarimeter was used simultaneously with the analyzing power measurement.

For measurements where the polarimeter was not usable, the Faraday cup after the energy analyzing magnet, known as the "analyzing" or "A" cup, is used to measure the quench ratio (see Fig. 17). Beam polarization measurements at the "A" cup have been shown to be good to at least 1/2%.¹⁰ For a final case where the direction of the spin is reversed at high speed, i.e., 500-1000 Hz, and small angle measurements make the polarimeter not usable, polarization measurements are not possible. In this case even the "A" cup is not usable, the reasons for which will be discussed in the section on rapid reversal. To make an estimate of the beam polarization, a polarimeter measurement is made with the Super-cube arms back in angle. This measurement is compared to the quench ratio measurement and a ratio between the two is calculated. This number, when multiplied by the quench ratio, gives the beam polarization.

The polarization is fairly stable with time. The amount with which the measurement of the polarization varies must be included as an error along with the uncertainty in the polarization measurement. The uncertainty in the polarization measurement using the quench ratio method is 0.4%.¹¹ The error associated with polarization variations is seen to be $\sim 0.5\%$. The latter effect is the dominating effect and is used as the beam polarization error. In general, this adds no more than 0.00002 to the final analyzing power measurement error.

Systematic Errors

Many tests were incorporated into the data acquisition for the $\vec{p}$ -p analyzing power measurements. One such test was the use of a reaction which had a large and accurately known analyzing power. $\vec{p}$ - ^4He is such a system and so the H_2 gas was replaced by ^4He for a sequence of

Figure 17. Tandem Van de Graff Plan

measurements. Predictions were obtained to compare with the experimental data.¹² Data were taken at 5 angles including a nonsymmetric detector point at 10° . The experimental techniques used to acquire this data were identical to those used for the $\vec{p}$ -p measurements. Besides the far forward angles a series of measurements were taken at 112° . At this point the analyzing power should be near 1.0, a maximum value.¹³

Unpolarized beam measurements of asymmetries provided another test for possible systematic errors. All the polarized source fields were turned off and the larger beam current was reduced at the source. Two different measurements were made with the source fields turned off. In both runs eleven points were measured; the first run, the angles were 11.5° , 14° , and 15° ; the second, measurements were all made at 13° . Since the unpolarized beam is in a much different state than the polarized beam used for normal measurements, this test is not as conclusive as the $\beta = 0^\circ$ test.

A second test for a systematic error was to precess the spin of the polarized beam so that $\beta = 0^\circ$. That is so that the spin axis is in the scattering plane. This results in a beam produced exactly as the experimental beam, but with the spin axis aligned along the beam axis. This should also show a zero effect for left-right asymmetry. A number of runs were taken with the beam in this configuration. Both normal spin reversal and rapid reversal data were taken.

Arm Angle Setting

Once the detector snout assemblies were installed and the optical shaft encoders were operational, a zero angle setting was obtained as follows. Using an alignment telescope zeroed on the beam collimator

slits, each snout was replaced by a brass plug which contained gold wire cross hairs. The cross hairs were 0.0008-in. diameter gold plated wire glued into "v" grooves machined into the brass plug. Each arm was positioned to 0° using the telescope and then the optical shaft encoder coupling was loosened. The optical shaft encoders were adjusted so that 0° corresponded to binary 8192, where the range is from 0 to 16384. Setting 0° at half scale, rather than zero, allowed continuous reading of the encoder output regardless of which side of zero the detector arm was on.

One final adjustment to the zero angles was then made using unpolarized nuclear scattering. Using an unpolarized beam, both pulse height (energy) and count rate measurements were taken for arm 0 and arm 2. These data were plotted vs encoder reading (see Fig. 18). Each arm was then positioned on the opposite side of zero and another angular distribution was taken. Since the absolute change in angle is known and only the absolute zero angle is in question, each plot for positive angles is superimposed on the one for negative angles. The difference between both the count rate curves and the peak channel curves gives two effective zero angles for each arm. The counting rate variation with angle is quite steep in this forward angle region, giving a good test of arm position. Kinematic changes due to angle show less variation, but still are useful for this test. The difference for arm 0 was +5 encoder steps or 1.9 mR (0.110°), and for arm 2 it was -19 encoder steps or 7.3 mR (0.417°). These two numbers were then used as offsets when arm angles were set.

Figure 18. Zero Angle Measurement Data

1 degree = 45.5111 encoder steps. The left plot are measurements for arm 0, the right plot for arm 2

Normal Spin Flip Electronics

One of our goals was to keep the system resolution as high as possible, as will be discussed shortly. For this reason, the first stage of the preamplifier was installed inside the Supercube main chamber (see Figs. 8 and 19). This reduces the distance from the silicon surface barrier detector to the preamplifier input and hence the capacitance of the interconnecting coaxial cable is kept low. The capacitance load on the input to the preamplifier is one of the major limits of the system's noise, and the smaller the capacitance the lower the noise of the electronics.

The bias high voltage for the detectors is supplied by a 24-channel high voltage supply built by the Electronics Division at LASL. Each of the 24 channels may be monitored for both voltage and current. The lowest current which can be measured by this system is 10 nA. Both detectors, when cooled by the thermoelectric coolers, had approximately 300 nA of current flowing through them. When the detectors are not cooled each will draw 3-5 μ A of current. This current is the major resolution limitation of the detector and therefore the lowest possible current is desired. By cooling the detectors, the resolution may be improved from ~ 80 keV to ~ 30 keV. This only marginally improves the resolution since at forward angles the overall system resolution is, including kinematic effects from the finite geometry employed, 140 keV. Coaxial cables connected the first stage preamplifier output through the vacuum coaxial feedthroughs to the final preamplifier stage located near the Supercube. The overall conversion gain of the detector preamplifier system is 200 mV/MeV.

Figure 19. Target-Detector Configuration
Detectors are shown at 15° scattering angle

Since the first stage of the preamplifier raises the detector signal level to several volts, the cable length between the first and final stage of the preamplifier is not of crucial importance. The preamplifier output signals are conducted over coaxial cables 76 m to the tandem control room. The bias high voltage supply and other electronics are also in the tandem control room.

To keep the signal level well below any amplifier saturation, 6 db of attenuation is inserted before the main amplifier input (see Fig. 20). The main amplifier is a Tennelec TC202 NIM module amplifier. The output from the amplifier is a direct (non-inverting) bipolar signal. The average amplifier signal was approximately 5 volts. These output signals are delayed 1.25 μ sec by a LASL designed and built model 8003 dual delay NIM module. This delay was needed since the logic signal to be generated must proceed the delayed analog signal (see Fig. 20). The analog signal also goes to a model 8071 low-level discriminating coincidence. The coincidence was disabled and the unit was used as a low-level discriminator using zero crossing timing. The discriminator setting was such that signals less than approximately 1 volt were rejected. This reduced the electronics dead time by rejecting a large number of low energy events. Each of the delayed analog signals were sent to separate analog-to-digital converters (ADC's). The output from each of the low-level discriminators were sent to a model 8028 dual "OR" gate. The output of the "OR" gate was sent to the ADC's linear gate inputs. Both ADC's were gated by a trigger from either discriminator and the gates were arranged so that no new event was accepted while either ADC was busy. This requirement was imposed to insure equal dead time in both the left and right channels.

Figure 20. Electronics Block Diagram

The ADC's digitized each input signal when a linear gate was present, unless an event was already being processed, or finished being processed but had not been accepted by the XDS 930 computer. In either of these two cases an output pulse was generated by the ADC to signify a valid event was lost. These lost events were counted by a scalar and later read by the computer. When the computer accepted a valid event from the ADC, another pulse was generated and was counted by a similar scalar. The dead time correction was calculated from the ratio of events lost to events accepted and was added to unity. If the dead times were not the same for each channel of the system, a different correction would be required for each channel. Dead time corrections were calculated, even though they were not used to correct the counts. This was done to monitor the dead time, which was kept under 20%. Higher dead times caused uncertainties in the electronics which are not fully understood.

Events which are accepted by the computer are displayed on a TV monitor as a spectrum of counts per channel vs signal magnitude (energy). The sum for each peak is kept by the computer and is available for later computation. The main proton peak was easily identified and a gate was set with the following criteria: The lower and upper end points should be approximately the same height, and the peak should include no other peaks or slope changes. This resulted in a rather tight gate on the peak and had the purpose of rejecting a maximum number of events which were not due to elastic proton-proton scattering.

A background was established using the computer program and TV monitor. This background, which could be set at any level under the peak, was used to estimate and subtract the background which was under the elastic peak but was not due to elastic events. The counts under

the background and between the upper and lower gate limits were subtracted from the main gate counts. These main gates and background gates were set for both left and right channels, and were changed for each new detector angle. Otherwise between spin states, Supercube rotations, or separate data runs with identical conditions, the gates were not changed. Figure 12 is a typical raw data spectrum for both the left and right detectors. Note that the ordinate scale is 6 cycle log and the abscissa is detected particle energy. The small high energy peak was due to protons scattered off of target gas contaminants. In all cases this peak was well enough resolved from the proton peak to reduce any contributed asymmetry to an insignificant level.

Background subtraction is important because, in general, the background has a larger asymmetry than the proton-proton elastic peak. Three sources were believed to contribute to the background: slit edge scattering, exit foil scattering, and electronics pile-up. Two methods were used to give an estimate of the magnitude of the background asymmetry. The counts subtracted as background for each detector arm and spin state could be combined as an asymmetry. This gave a result of ± 0.05 as a maximum value for the analyzing power. Another method was to set a gate on a section of the spectrum near the proton peak, but not including the peak. This method also resulted in ± 0.05 as a maximum value for the analyzing power.

During the early accelerator runs background subtractions ranged from 3-5%. When this background is subtracted from the elastic proton peak an 0.00250 effect results. If the background subtraction is accurate to 10%, then a possible 0.00025 error could be present. When the detectors were cooled, the circular target was used along with 1/2%

angular resolution slits and the single detectors rather than detector telescopes were used, the background subtractions fell to 0.2% at 20° and 0.8% at 11.5° . Using the same error in the background of 10%, the false asymmetry effect is reduced to 0.00004 as a maximum.

Rapid Reversal Electronics

Two changes were incorporated into the electronics to allow for the rapid spin reversal used in the rapid reversal method. One change involved the spin state labeling signal and the other was due to the addition of the polarimeter.

The latter change involved only the addition of a parallel electronic system identical to that used for the main detector arms. These signals were routed into 2 additional ADC's and displayed on the computer graphics display as 4 additional spectra.

The former change took two forms. The earlier method for informing the computer which spin state the beam was in for each event was to provide a spin state square wave to an input line of the computer. After each event was digitized, the computer checked the input line and labeled the event accordingly. A delay by the computer in accepting an event caused mislabeled events to be accepted. A new procedure was sought which would not mislabel events.

The computer has an input known as ADC 9 which, while not being an ADC, has some things in common with the other computer interface ADC's. Four signals may be accepted by ADC 9 to act as router bits when more than one detector is coupled to a single ADC. These four bits are accepted by the computer when the linear gate is sent to the ADC's. Since this signal is read when an event occurs rather than after it is

digitized, a delay is not possible. The spin state signal and the blocking signal were input to the ADC 9 in the final data runs. The blocking signal is still needed to block events which occur so close to the spin flip transition region that the spin state is not well known. This time was determined to be approximately 60 μ sec.

Polarized Ion Source

The polarized ion source is described in detail elsewhere.¹⁴ For rapid reversal new techniques are used which will be briefly described. A complete detailed account of rapid reversal has been given in a dissertation thesis by J. Potter.¹⁵

The precision solenoid region of the source is where the spin state of the hydrogen atom is selected (see Fig. 21). The spin of the hydrogen atom aligns with the $\vec{B}$ field of the solenoid. For normal operation, the solenoid field in the argon region was in the same direction as that of the spin filter (precision solenoid) region. For rapid reversal the field in the argon region was opposite in direction. If the transition between the two oppositely directed fields was smooth and monotonic, the spin of the hydrogen atom would have tended to follow the field and thus reverse direction. If the transition region was abrupt the spin was not able to follow the field and did not change direction. For each of these processes some, but not all, of the atoms would behave as desired. This accounts for the reduction of the beam polarization from that measured with the quench ratio and for the possibility that the polarization of both spin states might not have been equal.

A small transverse field (~ 2 Gauss) was used to change the

Figure 21. Polarized Ion Source
 Rapid reversal transition region is between spin filter and argon cell

transition region from smooth to abrupt. This coil, which was small, was able to change field directions at a frequency in excess of 1000 Hz.

Nominally, the beam in the transition region was neutral and was not affected by the magnetic fields. The argon region allows some argon gas to escape into the transition region and convert approximately 5% of the beam to H^- .¹⁶ This portion of the beam would have been affected by the changing fields of the spin reversing coil. Since the field was on for one spin state and off for the other, beam position changes correlated with spin state could have been possible. To counter any such effect the direction of the transition region magnetic field was reversed each time the field was applied. If an effect was produced from the transition magnetic field, it was in the opposing direction on alternate cycles and the false asymmetries produced should average out. To further reduce possible effects, an electric field was created to balance any forces produced by the magnetic field.

Since there were two directions possible for the spin filter magnetic field, the spin could have been either up or down when the transition field was applied. This option was used to further reduce the possible effects of beam position changes.

¹"The Basel Convention," Helv. Phys. Acta, Suppl. VI (1961).

²Ibid.

³Gerald G. Ohlsen, P. W. Keaton, Jr., "Techniques for Measurement of Spin-1/2 and Spin-1 Polarization Analyzing Tensors," Nucl. Instr. and Meth., 109 (1973), 43.

⁴Ibid.

⁵Yardley Beers, Introduction to the Theory of Errors, (2nd ed., Reading, Massachusetts: Addison-Wesley, 1957), p. 29.

- ⁶op. cit., 44-45.
- ⁷Gerald G. Ohlsen et al., "Precise Proton-Polarization Standards Determined with a Lamb-Shift Ion Source Incorporating a Nuclear Spin Filter," Phys. Rev. Letts., 27 (1971), 594-595.
- ⁸Ohlsen, op. cit., 599-600.
- ⁹Ohlsen, op. cit., 599-600.
- ¹⁰Ohlsen, op. cit., 601.
- ¹¹Ibid.
- ¹²Based on personal correspondence between Dr. Gerry Hale, Staff Member at the Los Alamos Scientific Laboratory, and the author, Spring 1975.
- ¹³Ohlsen, op. cit., 601.
- ¹⁴G. P. Lawrence, G. G. Ohlsen, J. L. McKibben, "Source of Polarized Negative Hydrogen and Deuterium Ions," Phys. Letts., 28B (1969).
- ¹⁵James Martin Potter, "A Test on Parity Conservation in Proton-Proton Scattering at 15 MeV," (unpublished Ph.D. dissertation, University of Illinois, 1975), pp. 19-20.
- ¹⁶Based on personal correspondence between Dr. Joseph L. McKibben, Staff Member at the Los Alamos Scientific Laboratory, and the author, March 1975.

Chapter IV

RESULTS

Proton-Proton Analyzing Powers

Three data runs at the tandem were used to obtain the reported data. The first run was from 2/22/75 to 3/1/75 and consisted of 160 hours. The second run lasted from 3/25/75 to 3/27/75 and was 64 hours long as was the third run from 3/31/75 to 4/4/75. The final data are listed in Table 3 and are plotted with the LRL-X¹ phase shift predictions in Fig. 22. The stated errors are counting statistics only, since the systematic and scale errors were small enough to ignore.

Data were taken in small time periods, approximately 30 minutes, to reduce the possibility that failure of the tandem, ion source, computer, or Supercube electronics would not result in large data loss. This larger number of runs also allowed statistical techniques to be used to test the combined data for systematic errors. Analyzing powers at four scattering angles were measured during one accelerator run only, 16°, 18°, 25°, and 35°, as is shown in Table 4. For measurements combined with the same statistical errors the combined error is taken as a single measurement error divided by the square root of the number of measurements.

The 20° measurement details are listed in Table 5. The data are combined using a weighted average for the average value and a weighted deviation for the error.

Tables 6 and 7 give the details for the 15° measurement along with the combined data.

Table 3
 $\vec{p}$ -p Analyzing Powers Summary

<u>Scattering Angle (Laboratory)</u>	<u>θ (c.m.)</u>	<u>Analyzing Power</u>
10°	20.08°	-0.0043±0.0004
11.5°	23.09°	-0.0041±0.0002
13°	26.11°	-0.0035±0.0003
15°	30.12°	-0.0027±0.0002
16°	32.14°	-0.0018±0.0007
18°	36.15°	-0.0007±0.0008
20°	40.66°	-0.0010±0.0003
25°	50.19°	+0.0000±0.0012
35°	70.23°	+0.0001±0.0007

Figure 22. $\vec{p}$ - p Analyzing Power Measurements at 16 MeV

Table 4

 $\vec{p}$ -p Analyzing Powers at 16° , 18° , 25° , and 35°

Scattering Angle	Supercube Position	Method	Results*
16°	0°	Normal [†]	-0.0027 ± 0.0014
16°	0°	Normal	-0.0005 ± 0.0014
16°	180°	Normal	-0.0020 ± 0.0014
16°	180°	Normal	-0.0020 ± 0.0014
		Average	$\bar{x} = -0.0018 \pm 0.0007$
18°	0°	Normal	$+0.0008 \pm 0.0015$
18°	0°	Normal	-0.0012 ± 0.0014
18°	0°	Normal	-0.0020 ± 0.0015
18°	0°	Normal	-0.0004 ± 0.0015
		Average	$\bar{x} = -0.0007 \pm 0.0007$
25°	0°	Normal	$+0.0011 \pm 0.0017$
25°	0°	Normal	-0.0010 ± 0.0017
		Average	$\bar{x} = +0.0000 \pm 0.0012$
35°	180°	Normal	-0.0018 ± 0.0010
35°	180°	Normal	$+0.0020 \pm 0.0010$
		Average	$\bar{x} = +0.00010 \pm 0.0007$

*All errors listed in this table and those to follow are counting statistics only.

[†]Normal refers to normal spin flip methods; see text.

Table 5

 $\vec{p}$ -p Analyzing Power at 20°

Scattering Angle	Supercube Position	Method	Results
20°	0°	Normal	-0.0017 ± 0.0011
20°	0°	Normal	-0.0035 ± 0.0011
20°	180°	Normal	-0.0006 ± 0.0011
20°	180°	Normal	-0.0028 ± 0.0011
		Average	$\bar{x} = -0.00216 \pm 0.00055$
20°	0°	Normal	-0.0008 ± 0.0010
20°	0°	Normal	$+0.0024 \pm 0.0010$
20°	180°	Normal	-0.0018 ± 0.0010
20°	180°	Normal	-0.0013 ± 0.0010
		Average	$\bar{x} = -0.00038 \pm 0.00050$
20°	0°	Normal	$+0.0015 \pm 0.0015$
20°	0°	Normal	-0.0025 ± 0.0015
20°	0°	Normal	$+0.0011 \pm 0.0016$
		Average	$\bar{x} = +0.00003 \pm 0.00087$
20°		Combined	-0.0010 ± 0.0003

Table 6

 $\vec{p}$ -p Analyzing Power at 15°

<u>Scattering Angle</u>	<u>Supercube Position</u>	<u>Method</u>	<u>Results</u>
15°	0°	Normal	-0.0017 ± 0.0009
15°	0°	Normal	-0.0040 ± 0.0009
15°	180°	Normal	-0.0016 ± 0.0009
15°	180°	Normal	-0.0044 ± 0.0009
		Average	$\bar{x} = -0.00293 \pm 0.00045$
15°	0°	Normal	-0.0048 ± 0.0010
15°	0°	Normal	-0.0027 ± 0.0009
15°	0°	Normal	-0.0010 ± 0.0009
15°	0°	Normal	-0.0030 ± 0.0010
15°	0°	Normal	-0.0011 ± 0.0010
15°	180°	Normal	-0.0033 ± 0.0010
15°	180°	Normal	-0.0034 ± 0.0010
15°	180°	Normal	-0.0024 ± 0.0010
15°	180°	Normal	-0.0021 ± 0.0010
15°	180°	Normal	-0.0027 ± 0.0010
		Average	$\bar{x} = -0.00265 \pm 0.00035$

Table 7

 $\vec{p}$ -p Analyzing Powers at 15°

Scattering Angle	Supercube Position	Method	Results*
15°	0°	Rapid Reversal	-0.0012 ± 0.0013
15°	0°	Rapid Reversal	-0.0001 ± 0.0013
15°	0°	Rapid Reversal	-0.0039 ± 0.0013
15°	0°	Rapid Reversal	-0.0022 ± 0.0013
15°	0°	Rapid Reversal	-0.0022 ± 0.0013
15°	0°	Rapid Reversal	-0.0015 ± 0.0013
		Average	$\bar{x} = +0.00185 \pm 0.00052$
112°	0°	Polarimeter	$+0.7899 \pm 0.0065$
112°	0°	Polarimeter	$+0.7909 \pm 0.0063$
112°	0°	Polarimeter	$+0.7821 \pm 0.0065$
112°	180°	Polarimeter	$+0.7975 \pm 0.0063$
112°	180°	Polarimeter	$+0.7980 \pm 0.0064$
112°	180°	Polarimeter	$+0.8001 \pm 0.0064$
		Average	$\bar{x} = +0.79308 \pm 0.00276$
15°		Calculated [†] A_y	-0.0023 ± 0.0065
15°		Combined [§]	-0.00268 ± 0.00024

*Rapid reversal-results column lists only the raw asymmetry; the polarimeter data must be used to convert this number into an analyzing power.

[†]See text for method.

[§]All 15° data.

For the rapid reversal data the beam polarization must be measured with a scattering experiment since the quench ratio method does not yield the proper results. A measurement of the asymmetry was made using the polarimeter filled with helium gas and the detectors at 112° scattering angle. When this is combined with the known value for the analyzing power of $\vec{p}\text{-}^4\text{He}$ at 112° and 16 MeV, the beam polarization can be found. Using a value for A_y ($\vec{p}\text{-}^4\text{He}$ at 112° and 16 MeV) of 0.9936 ± 0.0040 , the beam polarization becomes 0.798. The error is calculated using standard error calculations giving

$$\Delta p = \frac{1}{A_y} \sqrt{(\Delta \epsilon)^2 + \left(\frac{\epsilon \Delta A_y}{A_y} \right)^2}. \quad (36)$$

Using the data above and from Table 7 gives an error in the polarization of $\Delta p = 0.0043$. This is then combined with the asymmetry to produce an analyzing power of $A_y(15^\circ) = -0.0023$. The error is found by using Eq. (14) which yields $\Delta A_y(15^\circ) = 0.0065$. The 13° scattering angle consisted of two data sets which are shown in Table 8. The two data sets were combined in the 13° scattering angle.

Four data sets were combined for the 11.5° scattering angle and are shown in Tables 9 and 10. The rapid reversal set was measured before the 10° asymmetric angle measurement; therefore, the 11.5° beam polarization calibration measurements comparing the quench ratio and the polarimeter are used for the 10° measurement. The ratio of the quench ratio to the polarimeter measurement of the beam polarization is 0.8034. This is the number the quench ratio value of the beam polarization should be multiplied by to give the correct beam polarization value.

Table 8

 $\vec{p}$ -p Analyzing Power at 13°

Scattering Angle*	Supercube Position	Method	Results
13°	180°	Normal	-0.0047 ± 0.0008
13°	180°	Normal	-0.0031 ± 0.0008
13°	180°	Normal	-0.0016 ± 0.0008
13°	180°	Normal	-0.0037 ± 0.0008
13°	180°	Normal	-0.0026 ± 0.0008
13°	180°	Normal	-0.0026 ± 0.0008
		Average	$\bar{x} = -0.00298 \pm 0.00045$
13°	180°	Normal	-0.0043 ± 0.0013
13°	180°	Normal	-0.0049 ± 0.0013
13°	180°	Normal	-0.0052 ± 0.0012
13°	180°	Normal	-0.0028 ± 0.0009
		Average	$\bar{x} = -0.00430 \pm 0.00053$
13°		Combined	$\bar{x} = -0.00353 \pm 0.00034$

*After the data set was completed it was discovered that the arms were at arm 0 = 12.5° , arm 2 = 13.5° . The error on this set was arbitrarily increased by 0.0002.

Table 9

 $\vec{p}$ -p Analyzing Power at 11.5°

Scattering Angle	Supercube Position	Method	Results*
11.5°	180°	Normal	-0.0054 ± 0.0006
11.5°	180°	Normal	-0.0022 ± 0.0006
11.5°	0°	Normal	-0.0020 ± 0.0006
11.5°	0°	Normal	-0.0070 ± 0.0006
		Average	$\bar{x} = -0.0042 \pm 0.0003$
11.5°	0°	Normal	-0.0034 ± 0.0011
11.5°	0°	Normal	-0.0025 ± 0.0011
11.5°	180°	Normal	-0.0050 ± 0.0011
11.5°	180°	Normal	-0.0042 ± 0.0011
		Average	$\bar{x} = -0.0038 \pm 0.0005$
11.5°	180°	Rapid Reversal	-0.0027 ± 0.0009
11.5°	180°	Rapid Reversal	-0.0031 ± 0.0009
11.5°	180°	Rapid Reversal	-0.0038 ± 0.0009
11.5°	0°	Rapid Reversal	-0.0027 ± 0.0009
11.5°	0°	Rapid Reversal	-0.0026 ± 0.0009
11.5°	0°	Rapid Reversal	-0.0027 ± 0.0009
11.5°	180°	Rapid Reversal	-0.0028 ± 0.0009
11.5°	0°	Rapid Reversal	-0.0034 ± 0.0009
		Average	$\bar{x} = -0.0030 \pm 0.0003$

*Rapid reversal data are raw asymmetries.

Table 10

 $\vec{p}$ -p Analyzing Power at 11.5°

Scattering Angle	Supercube Position	Method	Results
11.5°	180°	Rapid Reversal	-0.0027 ± 0.0009
11.5°	180°	Rapid Reversal	-0.0031 ± 0.0009
11.5°	180°	Rapid Reversal	-0.0038 ± 0.0009
11.5°	180°	Rapid Reversal	-0.0027 ± 0.0009
11.5°	180°	Rapid Reversal	-0.0026 ± 0.0009
11.5°	180°	Rapid Reversal	-0.0027 ± 0.0009
11.5°	0°	Rapid Reversal	-0.0028 ± 0.0009
11.5°	0°	Rapid Reversal	-0.0034 ± 0.0009
		Average	$\bar{x} = -0.00298 \pm 0.00032$
112°	180°	Polarimeter	$+0.8098 \pm 0.0060$
112°	180°	Polarimeter	$+0.8031 \pm 0.0062$
112°	180°	Polarimeter	$+0.7873 \pm 0.0057$
112°	0°	Polarimeter	$+0.7995 \pm 0.0061$
112°	0°	Polarimeter	$+0.7988 \pm 0.0061$
112°	0°	Polarimeter	$+0.8017 \pm 0.0059$
112°	180°	Polarimeter	$+0.7832 \pm 0.0061$
112°	0°	Polarimeter	$+0.8008 \pm 0.0060$
112°	Average		$\bar{x} = +0.79803 \pm 0.00213$
11.5°	Calculated A_y		-0.0037 ± 0.0004
11.5°	180°	Rapid Reversal	-0.0028 ± 0.0014
11.5°	180°	Rapid Reversal	-0.0033 ± 0.0014
11.5°	180°	Rapid Reversal	-0.0039 ± 0.0014
11.5°	180°	Rapid Reversal	-0.0038 ± 0.0014
11.5°	180°	Rapid Reversal	-0.0032 ± 0.0014
11.5°	0°	Rapid Reversal	-0.0039 ± 0.0014
11.5°	0°	Rapid Reversal	-0.0050 ± 0.0014
11.5°	0°	Rapid Reversal	-0.0038 ± 0.0013
11.5°	0°	Rapid Reversal	-0.0052 ± 0.0013
11.5°	0°	Rapid Reversal	$+0.0004 \pm 0.0013$
11.5°	180°	Rapid Reversal	-0.0026 ± 0.0015
11.5°	180°	Rapid Reversal	-0.0039 ± 0.0014
11.5°	180°	Rapid Reversal	-0.0005 ± 0.0015
11.5°	180°	Rapid Reversal	-0.0040 ± 0.0014
11.5°	180°	Rapid Reversal	-0.0041 ± 0.0015
11.5°	0°	Rapid Reversal	-0.0048 ± 0.0014
11.5°	0°	Rapid Reversal	-0.0044 ± 0.0014
11.5°	0°	Rapid Reversal	-0.0012 ± 0.0014
11.5°	Average		$\bar{x} = -0.00333 \pm 0.00036$

Table 10 (cont.)

Scattering Angle	Supercube Position	Method	Results
112°	180°	Polarimeter	+0.6925±0.0095
112°	180°	Polarimeter	+0.6913±0.0095
112°	180°	Polarimeter	+0.6879±0.0094
112°	180°	Polarimeter	+0.6883±0.0096
112°	180°	Polarimeter	+0.6891±0.0097
112°	0°	Polarimeter	+0.6746±0.0095
112°	0°	Polarimeter	+0.6845±0.0097
112°	0°	Polarimeter	+0.6800±0.0091
112°	0°	Polarimeter	+0.7175±0.0090
112°	0°	Polarimeter	+0.6936±0.0090
112°	180°	Polarimeter	+0.6981±0.0094
112°	180°	Polarimeter	+0.6974±0.0092
112°	180°	Polarimeter	+0.6960±0.0092
112°	180°	Polarimeter	+0.7047±0.0091
112°	180°	Polarimeter	+0.7155±0.0089
112°	0°	Polarimeter	+0.7221±0.0089
112°	0°	Polarimeter	+0.7279±0.0094
112°	0°	Polarimeter	+0.7098±0.0091
112°		Average	$\bar{x}=+0.69838\pm0.00219$
11.5°		Calculated A_y	-0.00474±0.00052

Quench Ratio Measurements

0.8756	0.8757	0.8692	0.8727
0.8746	0.8748	0.8733	0.8736
0.8749	0.8794	0.8731	0.8723
0.8768	0.8781	0.8721	0.8740
0.8808	0.8789	0.8720	0.8714
0.8719	0.8743	0.8733	0.8719
0.8760	0.8783	0.8698	0.8717
0.8849	0.8892	0.8736	0.8731
0.8735	0.8744	0.8728	0.8742
Average			$\bar{x}=+0.87489\pm0.00398$

The final analyzing power which was measured was 10° . This measurement was made using the asymmetric arm technique described in Chap. III. Table 11 gives the data taken for these runs. A computer code was used to reduce the raw counts to a final analyzing power and error.

Previously Published Results

Preliminary results of this experiment were presented at the Anaheim meeting of the American Physical Society.² Four of the seven data points (15° , 17° , 20° , 25°) presented are in very good agreement with the data reported here. The remaining three points (10° , 11.5° , 13°) show an effect which is much too large. Subsequent re-examination of the data showed that the three points in question were taken together during a period of very unstable beam operation. This unstable operation was later concluded to be due to the ion source filament since it burned out during the 10° measurement. The unstable beam operation did not return when a new filament was installed and the source was restarted. Only four measurements were involved in these three data points under question and a strong reason exists to remove them from the data set.

Since many measurements in later runs were self-consistent but in disagreement with the points in question and since the points in question were taken under very unstable operation, the data from the earlier accelerator run were removed from the data set.

Previous and Current Data

Before the development of polarized beams, analyzing powers could only be measured by double scattering experiments. The unpolarized beam was scattered off a target which had a high polarization power

Table 11

$\vec{p}$ -p Raw Data for Asymmetric Arm Measurements of A_y at 10°

	Sequence Number	Raw Data		
		Run 1	Run 2	Run 3
	1	170308	210010	823444
	2	154708	153470	1024281
	3	205567	199934	917893
	4	181857	169895	987428
	5	96526	100595	508811
	6	77512	85156	438967
	7	106980	103961	456590
	8	89670	98778	426485
	9	160150	166077	945650
	10	127195	140780	796363
	11	175497	170647	837347
	12	148749	165446	782579
	13	85072	105847	464099
	14	77137	76304	569895
	15	101967	99754	510741
	16	91917	85707	557091
		Run 1	Run 2	Run 3
Supercube 0°		-0.0027 ± 0.0014	-0.0020 ± 0.0014	-0.0047 ± 0.0007
Arm 0 15° Arm 2 10°	}	-0.0033 ± 0.0014	-0.0045 ± 0.0014	-0.0049 ± 0.0007
Arm 0 10° Arm 2 15°	}	-0.0038 ± 0.0015	-0.0028 ± 0.0014	-0.0043 ± 0.0007
Supercube 180°		-0.0044 ± 0.0015	-0.0053 ± 0.0015	-0.0045 ± 0.0007
		$\bar{x} = -0.0035 \pm 0.0010$	$\bar{x} = -0.0036 \pm 0.0010$	$\bar{x} = -0.0046 \pm 0.0005$
Combined Data A_y			$\bar{x} = -0.0043 \pm 0.0004$	

at some scattering angle. The scattered beam at that angle was collimated and used as the polarized beam for the measurement to be performed. The beam currents which were available for these polarized beam experiments were much less than 1 pA, and many times near 0.10 pA.

With this restriction on beam current most of the early (pre-1967) measurements were very low accuracy.^{3,4} One double scattering experiment by R. J. Slobodrian, et al., in 1967, claimed 20 to 30 parts in 10^4 error and measured A_y at five angles.⁵ The experiment was done at three energies; the middle energy was 15.6 MeV, very near the present work. Soon after Slobodrian's work was published, M. H. MacGregor, et al., attempted to incorporate the data into their newly completed p-p phase shift set.⁶ They found that the data were inconsistent with other (p-p) data at nearby energies.⁷ To resolve the contradiction P. Catillon, et al., in Saclay, performed the experiment at 20.2 MeV with accuracies from 30 to 6 parts in 10^4 and measurements at eight angles.⁸ This data set was consistent with the phase shift analyses at 20 MeV, and contradicted Slobodrian's data.

Until recently no major improvements were made to the data since the Saclay measurements. J. D. Hutton, et al., at Madison, have recently made a series of measurements at 10 MeV.⁹ The LRL-X phase shift set predicts a value of -0.0026 for 10° and the Madison group found the value to be -0.0019 ± 0.0002 . While this value is 3.5 standard deviations too small, the gradual increase of A_y with decreasing angle has the correct sign and form. These data have not as yet been formally published and are considered to be preliminary by the authors.

Systematic Error Evaluations

Two main checks were made on the systematic errors which might be present. The first check was on the accuracy with which a zero asymmetry measurement could be made.

An unpolarized beam produces no left-right asymmetry. The best unpolarized beam which can be produced by the polarized ion source is produced by turning off the source fields and extracting a direct negative beam. This 4- μ A beam is reduced in magnitude by defocussing the source output. During two different accelerator runs data were taken using this unpolarized beam. Table 12 lists the results for both these runs. The combined result was -0.00060 ± 0.00017 .

Another method for checking zero for a zero asymmetry is to place the spin axis along the beam axis or $\beta = 0^\circ$. This was done for four sets of measurements, the results for which are shown in Table 13. The combined results for all asymmetry measurements with $\beta = 0^\circ$ was -0.00016 ± 0.00020 .

One powerful check on the results was to check the internal errors against the external errors. S_{x_I} , the internal standard deviation, is defined as a single measurement error. This may include counting statistics, scale errors, and systematic errors. $S_{\bar{x}_I}$, the internal standard error, is defined as S_{x_I} divided by the square root of the number of measurements. S_{x_E} , the external standard deviation, is defined as

$$S_{x_E} = \sqrt{\frac{\sum_n (\bar{x} - x_n)^2}{n-1}}, \quad (38)$$

and $S_{\bar{x}_E}$, the external standard error, is defined as

Table 12

Zero Asymmetry Measurements, Unpolarized Beam

Method	Supercube Position	Results
Normal-Unpolarized	0°	+0.0010±0.0008
Normal-Unpolarized	0°	+0.0001±0.0008
Normal-Unpolarized	0°	-0.0011±0.0008
Normal-Unpolarized	0°	-0.0012±0.0008
Normal-Unpolarized	0°	-0.0005±0.0007
Normal-Unpolarized	0°	-0.0008±0.0007
Normal-Unpolarized	0°	-0.0018±0.0008
Normal-Unpolarized	0°	-0.0011±0.0006
Normal-Unpolarized	0°	+0.0005±0.0006
Normal-Unpolarized	0°	+0.0003±0.0006
Normal-Unpolarized	0°	-0.0003±0.0008
Average		$\bar{x} = -0.00040 \pm 0.00022$
Normal-Unpolarized	180°	-0.0029±0.0008
Normal-Unpolarized	180°	-0.0037±0.0008
Normal-Unpolarized	180°	-0.0027±0.0008
Normal-Unpolarized	0°	+0.0001±0.0007
Normal-Unpolarized	0°	+0.0007±0.0007
Normal-Unpolarized	0°	-0.0014±0.0008
Normal-Unpolarized	180°	-0.0008±0.0007
Average		$\bar{x} = -0.00134 \pm 0.00028$
Normal-Unpolarized	180°	+0.0022±0.0012
Normal-Unpolarized	180°	+0.0007±0.0012
Normal-Unpolarized	180°	+0.0017±0.0012
Normal-Unpolarized	180°	+0.0008±0.0012
Average		$\bar{x} = +0.00135 \pm 0.00060$
Combined		-0.00060±0.00017

Table 13

Zero Asymmetry Measurements $\beta = 0^\circ$

Method	Supercube Position	Results
Normal	0°	-0.0001 ± 0.0013
Normal	0°	-0.0027 ± 0.0013
Normal	0°	-0.0021 ± 0.0013
Normal	0°	-0.0009 ± 0.0013
Normal	0°	$+0.0009 \pm 0.0014$
Normal	180°	-0.0009 ± 0.0013
Normal	180°	-0.0013 ± 0.0013
Normal	180°	-0.0005 ± 0.0013
Normal	180°	$+0.0004 \pm 0.0013$
Normal	180°	-0.0001 ± 0.0012
Average		$\bar{x} = -0.00073 \pm 0.00041$
Rapid Reversal*	0°	$+0.0009 \pm 0.0014$
Rapid Reversal*	0°	$+0.0023 \pm 0.0014$
Rapid Reversal*	0°	$+0.0002 \pm 0.0014$
Rapid Reversal*	0°	$+0.0005 \pm 0.0014$
Rapid Reversal*	0°	$+0.0010 \pm 0.0014$
Rapid Reversal*	180°	-0.0013 ± 0.0014
Rapid Reversal*	180°	-0.0010 ± 0.0014
Rapid Reversal*	180°	$+0.0001 \pm 0.0014$
Rapid Reversal*	180°	-0.0012 ± 0.0014
Rapid Reversal*	180°	-0.0001 ± 0.0014
Rapid Reversal†	0°	$+0.0017 \pm 0.0014$
Rapid Reversal†	0°	$+0.0018 \pm 0.0014$
Rapid Reversal†	0°	-0.0003 ± 0.0014
Rapid Reversal†	0°	$+0.0001 \pm 0.0014$
Rapid Reversal†	0°	$+0.0000 \pm 0.0014$
Rapid Reversal†	180°	-0.0006 ± 0.0015
Rapid Reversal†	180°	-0.0030 ± 0.0014
Rapid Reversal†	180°	$+0.0012 \pm 0.0015$
Rapid Reversal†	180°	$+0.0003 \pm 0.0014$
Rapid Reversal†	180°	$+0.0030 \pm 0.0014$
Average		$\bar{x} = +0.00028 \pm 0.00032$
Combined		$\bar{x} = -0.0001 \pm 0.0003$
Normal	180°	-0.0007 ± 0.0008
Normal	180°	-0.0012 ± 0.0008
Normal	180°	$+0.0005 \pm 0.0008$
Normal	180°	-0.0001 ± 0.0008
Normal	0°	$+0.0003 \pm 0.0008$
Average		$\bar{x} = -0.00038 \pm 0.00036$

Table 13 (cont.)

<u>Method</u>	<u>Supercube Position</u>	<u>Results</u>
Normal	180°	-0.0006±0.0015
Normal	180°	+0.0019±0.0014
Normal	0°	-0.0001±0.0014
Average		$\bar{x}=+0.00044\pm0.00083$
Combined		$\bar{x}=-0.00016\pm0.00020$

*Rapid Reversal spin up when spin state signal present.

†Rapid Reversal spin down when spin state signal present.

$$S_{\bar{x}_E} = \frac{S_{x_E}}{\sqrt{n}} \quad .16 \quad (39)$$

Table 14 summarizes the zero asymmetry measurements giving the external and internal errors. Data with no systematic errors and enough measurements to provide statistical significance should show the internal and external errors in agreement. A study of Table 14 indicates a remarkably good agreement between internal and external errors with the exception of two measurements. Such good agreement gives validity to these data and the analyzing power measurements as well.

The combined result for all zero analyzing power measurements was -0.00040 ± 0.00013 . The question now arises as to what should be done with the negative 4 parts in 10^4 effect. If the above number is believed to be a true false asymmetry, then all the data should be reduced by -0.0004 and the error quadratically increased by 0.00013 . If a null result is expected and the above number is measured, then a possible explanation is that the measurement is a statistical fluctuation. The measurement is three standard deviations from a zero measurement and therefore it is unlikely to be a statistical artifact.

Another factor which must be considered is that two types of data were combined, zero polarized beam and $\beta = 0^\circ$. The latter measurements have more conditions similar to the actual beam used to acquire data. The zero polarization beam has different beam qualities from the $\beta = 0^\circ$ beam. The much larger beam current must be reduced by defocussing the beam, thus changing the beam optics. Source parameters which change

Table 14

Zero Asymmetry Measurements, Statistical Summary

Number of Meas- urements	$\bar{x}$	External		Internal		Comments
		S_x	$S_{\bar{x}}$	S_x	$S_{\bar{x}}$	
11	-0.00040	0.00085	0.00026	0.00073	0.00022	Unpolarized
7	-0.00134	0.00164	0.00062	0.00076	0.00029	Unpolarized
4	+0.00135	0.00072	0.00036	0.0012	0.0006	Unpolarized
10	-0.00073	0.00110	0.00035	0.00130	0.00041	$\beta=0^\circ$ Normal
20	+0.00028	0.00138	0.00031	0.00141	0.00032	$\beta=0^\circ$ Rapid Reversal
5	-0.00038	0.00074	0.00037	0.0008	0.00036	$\beta=0^\circ$ Normal
3	+0.00044	0.00132	0.00076	0.00143	0.00083	$\beta=0^\circ$ Normal
Overall Average		-0.00040 ± 0.00013				

with spin direction have no meaning when an unpolarized beam is used; therefore any beam changes correlated with spin state will not be present.

A choice must then be made as to whether to combine the two data sets or not. The author chose to use only the $\beta = 0^\circ$ measurements. These data were taken under conditions most representative of the actual data acquisition conditions. The large effect in the unpolarized beam data is due to three consecutive measurements with unstable beam operation. In two of the three unpolarized beam sets the internal and external errors do not agree. These two sets of data are the ones contributing the large negative effect.

Using the $\beta = 0^\circ$ measurements, no corrections have been made to the final data. The author chose to leave the final data errors stated with counting statistics only. The reader may choose to correct for the possible false asymmetry, as all the data are presented. If the false asymmetry were to be used as a non-null result, the correction would reduce the data by -0.00016 . The error in the polarization would add ± 0.00002 to the analyzing power errors.

The other check on systematic errors was to measure analyzing powers for a scattering system where the analyzing powers are large. $\vec{p}\text{-}^4\text{He}$ was chosen since it is convenient and the phase shift predictions were available. The purpose of this check was to show that when an effect was present, the Supercube was capable of making an accurate measurement of that effect. Figure 23 shows the results and Table 15 lists them and their errors. No error bars are shown in the figure since the errors are the same size as the data points plotted. It is interesting to note that the measured values are from -4.75 to 11.5 standard deviations from the predicted value. The only measurement which is below the predicted

Figure 23. $\vec{p}$ - ^4He Analyzing Power Measurements at 16 MeV
The phase shift predictions are from Gerry Hale, LASL

Table 15
 $\vec{p}$ - ^4He Analyzing Powers

θ_{lab}	$\theta_{\text{c.m.}}$	A_y	Predictions
10°	12.54°	-0.0167 ± 0.0004	-0.0148
11.5°	14.42°	-0.0290 ± 0.0005	-0.0323
15°	18.79°	-0.0623 ± 0.0007	-0.0704
20°	25.00°	-0.1120 ± 0.0004	-0.1152
25°	31.19°	-0.1532 ± 0.0005	-0.1564

value is the one at 10° scattering angle. The measurement at 10° is correlated with the measurement at 15° , and the measurement at 15° shows the largest disagreement with the prediction. This disagreement cannot be resolved without further measurements. It is hoped that these measurements will stir interest in improving the phase shift solutions in this angular region.

One further $\vec{p}$ - ^4He analyzing power measurement was made at 112° . The predicted value is $+0.9911$ and the measured value was 0.9936 ± 0.0040 . This value is used throughout the reported data to normalize the polarized beam measurements made in the polarimeter.

¹Malcolm H. MacGregor, Richard A. ARndt, Robert M. Wright, "Determination of the Nucleon-Nucleon Scattering Matrix. X. (p,p) and (n,p) Analysis from 1 to 450 MeV," Phys. Rev., 182 (1969), 1714-1728.

²P. A. Lovoi et al., " $\vec{p}$ -p Asymmetry Measurements at 16.000 MeV," Bull. Am. Phys. Soc. , 20(1975), 85.

³Karl W. Brockman, Jr., "Proton Polarization Measurements near 18 MeV," Phys. Rev., 110 (1958).

⁴William A. Blanpied, "Proton-Proton Polarization at 16 MeV," Phys. Rev., 116 (1959), 738-740.

⁵R. J. Slobodrian et al., "High-Precision Measurements of Proton-Proton Polarization Between 10 and 20 MeV," Phys. Rev. Letts., 12 (1967), 704-705.

⁶MacGregor, loc. cit.

⁷Ibid.

⁸P. Catillon, J. Sura, A. Tarrats, "Measurement of Proton-Proton Polarization at 20 MeV," Phys. Rev. Letts., 20 (1968), 602-603.

⁹Based on personal correspondence between Dr. Dave Hutton, University of Wisconsin-Madison, 21 April 1975.

Chapter V

CONCLUSIONS

The Supercube scattering chamber was constructed and brought up to operating condition. $\vec{p}$ -p and $\vec{p}$ - ^4He data were acquired using this chamber and the data appear to be of the accuracy and quality that was expected. The systematic errors seem to all be much less than 0.001 but more work is foreseen to put an accurate lower limit on them.

A new polarized beam method, rapid spin reversal, was tried and found to work, but the uncertainties with which it is still plagued seem to need much more systematic understanding. The method proved to yield data with low systematic uncertainties, but required more attention during the data acquisition and data reduction phases. The major conclusion concerning rapid reversal was that it was not needed to complete the present experiment.

The $\vec{p}$ - ^4He data showed the Supercube's abilities to measure large analyzing powers, but the large disagreement with the prediction has opened the door to a new experiment. It is hoped to repeat and extend these measurements in the near future.

The final data fit the available phase shift predictions and thus verified the present proton-proton phase shift solutions. The original goal to check accurately for significant errors in the phase shift predictions was accomplished.

ACKNOWLEDGMENTS

I wish to dedicate this thesis to Jerry Ohlsen without whom the Supercube would still be a dream. Bill Jarmie was an immense help to me with this experiment, physics in general, and with the many other aspects of graduate student life. Dave Stupin and Calvin Moss as well as Bill and Jerry spent many sleepless nights and long weekends watching over the data runs at the Tandem Van de Graaff. I wish to thank Joe McKibben for keeping the polarized ion source going, sometimes late at night or well into a weekend. The rapid reversal was made possible by many hours of work by Joe and many others from LAMPF.

My Physics Department advisors, Howard Bryant and Chris Leavitt, have given their support and encouragement to me through several unusual events. This support has carried me through many ups and downs for which I am most grateful.

Gerry Hale provided the $\vec{p}$ - ^4He phase shift predictions used in Fig. 23.

I wish to thank Associated Western Universities, Inc., for fellowship aid during my work at Los Alamos.

Ben Roybal, the P-9 draftsman, produced many new and innovative designs for the Supercube and drew dozens of blueprints for the chambers, detectors, slits and targets that collectively are known as the Supercube. Louie Morrison spent many months assembling, testing, wiring, and rebuilding the many subsystems of the Supercube. His patience with our requests and skills in mechanical assemblies were greatly appreciated.

The electronics division at LASL designed most of the electronics for the Supercube, but two persons deserve mention for their friendship

and support through some fairly heavy electronics messes. Dick Hiebert designed the 24-channel high voltage bias supply and the vacuum preamplifiers besides most of the LASL standard NIM modules. Art Greenwood designed the arm encoder and stepping motor controller including the interface to the computer, a project which grew beyond anyones wildest imagination.

To express thanks to each person at P-9 who in one way or another contributed to the Supercube or the experiment would fill pages, but thanks go to each of them.

Finally, but in no way least, my humble thanks to Judy Elder who typed this dissertation. If she is not one of the best secretaries in the world she is surely one of the nicest.

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APPENDIX

A BRIEF HISTORY OF THE SUPERCUBE

The new cube scattering chamber was conceived of in 1971 by Dr. G. Ohlsen. It was an outgrowth of an existing "cube" chamber. The early cube's limitations were becoming apparent in many ways and the major experiments to which the cube lent itself had been completed. The author oversaw the design, construction, and implementation of the Supercube.

The new cube was to have more precise and larger geometry, cooled detectors, remote drive and readout of the arm position, a polarimeter, and a better Faraday cup. With all this increase in size and complexity the new cube was dubbed "Supercube." Design work began in the fall of 1971 by Dr. Ohlsen and Ben Roybal, a P-9 draftsman. It soon became apparent that Ben would be unable to handle the amount and complexity of the work that needed to be done. This job needed a full-time engineer and Ben had many other duties. The job was then given to Bob Griffiths in SD-2 in August of 1971. The design was completed and detailed prints were finished, but the local shop did not wish to handle the job. This required the job to be bid outside the laboratory. Square Tool Company in South El Monte, California, was the low bidder for the construction job.

Construction on other parts of the Supercube system were progressing in parallel with the construction by Square Tool. The Faraday cup and polarimeter were designed by Ben Roybal, and the drive and support system was designed by Frank Newcom of P-2. Both of these items were built by LASL shops.

The Supercube arrived in September of 1972, and the assembly was soon underway. In February of 1973, the Supercube, stand and polarimeter were installed on the L2 beam line at the tandem Van de Graaff. Work was then begun on beam line and beam tube assembly by Louie Morrison, P-DOR.

Drawings of the detector arms, and the thermoelectric cooler support, antiscatter slit snouts, target support and targets were begun by Ben Roybal. These were constructed by the LASL shops. This completed the major mechanical design of the Supercube.