A POLARIZED $^3\text{He}$ ION SOURCE:
MEASURING THE POLARIZATION

by

David O. Findley

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF ARTS

Thesis Director's signature:

Stephen D. Baker

Houston, Texas

May 1967
ABSTRACT

A Polarized $^3$He Ion Source: Measuring the Polarization
by
David O. Findley

An ion source has been assembled at Rice University which uses the principle of optical pumping to produce polarized $^3$He$^+$ ions for extraction and acceleration. The design of an experiment to measure the degree of polarization of the ions is described. $^3$He$^+$ ions are accelerated to an energy of approximately 300 keV and produce protons through the $^2$H($^3$He,p)$^4$He reaction on striking a deuterated target. The polarization of the outgoing protons, measured through the left-right asymmetry of their elastic scattering in a helium-filled polarimeter, provides the information necessary to deduce the nuclear spin polarization of the $^3$He ions. The polarimeter and its associated equipment are described. The results of tests of the polarimeter system with alpha particles and with unpolarized protons are given.
# TABLE OF CONTENTS

## I. INTRODUCTION
A. Polarized Ion Sources
B. The Rice University $^3$He Polarized Ion Source

## II. MEASURING $^3$He BEAM POLARIZATION
A. General Considerations
B. Considerations for $^3$He Beam Polarization Determination
C. Polarimeters for Polarized Protons

## III. EXPERIMENTAL APPARATUS
A. Acceleration System
B. Deuterium Targets
C. The Polarimeter
D. Detectors
E. Electronics

## IV. TESTS OF DETECTORS
A. Tests of Polarimeter Detectors A and B with 5.5 MeV Alpha Particles
B. Tests of Polarimeter Detectors A and B with 6 MeV Protons

## V. PROPOSED TREATMENT OF DATA

## VI. APPENDICES
A. A 200 Watt, 100 MHz R.F. Exciter and Optical Pumping Lamp
B. Relationship of Left-Right Scattering Asymmetry to Beam Polarization and Reaction Analyzing Power
C. Polarization of Protons from the Reaction $^2\text{H}(^3\text{He},p)^4\text{He}$

D. Proton Yield of a Deuterium Target Stopping $^3\text{He}^+$ Ions of Energy $\leq 300$ keV

E. Calculation of Analyzing Power and Scattering Efficiency of the Polarimeter

REFERENCES AND NOTES

ACKNOWLEDGMENTS
I. INTRODUCTION

A. Polarized Ion Sources

1. Usefulness of Oriented Nuclei

Since nuclear forces have been shown to be spin dependent\(^1\), it is a definite advantage for the experimenter studying these forces to be able to prepare the initial nuclear spin state of the incident particle or the target nucleus, or both if possible. By the use of oriented nuclei, he avoids averaging over the various initial states permitted in the unoriented experiment and limits his study to one initial state or, at least, to fewer initial states. As a result, data extracted from experiments using oriented nuclei often yield information about a nuclear interaction which is not obtainable from experiments with unoriented nuclei.

Wolfenstein\(^2\), Simon\(^3\), and Schumacher and Bethe\(^4\) have discussed "complete" experiments made possible only by the use of oriented nuclei. In addition to the rather complicated complete experiments, experiments with interactions which have been previously studied with unoriented nuclei are being repeated as polarized beams and targets become available. An important application of polarized beams and targets is the verification of certain conservation laws\(^5\); or, in turn, conservation laws can be used to derive valuable information from very simple experiments with oriented nuclei\(^6\).

2. Definition of Vector Polarization

Before going on to describe polarized ion sources, we define a parameter to specify the orientation of a
nuclear spin system, particularly that of spin 1/2 particles, such as protons and \(^{3}\)He nuclei, which we will be encountering in this thesis.

For spin 1/2 particles one parameter, vector polarization, is sufficient to describe the orientation of the nuclear spins\(^7\).

If a space axis of quantization is defined by a non-vanishing magnetic field, a nucleus of spin \(I\) and a magnetic moment \(\mu_n I\) (where \(g\) is the gyromagnetic ratio and \(\mu_n\), the nuclear magneton) exists only in one of the \(2I + 1\) magnetic levels, which are non-degenerate due to the Zeeman splitting (in this discussion we are ignoring coupling of the nuclear spin to other momenta of an atomic system). These levels are labeled by the projection \(m_I\) of \(I\) on the axis, where \(m_I\) is restricted to the \(2I + 1\) integral values (half-integral if \(I\) is half-integral) which satisfy the relation \(|m_I| \leq I\). The vector polarization, \(P\), is a measure of the anisotropy of the populations of the magnetic sublevels; it is defined by\(^7\):

\[
P = \frac{\sum_m m I a_m}{\sum_m a_m}
\]

where \(a_m\) is the population of the \(m\)th sublevel. For spin 1/2 particles equation (1) can be stated equivalently,

\[
P = \frac{N_{\text{up}} - N_{\text{down}}}{N_{\text{up}} + N_{\text{down}}}
\]

where \(N_{\text{up}}\) is the number of nuclei in the system with spin up \((m_I = + 1/2)\), i.e. spin directed parallel to the applied magnetic field, and \(N_{\text{down}}\) the number with spin down \((m_I = - 1/2)\).
For nuclei with spin greater than 1/2, parameters other than polarization are required to give a complete description of the orientation.  

3. Producing Polarized Ions

The first sources of polarized nuclear projectiles for nuclear physics experiments were those special cases of nuclear scattering and nuclear reactions in which a scattered or product nucleus is polarized by the mechanisms of the interaction. For example, protons elastically scattered from $^4$He or from $^{12}$C attain polarizations of nearly 100% at certain energies and angles and have been used in double-scattering experiments. Polarized particles produced in this manner are of limited use, however, because of the very low intensity of a well-defined scattered beam and because of the difficulty in producing scattered beams of arbitrary energy with large polarizations.

A preferable source of polarized nuclear beams would be a source of low energy polarized ions capable of being injected into an accelerator of conventional design. Four basic methods have been proposed for producing polarized ions (or polarized atomic beams) for use in accelerators. These schemes are differentiated among themselves by the process by which a selective population or depopulation of certain of the magnetic sublevels of the nucleus involved is accomplished. The four methods, as cited by Dickson, are: 1) a Stern-Gerlach type arrangement, in which the hyperfine states of an atomic beam are separated in an inhomogeneous magnetic field; 2) enrichment of selected hyperfine states by optical pumping; 3) separation of hyperfine states by means of the Lamb Shift; and
4) polarization in magnetic films. To date, only the first method has been used to produce operational ion sources.

Daniels\textsuperscript{7}) and Dickson\textsuperscript{9}) have written excellent review articles describing the characteristics of the polarized ion sources which have been built or which are in an advanced state of construction. By means of these ion sources, beams of energetic polarized protons and deuterons have been successfully produced in a wide variety of accelerators—linear, orbital, and electrostatic types. In work too recent to be included in the above reviews, Haeberli and co-workers at Wisconsin have reported the production of negative ions of polarized deuterium and hydrogen and the acceleration and stripping of these ions with negligible loss of polarization in a Tandem accelerator\textsuperscript{10}).

4. Polarized $^3$He Ions

The merits of $^3$He as a nuclear projectile are discussed in a lengthy review article by Bromley and Almqvist\textsuperscript{11}). The authors cite the particular usefulness of $^3$He in the study of reaction mechanisms in one and two nucleon transfers and in the study of isotopic spin multiplets. The extra control that polarization of the $^3$He nuclei would give over experiments with $^3$He induced reactions has produced an interest in polarized $^3$He ion sources. This interest has led to efforts by two groups—one at Rice University and the other at the University of British Columbia—to demonstrate an operational ion source.

The University of British Columbia source, which is still under development, utilizes the field of a sextupole magnet to separate the hyperfine levels of the ground state $^1S_0$ $^3$He atom at liquid helium temperatures. Ionization follows extraction of the polarized atomic beam\textsuperscript{12,13,14}).
The Rice University source, which uses an optical pumping technique, is discussed in the next section of this thesis.

B. The Rice University $^3\text{He}$ Polarized Ion Source

In a series of papers\textsuperscript{15,16,17}, Walters, Schearer and Colegrove have reported the nuclear polarization of $^3\text{He}$ gas by an optical pumping technique\textsuperscript{18}. Large ($\approx 60\%$) $^3\text{He}$ polarizations have been produced in this manner\textsuperscript{19}; and polarized gas samples have been used successfully for targets in nuclear scattering experiments\textsuperscript{20,21,22}. In Ref. 16, Walters, de Wit, and Phillips suggested using polarized $^3\text{He}$ gas as a source of polarized ions. Stockwell has described a method for extracting helium ions from a modified optical pumping cell\textsuperscript{23}, and progress on an ion source using this approach has been reported by workers at Rice University\textsuperscript{24}.

1. Optical Pumping in Helium Three

Figure 1 shows those energy levels of the $^3\text{He}$ atom which are relevant to a discussion of the optical pumping process. A weak, self-sustaining electric discharge in the gas, produced by a 50 MHz RF field around the optical pumping cell, excites some $^3\text{He}$ atoms to the $^2S_1$ metastable state. Radiative transitions back to the ground state are doubly forbidden, and the lifetime of the metastable atom is assumed to be sufficiently long to permit the polarization processes to be described to take place. Shortening of the metastable lifetime by various relaxation processes will prevent the attainment of appreciable nuclear spin polarization; and, wherever possible, methods must be devised to inhibit those relaxation processes.
Right-hand circularly polarized resonance light, directed into the cell along the axis of the applied magnetic field, produces $\Delta m_F = +1$ transitions from the lower $(m_F = -\frac{3}{2}, -\frac{1}{2})$ $^3S_1$ hyperfine sublevels to the $^3P$ levels. From the $^3P$ levels the atoms de-excite to the various $^3S_1$ levels with virtually equal probabilities. This process is repeated over many cycles, and in this manner atoms are removed from the lower hyperfine levels of the metastable atoms and placed in the higher levels, producing a polarization of the metastable atoms. The lower levels can be populated in the same way using left-hand circularly polarized light; a polarization of the opposite sign results.

The metastable atoms are far less numerous than the ground state atoms—the ratio of the number densities is approximately $10^{-6}$ under the pressure and discharge conditions prevailing. However, by metastability exchange collisions, the metastable atoms transfer their polarization to the ground state atoms; and, under continuous illumination from the pumping light, the ground state polarization reaches an equilibrium value equal to that of the metastable atoms with a characteristic time of about 30 seconds under the conditions selected for operation of the ion source.

The choice of resonance light to accomplish the $^3S_1 - ^3P$ transitions with a maximum resultant ground-state polarization depends on the pressure of the $^3$He gas in the optical pumping cell. The pressure to be used in the ion source bottle will be selected by experiment but will be in the range 0.2 to 1.0 torr. As discussed in Refs. 16) and 23), the $^3S_1 - ^3F_{1,2}$ resonance light
from a $^4$He lamp is the proper wave length to stimulate $^3S_1-^3P_0$ transitions in $^3$He with no intense component to stimulate transitions to the $^3P_{1,2}$ states in $^3$He, a fortuitous result of the isotope shift in the spectra. At the lower end of the 0.2 to 1.0 torr pressure range, both spectral components, $^3S_1-^3P_{1,2}$ and $^3S_1-^3P_0$, are effective in producing polarization, and a He lamp would probably be used. At the higher end of the pressure range, collisional mixing of the $^3P$ states reduces the effectiveness of the $^3S_1-^3P_{1,2}$ resonance light from $^3$He for producing polarization, and the light from a $^4$He lamp is the more effective.

Resonance radiation from the lamp is passed through a linear polarizer and a quarter-wave plate, and, as a result, is circularly polarized. The sense of circular polarization can be reversed by rotating either the quarter-wave plate or the linear polarizer by $90^\circ$.

2. The Ion Source: Description

Figure 2 is a drawing of the ion source bottle, in which optical pumping takes place.

A solenoid is mounted around the ion source bottle and baseplate coaxially with the exit canal. The magnetic field supplied by this solenoid serves a dual role: it defines the axis of polarization and supplies the axial magnetic field needed at the exit canal for focusing.

Ions are created in the weak electric discharge in the optical pumping cell. These ions are removed from the cell through the exit canal in the baseplate and are focused under the influence of the fields due to the extraction bias, the axial magnetic field and the Einzel lens, as shown in Figure 2.
As ions and neutral atoms leave the cell through the exit canal, $^3$He gas must be added to keep the cell pressure at the proper level for the optical pumping process—the gas flow and pressure are selected to keep the average atom in the cell over several pumping times$^{23}$. Contamination of the $^3$He gas in the ion source bottle by impurity atoms will reduce the polarization attained in the cell. For this reason careful cell cleaning procedures have been devised, and gas flowing from cylinder to ion source bottle passes through a liquid helium cold trap$^{23,26}$. In addition magnetic field gradients in the vicinity of the optical pumping cell will destroy polarization. Therefore, the solenoid is designed to produce a very uniform field in the pre-acceleration region; and, ferromagnetic materials are kept as far away as possible from the optical pumping cell.

The maximum polarization obtained in the cell is also dependent on the intensity of the pumping light. A 200 watt, 100 MHz RF exciter has been adapted from a design used by Gamblin and Carver$^{19,27}$ to provide an intense pumping light. This light source is discussed in Appendix A.

3. Necessity of an Experiment to Measure Ion Polarization

When a $^4$He pumping light is used, there exists a simple relationship between the nuclear spin polarization of atoms in the cell and an easily measurable optical signal$^{17}$. Unfortunately, there is no simple relationship between the polarization of the neutral atom and the polarization of the ion—relaxation mechanisms are acting on the ions both before and after extraction from the cell.
Among these relaxation mechanisms are: collisions with walls; diffusion through magnetic gradients; and collisions with impurity atoms and with $^3$He atoms. It is possible that collisions with polarized $^3$He atoms may enhance the ion polarization.

Because of the presence of relaxation mechanisms, it is clearly necessary to measure the nuclear spin polarization of the ions directly. It is the purpose of this thesis to describe a nuclear physics experiment to measure the polarization of the extracted $^3$He$^+$ ion beam.
II. MEASURING $^3$HE BEAM POLARIZATION

A. General Considerations

Since the nuclear force has been shown to be spin dependent, the outcome of a nuclear interaction may be affected by the spin orientation of the projectile; if such an effect is experimentally measurable, it may provide the information necessary to determine the polarization of the beam.

Elastic scattering of spin $1/2$ particles from spin zero nuclei can, for example, give rise to large nuclear spin polarizations of the scattered particles when spin-orbit forces are present. The polarization induced in the scattered particles is often called the analyzing power, $P_D$, of the reaction, because, if the incident projectiles were polarized before the interaction, with their nuclear spins oriented perpendicular to the plane of the scattering, there will be left-right dependence to the scattering. The magnitude of the experimentally measured counting asymmetry, $a$,

$$a = \frac{N_L - N_R}{N_L + N_R}$$

where $N_L$ is the number of counts in the left detector, $N_R$ the number in the right.

is shown to be (Appendix B)

$$a = P_B P_D$$

where $P_B$ is the polarization of the incident nuclei, and $P_D$, the analyzing power of the reaction.

At this point a discussion of the availability of analyzing powers of various reactions is included, as this information surely affects the design of an experiment to
measure beam polarization. All of the reactions discussed are elastic scattering of spin 1/2 projectiles from spin zero targets.

Contour plots of polarization (analyzing power) as a function of energy and scattering angle can be constructed from the scattering phase shifts. This method is discussed by Phillips and Miller, who present contour plots for the reactions $^{12}\text{C} (p,p)$, $^{4}\text{He} (p,p)$ and $^{4}\text{He} (^{3}\text{He}, ^{3}\text{He})$.

Calculations of the proton polarizations have been made at Rice University from more recent phase shift data for $^{12}\text{C}$ scattering and for $^{4}\text{He}$ scattering. Measurements of $P(\theta, E)$ can also be made by double scattering experiments. Such experiments have been done at the University of Wisconsin for $^{12}\text{C}$ and for $^{4}\text{He}$ and at Rice University for $^{12}\text{C}$.

B. Considerations $^{3}\text{He}$ Beam Polarization Determination

1. Elastic Scattering

S-wave elastic scattering of unpolarized spin 1/2 particles from spin zero nuclei cannot result in polarization of the scattered particles (and hence cannot give rise to an asymmetry) because the spin-orbit term in the interaction potential vanishes. Accelerator scheduling difficulties make it impractical at the present stage of ion source development to accelerate the polarized ions to a high enough energy to get p-wave scattering. Also, the axis of nuclear spin polarization of the $^{3}\text{He}$ ions would have to be reoriented to be perpendicular to the direction of ion motion (rather than parallel to the direction of motion as it is as the ion emerges from the source) in order that the spin-orbit term $\propto S \cdot L$ (where $S$ is the spin
angular momentum vector and $\mathbf{L}$ is the orbital angular momentum vector in the interaction) be non-vanishing.

2. $^2\text{H}(^3\text{He},p)^4\text{He}$ Reaction.

Although the difficulties in performing the $^4\text{He}(^3\text{He},^3\text{He})$ experiment to measure the beam polarization can be overcome in principle, a less difficult method is to use an exoergic nuclear reaction to produce polarized spin $1/2$ particles of sufficient energy to make polarization analysis by elastic scattering possible.

The reaction to be used is $^2\text{H}(^3\text{He},p)^4\text{He}$ ($Q = +18.36 \text{ MeV}$). This reaction is discussed in Appendix C; there it is shown that the emitted protons are polarized if the $^3\text{He}$ ions incident on the deuterium target are polarized, reaching a maximum polarization:

$$P_P = -0.67 P_B$$  \hspace{1cm} (4)

at an angle of $90^\circ$ with respect to the incoming beam polarization. The minus sign implies that the direction of proton polarization is anti-parallel to that of the $^3\text{He}$ ions; and, because the angle of emission is chosen to be perpendicular to the direction of $^3\text{He}$ ion motion, the proton spins are oriented perpendicular to the proton's direction of motion, as illustrated in fig. 3.

The cross-section versus energy curve of the $^2\text{H}(^3\text{He},p)$ reaction, shown in figure 4, shows a strong peak at the $16.64 \text{ MeV}, 3/2 +$ resonance in $^5\text{Li}$, $^3\text{He}$ bombarding energy. The cross-section falls off rapidly at lower energies, revealing the necessity of accelerating the ions to an appreciable energy in order to obtain a sufficient yield of protons for polarization analysis. In Appendix D the proton yield of a deuterium
Asymmetry = \frac{N_A - N_B}{N_A + N_B} = +0.4 P_{3He}^0

3He ion beam

Deuterium target

Protons from $2H(3He, p)$ reaction

A detector

B detector

$60^\circ$ Polarimeter (analyzing power $\approx 0.6$)
The graph shows the relative total cross section $^2\text{H}(\text{He},p)$ for deuterium as a function of $^3\text{He}$ lab energy (keV). The vertical axis represents the ratio of the cross section to the total cross section, while the horizontal axis shows the $^3\text{He}$ lab energy in keV. The graph includes two curves, one solid and one dashed, indicating different data sets or approximations.
target in which the $^3\text{He}$ ions are completely stopped is estimated. A comparison of the yields for 150 keV and $^3\text{He}$ ions incident reveals that the yield is greater by a factor of 12 at the higher energy; therefore the data accumulation time for the higher energy would be twelve times less. In view of the low counting rates associated with double scattering experiments, it is considered well worth the effort to achieve acceleration to 300 keV or higher in order to reduce data acquisition time.

C. Polarimeters for Polarized Protons

For protons in the energy range 5-15 MeV, two target substances have been used as polarization analyzers: carbon and helium. For both these substances careful measurements of analyzing power have been made $^{29,30,31,32}$.

Carbon and helium polarimeters were introduced in the late 1950's $^{36,37}$ and are now widely used to measure polarization of nuclear beams $^{38}$.

In choosing between carbon and helium polarimeters for a specific application—specifically, for measuring the polarization of the 14.7 MeV protons from the $^2\text{H}(^3\text{He},p)$ reaction—we seek an accurate measurement in the shortest time. First, in order to minimize error due to uncertainties in energy and angle resulting from finite target thicknesses and scattering geometry, we locate a region of energies and an angular range for which the analyzing power is smoothly and slowly varying. Second, it is desirable that both the scattering asymmetry and the cross-section be large enough to permit good counting statistics in a reasonable data acquisition time. A figure of merit most often used in describing analyzing reactions and
polarimeters is \( P^2 \sigma \)--the product of the cross section and the square of the polarization. The asymmetry, \( a \), is proportional to \( P \) and independent of scattering cross section and counting time, while the uncertainty, \( \Delta a \), in the asymmetry is related to the statistical accuracy of the number of counts in the two detectors, i.e., \( \Delta a 
abla \frac{1}{\sqrt{N}} \), where \( N \) is the number of counts; we may also write \( \Delta a \propto \frac{1}{\sqrt{\sigma}} \), where \( \sigma \) is the differential cross section, or \( \Delta a \propto \sqrt{T} \) where \( T \) is the counting time, since \( T \propto \frac{1}{\sigma} \). Therefore, \( \frac{(\Delta a)^2}{a} \propto \frac{1}{P^2 \sigma} \). This result may be summarized in two ways: the minimum fractional error in a given time is obtained where \( P^2 \sigma \) is maximum; or the time required for a measurement of \( a \) with a given fractional error is inversely proportional to \( P^2 \sigma \).

Contour plots of \( P^2 \sigma (\theta, E) \) for \(^4\text{He}(p, p)\) and \(^{12}\text{C}(p, p)\) are presented in Figures 5 and 6. For \(^4\text{He}(p, p)\), note two regions--60° ± 10° (73° in C.M. system), \( E_p = 6 \) to 10 MeV; and 120° ± 10° (133° in C.M.), \( E_p = 5 \) to 9 MeV--in which \( P^2 \sigma \) is greater than 40 mb/sr (where \( 0 \leq |p| \leq 1.00 \)).

In both these regions \( P \) is slowly and smoothly varying over the entire range of energy and angle. Figure 7 is a contour plot of \( P_p (\theta, E) \) for \(^4\text{He}(p, p)\).

Figure 8 is a contour plot of \( P_p (\theta, E) \) for \(^{12}\text{C}(p, p)\). Note that there are very few regions in which \( P_p \) is slowly and smoothly varying; thus more careful determination of energy and angular resolution is required than for \(^4\text{He}(p, p)\).

However, \( P^2 \sigma \) in \(^{12}\text{C}(p, p)\) reaches much higher values than in \(^4\text{He}(p, p)\). In the region 6 ± 0.5 MeV, \( \theta_{\text{LAB}} = 35° \pm 5° \), \( P^2 \sigma = \geq 100 \) mb/sr; and in the region 6.75 ± 0.5, \( \theta_{\text{LAB}} = 115° \pm 10° \), \( P^2 \sigma = \geq 50 \). Energy-retarding foils could be used to bring down the proton
energy to these regions of high $P_2^a$.

In order to get an indication of the relative effectiveness of carbon and helium polarimeters for carrying out the proton polarization analysis, we can evaluate the ratio of the quantities $P_2^a (\Delta E/Z)$ for the two targets. As mentioned previously the quantity $P_2^a$ is inversely proportional to the time required for a measurement of scattering asymmetry with a given fractional error. In order to include differences in the greatest target thickness which permits an accurate determination of analyzing power, $P_2^a$ is multiplied by $\Delta E/Z$, the target thickness in MeV. ($\Delta E$, the energy lost in the target by the protons, is divided by $Z$, the atomic number of the target, to correct for the difference in proton stopping powers of the target substances.) Since approximately equal detector solid angles are realizable in carbon and helium polarimeters, solid angle is not included in the following calculation.

Target thicknesses and angular resolutions are selected from Figs. 5 and 6 by locating the regions where $P_2^a$ reaches its maximum value.

For carbon the range $E_p = 6.25 \pm 0.75$ MeV and $\theta = 35 \pm 10^\circ$ is selected. Here $P_2^a \approx 100$ and $\Delta E = 1.5$ MeV. $Z = 6$.

For helium the selected range is $8.0 \pm 2.5$ MeV and $\theta = 60 \pm 10^\circ$. $P_2^a \approx 40$ and $\Delta E = 5.0$ MeV. $Z = 2$.

For a given fractional error in the asymmetry measurement:

$$\frac{\text{Time (}^{4}\text{He})}{\text{Time (}^{12}\text{C})} = \frac{\left(\frac{P_2^a \Delta E}{Z}\right)^{12}\text{C}}{\left(\frac{P_2^a \Delta E}{Z}\right)^{4}\text{He}} = \frac{100 \left(\frac{1.5}{6}\right)}{40 \left(\frac{5}{2}\right)} = 0.25$$
The time required using helium target would be only a fourth that for a carbon target— a very significant difference in view of the low counting rates always encountered in double scattering experiments. For this reason the polarimeter which will be used to analyze the polarization of the protons from the reaction will utilize a helium target.
III. EXPERIMENTAL APPARATUS

A. Acceleration System

A view of the experimental arrangement used in the polarization measuring experiment is shown in Fig. 2b. The apparatus shown there can be divided into three groupings: the ion source and its associated equipment; the accelerator tubes and vacuum equipment; and the target and polarimeter system.

The ion source is mounted on a wooden table (4' x 7' surface area) insulated from ground by legs of Texolite phenolic tubing. With the ion source on the table are power supplies for the pumping lamp, an Einzel lens power supply, an extraction bias supply, an accelerating (30 kV) voltage supply, solenoid power supply, and vacuum gauges, as well as the handling system for the three gases used ($^3$He for acceleration and $^1$H and $^4$He for clean-up), a 2 inch oil diffusion pump, and a mechanical forepump. Air for cooling the lamp and oil for cooling the diffusion pump are brought up to the table by plastic tubing. 110 VAC for the equipment is supplied by a 3KVA isolation transformer, with insulation to withstand 150 kV between primary and secondary. A voltage-doubler type power supply is used to raise the ion source table to a potential of 150 kV above ground.

The equipment at the target end of the experiment includes the polarimeter and its associated electronics, which are mounted on a wooden table (surface area 4' x 4') of construction similar to that of the ion source table. This table is lowered to a potential of 150 kV below earth ground by another voltage-doubler type power supply. This
supply contains an isolation transformer, which is used to power the polarimeter equipment.

Both tables are enclosed by aluminum screening to protect the equipment from high voltage arcs to ground and to shield the detector circuitry from corona noise. An epoxy resin which has a putty-like consistency before hardening (Brado Plastics type Epo-950) was used to mold rounded anti-corona surfaces for the corners where the aluminum screens meet. These epoxy forms have proven to be very effective in suppressing corona at the sharp edges of the table and screens. Experience has shown that the two tables can be maintained at potentials of 150 kV in the rather humid basement location they occupy.

Between the two tables is located a grounded aluminum platform. This platform supports two twenty-two electrode Texas Nuclear accelerator tubes. The base plates of the two accelerator tubes are separated about twelve inches by a vacuum manifold, onto which are mounted a 4 inch oil diffusion pump and a liquid nitrogen cold trap. Two banks of resistors, mounted on either side of the platform, drop the potential uniformly along the length of the accelerator tubes. Provision is made for roughing out the accelerator tubes, the cold trap, and the target chamber with a mechanical vacuum pump. A Bayard-Alpert type ionization gauge is mounted near the base of the cold trap to monitor the pressure in the accelerator tubes. The platform and the equipment mounted on it are shown in Fig. 2c.

Because a $^3\text{He}^+$ ion has an unpaired electron, its magnetic moment is characterized by the Bohr magneton. The ion has a precession period of 0.7 microseconds-gauss, and, since the acceleration time is on the order of 1 micro-
second, it could lose its spin orientation if it encounters a net magnetic field along the accelerating column which is non-axial with a magnitude of the order of the earth's field. Therefore, an axial guide field is needed along the accelerating column, a requirement which is not usually encountered when accelerating polarized protons and deuterons, whose magnetic moment is of the order of a nuclear magneton.

To supply the guide field four coils are centered about the axis of the acceleration tubes, one on either side of the platform between the ion source and target tables and one on each of the facing ends of the two tables. Consisting of 100 turns of #16 gauge copper wire with an average radius of 16.25 inches, each coil will furnish a field of approximately 1.5 gauss per ampere at its center.

B. Deuterium Targets

Two target chambers have been assembled for evaluation. The first chamber, shown in Fig. 2d uses a titanium-deuterium strip (Texas Nuclear Model 9592), which is prepared by absorbing deuterium into a layer of titanium which has been evaporated onto a copper backing. The vendor reports yields of $10^3$ protons per second per microampere with 150 keV $^3$He ions incident$^{39)}$. This yield is extrapolated by a method described in Appendix D to $10^4$ per second per microampere at 300 keV, comparing very poorly to the theoretical yield of $6 \times 10^6$ per second per microampere for an ideal, pure deuterium target (Appendix D). The target chamber is mounted on the -150 kV end of the accelerator tubes. Twin circular apertures, 0.125 inches in diameter and located 3.125 inches apart collimate the beam onto the target, which is located 0.625 inches from the end of the
collimation barrel. The target holder, a 0.375 inch brass rod, can be rotated and translated vertically while the target chamber is evacuated. The target holder is electrically insulated from the target chamber and polarimeter by the lucite end pieces visible in the photograph so that beam current can be measured. The Ti-D target strip occupies the center position on the target holder. For lining up the beam a small quartz is bonded to the brass rod on one side of the target. A lucite window is located opposite the proton exit aperture for viewing the quartz and the position of the target.

The low counting rate in the experiment encouraged the consideration of targets containing higher concentrations of deuterium atoms than the Ti-D strip, and a solid deuterium oxide (heavy ice) target has been constructed. This target chamber is shown in Fig. 2e. A 0.250 inch diameter copper rod is immersed in liquid nitrogen contained in a dewar located below the top surface of the polarimeter table. The top 0.375 inches of the copper rod is milled diagonally so that a flat surface of maximum thickness 0.100 inches remains. The plane of this surface makes an angle of 45° with the incoming beam direction. The beam is collimated by a 0.125 inch diameter aperture in a 0.0625 thick brass plate located approximately 0.625 inches from the target. A valve with an inner diameter of approximately 0.250 inches is located between the accelerator tube base and the target. In practice the target chamber is first evacuated by the accelerator tubes vacuum system and the small valve is then closed. The vapor from the deuterium oxide handling system shown in the photograph (Fig. 2e) is directed onto the flat surface of the cold copper rod by
a nozzle. A coating of ice approximately 0.125 inch thick builds up quickly on the rod with the expenditure of about 1 cc of heavy water. The deuterium oxide can be recovered by heating the copper rod while cooling a glass trap in the D$_2$O handling system with the valve to the accelerator tube closed.

In both target chambers, protons leave the target at an angle of 90° with the incoming $^3$He beam and exit through a 0.0008 inch aluminum foil window. From the kinematics of the reaction the protons have an energy of 14.7 MeV. There is negligible energy loss in the target material ($\leq 20$ keV) and protons leave the chamber with an energy of $\sim 14.6$ MeV, having lost $\sim 140$ keV in the exit foil.

A preliminary comparison of the two types of targets has been made. Because the accelerator tubes had not been aligned properly at the time of the test, the $^3$He acceleration energy was set at 105 kV where the best beam focusing was obtained. The target table was left at ground potential to facilitate the testing of the target chambers.

A proton detector consisting of a piece of NE102 plastic scintillator coupled directly to a photomultiplier tube was placed in front of the proton exit port of the target chamber. Approximately $8.8 \times 10^{-3}$ of the total (4$\pi$) target solid angle was subtended by the detector. The beam current on the Ti-D target was measured and found to be 1.5 $\mu$amps. The current on the ice target could not be measured because of unidentified difficulties which could not be remedied at the time of the test; however, no changes in the ion source parameters were made during the test, and we shall assume that the current on the ice target was also 1.5 $\mu$amp.
The observed counting rate at 105 kV was 320 sec$^{-1}$ for the ice target and 35 sec$^{-1}$ for the Ti-D target. Assuming that the yield at 300 kV will be 50 times greater than the yield at 105 kV (see Figure 4 and Appendix D), we find that the rate of production of protons in the ice target is $1.2 \times 10^6$ sec$^{-1}$ μamp$^{-1}$ and in the Ti-D target, $1.3 \times 10^5$ sec$^{-1}$ μamp$^{-1}$ at 300 keV $^3$He$^+$ energy. No melting of the ice by the beam was observed.

The results of this test are encouraging. With a scattering efficiency of $5 \times 10^{-7}$ for the polarimeter (see Appendix E for definition and computation) we can expect about 0.5 counts per second in the polarimeter for a 1 microampere beam at 300 kV acceleration energy, using the ice target. Therefore the experiment is entirely practical and should take less than one day of data accumulation time to complete.

C. The Polarimeter

The helium polarimeter is based on similar polarimeters designed and used by Rosen and Brolley$^{36}$ and by Lush$^{38}$ et al. A drawing of the polarimeter is presented in Fig. 9.

The main body of the polarimeter is an aluminum pressure vessel, which has been tested at 1000 psig. Two detectors, each a thin plastic scintillator bonded to a lucite light pipe, are mounted inside the pressure vessel. The light pipes pass through pressure sealed openings in the rear wall of the polarimeter.

Two racks of brass vanes are mounted in an aluminum vane holder, in which the detector light pipes fit. The vane holder fits tightly inside the pressure vessel and is held in position by a 2" thick bronze end plate with rubber
23.

O-ring seal. A threaded bronze retainer ring screws into the pressure vessel and compresses the O-ring tightly against the retaining wall of the pressure vessel. The purpose of the vanes is to collimate the scattered protons onto the scintillator material and to define the angular resolution. Forward angles of $60 \pm 10^\circ$ were chosen over the backward angles of $120 \pm 10^\circ$ over which $P^2\sigma$ is slightly higher. The reason for choosing forward angles is to obtain higher energy protons on the detector to reduce noise problems. The energy of protons scattered through an angle of $60^\circ$ is approximately 1.6 times the energy in the case of $120^\circ$ scattering.

Each vane is 0.020 inches thick and extends 0.8 inches into the gas at an angle of $60^\circ$ with the scintillator surface. The 23 vanes are mounted parallel with a spacing of approximately 0.215 inches between edges. The three vanes nearest the entrance are not used because at these positions protons could be scattered directly by the aluminum entrance foil onto the detectors. The remaining 20 vanes divide the active surface of the scintillator into 19 portions, each two inches wide and 0.215 inches long.

Protons entering the polarimeter through a one-inch diameter hole in the bronze end plate are collimated first by a 5/8 inch diameter antiscattering slit on the low pressure side of the brass round, and, after passing through a 0.006 thick aluminum foil, by a 0.65 inch square brass antiscattering slit, which also serves as the entrance foil retainer.

In Appendix E we calculate the analyzing power of this polarimeter and estimate its scattering efficiency.

The helium gas in the polarimeter is pressurized to 35
atmospheres to increase the effective target thickness for proton scattering. Pressure in the polarimeter is monitored by a 0-1500 psig Heise gauge. In order to reduce the possibility of proton scattering from atoms other than helium, the polarimeter is evacuated with a mechanical vacuum pump before pressurization. Both the vacuum pump and the helium supply bottle are removed when high voltage is applied to the table.

D. Detectors

1. The trigger detector. A detector, referred to as the trigger detector, is located in the proton flight path between the target and the polarimeter. This detector furnishes a gate pulse for the coincidence system to be described in a later section.

All protons which enter the scattering volume of the polarimeter must first have passed through a thin section (14 mils) of Pilot-B plastic scintillator in the trigger detector. Approximately 1.3 MeV is dissipated in the scintillator by the protons, and the light produced is conducted in a lucite light pipe to the photocathode of a photomultiplier tube. The light pipe of the trigger detector, shown in the upper half if Figure 10, is designed to fit onto the exit port of the target chamber. The photomultiplier tube and its base-preamplifier are supported on a stand on the target table. The relative positioning of the target chamber, trigger detector and the polarimeter is shown in Fig. 2d.

All external surfaces of the light pipe, except for the surface placed against the photomultiplier tube, are painted with Pilot reflective coating. A lucite washer holds the thin scintillator against the recessed surface of
the light pipe. Optical coupling between the scintillator and the light pipe and between the light pipe and the photomultiplier tube is provided by Dow-Corning DC-200 silicone fluid. Exposed surfaces of the light pipe are covered by 0.0005 inch aluminum foil to exclude external light. Black plastic electrical tape secures the foil and completes the light shielding. The protons pass through the aluminum foil covering.

2. **Detectors inside the polarimeter.** Two detectors are located within the polarimeter. In practice these two detectors (henceforth referred to as the A detector, the upper one; and the B detector, the lower one) are oriented one over the other and parallel to the target table surface. The planes of the detectors are parallel to the plane containing the incident proton spin and momentum vectors (see Fig. 3).

The scintillating material is the plastic NE-102 (Nuclear Enterprises, Ltd.) in the form of a strip two inches wide, 5.13 inches long, and 0.05 inches thick. The scintillator is bonded to the lucite light pipe by Pilot Bonding Epoxy (Pilot Chemicals). The light pipe, shown in the lower half of Fig. 10, is fabricated from a single piece of 0.250 inch lucite sheet, except for two lucite butt plates which are cemented to the main body. The butt plates seat on the inside rear wall of the polarimeter and hold the light pipes in against the pressure in the polarimeter. Tests with alpha particles revealed that the best light transmission to the photomultiplier tube occurred when the 0.250 x 2 inch end of the light pipe was painted with Pilot reflective coating (Pilot Chemicals).
A pressure seal is made on the outside rear surface by means of a rubber O-ring held in place around the light pipe by a brass plate mounted onto the polarimeter pressure vessel. The brass plate also serves as a mounting for the photomultiplier base-preamplifier. Four threaded brass rods between the preamplifier chassis and the brass plate hold the photomultiplier tube firmly against the end of the light pipe. The photomultiplier tube is held firmly against sidewise motion by a brass collar which mounts directly onto the brass plate. The brass collar also provides shielding of the photomultiplier tube from external light. Figure 2(f) is a photograph illustrating how the photomultiplier tubes and preamplifiers mount onto the polarimeter.

D. Electronics

1. Detector Pulses. The electronics system used to process light pulses from the three scintillators is shown schematically in Fig. 11.

The photomultiplier tube bases and the pulse preamplifiers for the three detectors were built according to the circuit diagrams of Fig. 12. The P-M base can be used for RCA 6342A or Dumont 6292 P-M tubes. In practice, the A and B detectors use RCA 6342A tubes, and the trigger detector uses a Dumont 6292 tube. The tubes are enclosed in mu-metal shields for magnetic shielding. B+ and filament current for the three preamplifiers are supplied by a single [Lambda Electronics Model 28] regulated power supply. A [Baird-Atomic Model 312A] regulated high-voltage power supply furnishes +1100 volts for the photomultiplier tubes.

Negative pulses from the preamplifier are fed into the input of an Atomic Instrument Model 204-B linear ampli-
fier. The amplified pulses are then passed through a discrim
inator circuit built into the amplifier. The discrim
inator circuit gives an output pulse of fixed voltage
(approximately +9 volts) and fixed rise time (~0.3 µ sec)
for each input pulse whose peak amplitude is above the bias,
or discrimination, level.

2. **Coincidence Requirement.** Extraneous pulses will be
present in the output of the preamplifiers. Some of
these pulses will be proton associated, such as neutrons
and γ's from the $^{27}$Al(p,n) and $^{27}$Al(p,γ) reactions and
secondary electrons emitted in the polarimeter volume when
protons strike metal surfaces. Other spurious pulses may
originate from noise in the electronics.

Random noise can be almost eliminated in the low
counting rate situation of the polarimeter by introducing
a coincidence requirement: a pulse from a detector must
be matched by a pulse from the trigger circuit which
arrives within the resolving time, $T$, of the coincidence
circuit if it is to be counted.

The circuit (shown in Fig. 13) which accomplishes
the coincidence requirement is designed around a 6BN6 gated
beam tube $^{40}$. This tube is so constructed that positive
pulses, of a magnitude determined by the B+ and resistance
in the cathode circuit, must be present on both grids 1
and 3, within a length of time dependent on the electron
transit time between the two grids ($\sim 2 \times 10^{-9}$ sec), for an
output pulse (negative) to appear at the plate of the 6BN6.
If a pulse appears, it is capacitively coupled to the input
of a 6AK5 cathode follower. The negative pulse from the
output of the cathode follower is counted by an **Atomic Instrument** Model 101-A scalar.
Two such coincidence circuits are used; they share a common input to the number 3 grid of each 6BN6 tube. The 100Ω resistor across the input and ground is shared also. The trigger pulse is fed into the common input; pulses from one detector in the polarimeter are fed into the number 1 grid input of the 6BN6, and pulses from the other detector, into the number 1 grid input of the other 6BN6. In this way T-A coincidences are counted in the A scalar, and T-B coincidences in the B scalar, as illustrated in Fig. 11. B+ for the coincidence circuits was selected by trial to be 120 volts; it is supplied by a Lambda Electronics Model 25 regulated DC power supply.

The cathode bias for the coincidence circuit is chosen in the following manner:

(1) The output of a pulse generator is divided and fed into the test inputs of the trigger preamplifier and the A preamplifier. No delay lines are used in either side. The discriminator bias level on each linear amplifier is set to give a pulse from the discriminator output on the front panel of the amplifier for each pulse from the generator. Pulses are fed from the discriminator outputs to the inputs of the coincidence circuit.

(2) Observing the output pulse from the coincidence circuit on an oscilloscope with a horizontal sweep period of about 2 μ sec per centimeter, the cathode bias potentiometer is adjusted to lengthen the pulse decay time until an overshoot is observed at about 3.8 microseconds. The bias is then adjusted in the other direction until the overshoot just disappears.

(3) The procedure is repeated for the B side of the coincidence circuit. When the cathode bias on the 6BN6 has
been so adjusted, the output pulse will appear somewhat like the illustration in Fig. 13.

If either input signal (T or A) is removed, an output pulse is still present, although its amplitude is never greater than \(-1\) volts. As delay lines are placed into one side of the coincidence circuit input, the peak signal voltage of the output pulse declines from \(-4\) volts in the direction of \(-1\) volts, with increasing delay (as previously mentioned, the input signals to the coincidence unit have a constant peak voltage and rise time). Therefore, the resolving time of the coincidence unit will depend on the discriminator bias setting on the scalar. The discriminator setting was selected by noting the pulse level at which a delayed pulse began to be severely distorted from the shape shown in Fig. 13. With the discriminator bias set at \(-2\) volts, the resolving time was found to be 0.6 microseconds by means of calibrated delay lines.
$V_{1a} = V_{1b} = \frac{1}{2} 6BQ7A$
IV. TESTS OF DETECTORS

A. Tests of Polarimeter Detectors A and B with 5.5 MeV Alpha Particles

The response of the two detectors located within the polarimeter pressure vessel, A and B, was tested initially with 5.5 MeV alpha particles. The purpose of the tests was twofold: to determine the uniformity of the collection efficiency of various portions of the detector surface and to demonstrate resolution of 5.5 MeV alpha particles above noise. A demonstration of clear resolution and efficient collection of 5.5 MeV alpha particles would indicate that protons of the same energy could also be detected, since the relative pulse heights are much greater for protons than for alpha particles in plastic scintillators. [In section IV-B we cite evidence that the magnitude of pulses from 4.4 MeV protons is about five times that of pulses from 5.5 MeV alpha particles.]

The advantage in using a small alpha particle source in initial tests of the detectors was that changes in the experimental arrangement could be made and evaluated without the difficulties of scheduling time on a proton accelerator. A constant-flux source, such as $^{241}$Am, is also well-suited for measuring the collection efficiency of small areas of the scintillator surface with no attendant difficulties in masking off areas of the surface or in normalization. As mentioned in the preceding section, the alpha particles tests led to the selection of epoxy over silicone fluid as the medium of optical contact between scintillator and light pipe and to the choice of areas of
the light-pipe surface to be painted with reflective coating.

In order to obtain a good comparison of the performance of the two detectors, the same linear amplifier was used following the preamplifier of the detector being tested. Positive pulses from the amplifier were fed into the input of a Nuclear Data 1024 channel analyzer in the 4 x 256 channel mode. Amplifier and analyzer gains were kept constant for tests on both detectors and data were collected over a period of a few hours.

An Ortec $^{241}$Am source (active diameter 3 mm and nominal activity 0.1 microcuries of 5.5 MeV alphas) was used for the tests. With the vane holder removed from the polarimeter, the source was placed successively on nine different positions on the surface of each scintillator: centered 1/2" in on the right edge, in the middle and 1/2" in on the left edge for three distances along the 4.77 inch length of the scintillator: 1/2" in from the end nearest the P.M. tube, midway, and 1/2" in from the other end.

Pulse height spectra are shown for the center positions on the A detector in Fig. 14. Spectra for the right and left positions were in all cases almost identical to the center positions for the same distance along the length of the scintillator and therefore are not reproduced here. Background is not subtracted and no dead-time corrections are made. The number in parentheses alongside each spectrum is the total number of counts in 256 channels, typically 62,000.

Except for a higher background in the B detector, the spectra for the A and B detectors are very similar. As anticipated more large pulse heights are seen for the
position (#2), in which the source is nearest the photomultiplier tube, because the photons of light created in the scintillator by the stopping of the alpha particles travel the shortest distance to the photocathode. A result which was not anticipated is that more large pulse heights are recorded when the source is at the farthest position from the P.M. tube than when the source is in the center of the scintillator. The total number of counts in one minute of live time is slightly greater for the #2 (near P.M.) position than for the #8 (far) position and slightly greater for the #6 position than for the #5 (middle) position.

If a discriminator had been set to reject all pulses falling below channel #10 in Figure 14, the number of background counts would have been reduced by 50%, while the alpha spectra counts would have been reduced by only 5%. If data had been taken with a scalar instead of a pulse height analyzer, this choice of discriminator level in the amplifier would have doubled the signal to noise ratio (defined here as the sum of the counts above a certain channel with the alpha source in place divided by the number of background counts in the same channels) with only a small loss in the number of alpha particles counted.

For detector A, the signal to noise ratio is $\sim$ 300 to 1 with a discriminator level set at channel 10. For detector B, which had a higher background, the signal to noise ratio is $\sim$ 60 to 1 with the same discriminator setting.

The conclusion drawn from the tests summarized in Figure 14 is that 5.5 MeV alpha particles can be well resolved from background noise.
B. Tests of the Polarimeter Detectors A and B with 6 MeV Protons

After tests had shown that the polarimeter detectors were capable of counting 5.5 MeV alpha particles, an investigation was made of the response of the detectors to protons.

The Rice University Tandem Van de Graaff accelerator provided an analyzed beam of 9.27 MeV protons. Protons left the beam tube through a 0.0045 inch aluminum foil window and were collimated by a 0.320 inch diameter hole in a lead sheet. The protons traveled ~12.6 cm in air before reaching the 0.006 inch aluminum entrance window of the polarimeter. On entering the polarimeter, the protons had a residual energy of approximately 5.7 MeV. With one atmosphere helium gas, the protons arrived at the rear of the polarimeter with an energy of approximately 5.5 MeV. Therefore, protons scattered from helium in the polarimeter in this test were of slightly lower energy than the least energetic (~4 MeV) of the protons scattered into the detectors during the experiment for which the polarimeter is designed.

Pulses from a polarimeter detector preamplifier were amplified and pulse height analyzed by a TMC 400 channel analyzer. Cosmic Model 901 amplifiers were used instead of the Atomic Instrument amplifiers, which will be used for the ion source experiment, because negative pulses are required by the TMC analyzer. The monitor detector used to normalize the data was an Ortec model 3-9B silicon surface barrier detector mounted on the end of the beam tube. Protons back-scattered from the external brass antiscattering aperture on the polarimeter were detected. The monitor
detector was followed by a Hamner model N-357 preamplifier, and pulses from the preamplifier were analyzed by the TMC analyzer.

The polarimeter axis was aligned visually with the beam tube axis. The alignment was checked by viewing the beam on a quartz centered in the external antiscattering aperture of the polarimeter. Figure 15 shows spectra recorded at two polarimeter pressures: 30 microns of mercury and 1 atmosphere. The spectra are normalized to the 30 \( \mu \) data. The spectra for the A and B detectors are entirely similar—indicating that the scattering geometries of the two detectors are identical for a beam which is incident along the polarimeter axis. Figure 15 is the A spectra. The spectrum at 30 \( \mu \) pressure is presumed to be due to undesirable background radiation—neutrons, \( \gamma \)'s, electrons—induced by the proton beam striking metal surfaces. Assuming that the 30 \( \mu \) spectrum represents background that will be present regardless of helium gas pressure, the signal-to-noise ratio is 30 to 1 when the counts are summed from channels 1 to 99; but 60 to 1 when counts in the first 10 channels are subtracted. As in the case with alpha particles, only 5\% of the counts in the 1 atm spectrum are lost when the first ten channels are subtracted, while more than 50\% of the 30 \( \mu \) counts are lost.

At the conclusion of the proton experiment, a brief test was conducted with the \( ^{241} \)Am alpha particle source. The identical detector-amplifier-analyzer system was used so that a direct comparison of alpha particle and proton pulse heights in the detectors could be made.

The source was placed on the vanes of the B detector, and the polarimeter was evacuated to a pressure of 35 \( \mu \).
The peak of the alpha particle spectrum occurred in channel 23; for the same gain settings, the peak of the proton spectrum, corresponding to scattered protons of energy 4.4 MeV, occurred in channel 90, indicating that proton pulse heights in the detector are about five times as great as those for alpha particles of the same energy.

The conclusion from the tests with protons was that the detector system had been shown to be effective in counting protons of the energies involved in the experiment in the presence of background noise.
V. PROPOSED TREATMENT OF DATA

It is not desirable to make a single measurement of scattering asymmetry (\(\alpha^+\), for example, where the plus sign denotes positive beam polarization) because the detector solid angles and efficiencies are not known with sufficient precision. For small scattering asymmetries, instrumental asymmetry could mask even the sign of the beam polarization. Fortunately, however, there exist procedures which obviate the necessity for absolute determinations of detector solid angles and efficiencies. These procedures make use of our ability to change the sign of the asymmetry by reversing the direction of spin orientation of the polarized beam. (In this section the treatment and notation of R. C. Hanna\(^{41}\) are closely followed.)

There are three stages of ion source beam polarization: nuclear spin oriented in the direction of motion of the ions, \(P_+\); no spin orientation, \(P_0\); and spin oriented antiparallel to the direction of motion, \(P_-\). The change from \(P_+\) to \(P_-\) is effected by reversing the sense of the circular polarization of the pumping light. Beam polarization can be destroyed by extinguishing the pumping light (an unpolarized beam will be used to check for instrumental asymmetries).

With beam polarization \(P_+\), two quantities are measured experimentally: \(N_{A+}\), the number of counts in the A detector, and \(N_{B+}\), the number of counts in the B detector. Similarly, with beam polarization \(P_-\), \(N_{A-}\) and \(N_{B-}\) are measured. In terms of the beam integration, \(k\), the detector efficiencies and solid angles, \(\Omega_A\) and \(\Omega_B\), and the analyzing power of the polarimeter for each detector \(p_A\)
and $P_B$, the quantities $NA$ and $NB$ may be written:

$$\begin{align*}
NA_+ &= \frac{1}{2} k \sum A_+ (1 + P_+ P_{A+}) \\
NB_+ &= \frac{1}{2} k \sum B_+ (1 - P_+ P_{B+}) \\
NA_- &= \frac{1}{2} k \sum A_- (1 - P_- P_{A-}) \\
NB_- &= \frac{1}{2} k \sum B_- (1 + P_- P_{B-})
\end{align*}$$

(5)

Experience with polarized targets of $^3$He gas, which use an identical optical pumping process as the polarization mechanism, has shown that $|P_-| = |P_+|$ in practice, when the magnetic field magnitude is the same for both beam polarizations and the sense of the pumping light is exactly reversed.

In addition, the experiment with unpolarized protons reported in this thesis demonstrated that the scattering geometries for the A and B detectors are very nearly the same. Furthermore, it is reasonable to assume that the beam direction (and hence the scattering geometry) is not affected by a change in beam polarization.

These observations and assumptions lead to the following simplifications in the expressions for the observed counting rates:

1) If scattering geometry is unchanged when beam polarization is reversed:

$$\begin{align*}
\sum A_+ &= \sum A_- \\
\sum B_+ &= \sum B_- \\
P_{A+} &= P_{A-} \\
P_{B+} &= P_{B-}
\end{align*}$$

(6)

2) If scattering geometries for A and B detectors are almost identical:
\[ P_A \simeq P_B, \text{ i.e. } P_A = P_B (1 + \delta P_D) \]
and \[ P_B = P_B (1 - \delta P_D) \]

where \( P_D \) is the polarimeter analyzing power calculated in Appendix E, and the \( \delta \)'s are small corrections.

(3) If the magnitude of beam polarization is affected only slightly, if at all, by a reversal in direction of orientation of the spins.

\[ \left| P_+ \right| = P_B (1 + \delta P_B) \]

\[ \left| P_- \right| = P_B (1 - \delta P_B) \]

With the above simplifications an expression for the asymmetry can be written which does not involve beam integrations, detector efficiencies (and their associated uncertainties):

\[ \frac{(N A_+)(N B_-)}{(N B_+)(N A_-)} = \left( \frac{1 + a}{1 - a} \right)^2 C \]

(9)

\( C \) is a correction factor, derived by R. C. Hanna:

\[ C = \left\{ 1 - \delta P_B \delta P_D \cdot \frac{8a^2}{(1-a)^2(1+a)} + (\delta P_B^2 + \delta P_D^2) \cdot \frac{4a^2}{(1-a^2)^2} \right\} \]

(10)

Since \( \delta P_B \) and \( \delta P_D \) are small corrections

\( C \approx 1 \)

The asymmetry can now be written

\[ A = \frac{\sqrt{w} - 1}{\sqrt{w} + 1}, \text{ where } w = \frac{(N A_+)(N B_-)}{(N B_+)(N A_-)} \]

(11)

For a beam polarization which is anticipated to be about 10% or more, experimental asymmetries will be small,
in the neighborhood of 0.04. The number of counts in each
detector are approximately the same, if we take data with
one beam polarization state for approximately the same time
as with the other polarization state. With $W$ approximately
equal to unity, the uncertainty in $\mathbf{a}$ due to counting
statistics can be expressed.

$$\delta \mathbf{a} \approx \frac{1}{\sqrt{N}} , \quad \text{where} \quad N = N_{A+} + N_{A-} + N_{B+} + N_{B-} \quad (12)$$

To assign limits of $\pm 0.01$ on $\mathbf{a}$ or $\pm 0.025$ on $P_B$ would re-
quire $N = 10,000$. 
APPENDIX A

A 200 Watt, 100 MHz R. F. Exciter and Optical Pumping Lamp

The lamp which furnishes the resonance light for optical pumping in the ion source gas cell is copied from the design which Gamblin and Carver used to achieve high polarization levels in $^3$He gas samples$^{19,27}$. The very simple circuit of the R. F. exciter is shown in Figure 16. Typical screen voltage is +200 volts at 30 milliamperes, while the anode supply is +1050 volts at 200 milliamperes. The power input level is limited at the present time by the current capacity of the anode supply.

The R. F. exciter (the front of which is visible in Figure 2a) is built in an aluminum chassis which mounts onto and slides along a length of aluminum channel inside the solenoid. R. F. energy, with a frequency of approximately 100 MHz, is conducted from the plates of the two 4CX300A tetrodes by two 6 inch lengths of 0.188 inch copper tubing, whose centers are separated by 0.5 inch, to the tank coil. The tank coil consists of two turns of #10 lacquered copper wire and has an inner diameter of 1.250 inches.

A button-type Vycor glass lamp fits inside the tank coil. The external dimensions of the button are 0.25 inches thickness and 1.125 inches diameter. Because helium diffuses through Vycor at an appreciable rate, a reservoir of gas is provided to keep the gas at a nearly constant pressure for long periods (~weeks) of operation. The reservoir is a pyrex bulb with a volume of about 70 cc. The bulb is connected to the button lamp by a convenient
length of glass tubing which permits the placement of the pyrex bulb out of the way in the rear of the exciter. In order to increase the amount of light from the lamp entering the optical pumping cell, a 154 mm diameter second surface concave mirror (focal length 55 mm) is placed behind the lamp (see Figure 2a).

As we mentioned on page 6, the pressure of the gas in the ion source bottle has not yet been settled upon, and the final choice of gas for the lamp will depend on the pressure in the ion source cell. McSherry\(^4\) discusses how a pressure of 10 torr of \(^4\)He was selected for a lamp to pump a 4 torr sample of \(^3\)He by maximizing the absorption of 1 micron resonance light. We shall follow an identical procedure, maximizing the light absorbed in a bulb of \(^3\)He gas at the pressure selected for operation of the ion source.

The arrangement of exciter, mirror, lamp, circular polarizer and optical pumping cell is shown in Figure 2a. Compressed air is used to cool the anodes of the 4CX300A tubes, the linear polarizer and the button lamp.
APPENDIX B

Relationship of Left-Right Scattering Asymmetry to Beam Polarization and Reaction Analyzing Power

From the definition of beam polarization

\[ P_B = \frac{N_{\text{up}} - N_{\text{down}}}{N_{\text{up}} + N_{\text{down}}} \]  

(where \( N_{\text{up}} \) is the number of particles in the beam with spin up and \( N_{\text{down}} \) the number with spin down). It follows—

with \( N_{\text{up}} + N_{\text{down}} = N = 1 \)—that the fraction of particles with spin up is \( \frac{1}{2}(1 + P_B) \) and the fraction with spin down is \( \frac{1}{2}(1 - P_B) \).

Similarly, in a nuclear reaction for which the analyzing power (which is the polarization induced in the scattering of an unpolarized beam) is \( P_D \), the fraction of particles scattered to the left with spin up is \( \frac{1+P_D}{2} \); with spin down, \( \frac{1-P_D}{2} \). For scattering to the right, the probabilities are reversed. Thus, for right scattering with spin up the fraction is \( \frac{1-P_D}{2} \); with spin down \( \frac{1+P_D}{2} \).

If the incident beam is polarized, with spins oriented perpendicular to the scattering plane, the probabilities for scattering (to the left with spin up, UL; to the left with spin down, DL; to the right with spin up, UR; and to the right with spin down, DR) are:

\[
\begin{align*}
UL &= \left( \frac{1+P_B}{2} \right) \left( \frac{1+P_D}{2} \right) \\
UR &= \left( \frac{1+P_B}{2} \right) \left( \frac{1-P_D}{2} \right) \\
DL &= \left( \frac{1-P_B}{2} \right) \left( \frac{1-P_D}{2} \right)
\end{align*}
\]  

(B1)
The left-right asymmetry, $\alpha$, is then

$$\alpha = \frac{\# \text{left} - \# \text{right}}{\# \text{left} + \# \text{right}} = \frac{(UL+DL) - (UR+DR)}{UL+DL + UR+DR} = \frac{P_B}{P_D}$$

The directions right, left, up, and down must, of course, be defined unambiguously for a particular experiment. The Basel Convention*, used here, defines the direction of positive polarization to be the direction of the vector product $k_i \times k_o$, where $k_i$ is the unit vector in the direction of the incoming beam, and $k_o$ the unit vector in the direction of propagation of the scattered wave.

APPENDIX C

Polarization of protons from the reaction
\[ ^2\text{H} (^3\text{He}, p)^4\text{He} \]

Assuming that the reaction \( ^2\text{H} (^3\text{He}, p)^4\text{He} \) at low energies (< 1 MeV) is initiated by S-waves and proceeds entirely through the \( J = \frac{3}{2}^+ \) resonance in \(^5\text{Li} \), the following analysis can be made:

\[ ^{3}\text{He} + ^{2}\text{H} \rightarrow ^{5}\text{Li} \rightarrow ^{4}\text{He} + p \]

Intrinsic spin and parity: \( 1/2^+ \quad 1^+ \quad 3/2^+ \quad 0^+ \quad 1/2^+ \)

Orbital angular momentum: \( \ell = 0 \, (s\text{-wave}) \quad \ell = 2, \, (d\text{-wave}) \)

Channel spin and parity: \( 3/2^+ \quad 3/2^+ \quad 3/2^+ \)

Using tabulated values for Clebsh-Gordan (vector addition) coefficients, we illustrate the composition of the states \( |J, M_J\rangle \) of the compound nucleus in terms of the states \( |S, M_S\rangle \) of the projectile deuteron spin and target nuclei. (The spatial part of the state function \( |\ell, M_L\rangle \) is simply a constant, \( |0,0\rangle \), because the incoming channel is S-wave and has no angular dependence.)

\[
\begin{align*}
|\frac{3}{2}, \frac{3}{2}\rangle &= |\frac{1}{2}, \frac{1}{2}\rangle |1,1\rangle \\
|\frac{3}{2}, \frac{1}{2}\rangle &= \sqrt{\frac{2}{3}} |\frac{1}{2}, \frac{1}{2}\rangle |1,0\rangle + \sqrt{\frac{1}{3}} |\frac{1}{2}, -\frac{1}{2}\rangle |1,1\rangle \quad \text{(C2)} \\
|\frac{3}{2}, -\frac{1}{2}\rangle &= \sqrt{\frac{1}{3}} |\frac{1}{2}, \frac{1}{2}\rangle |1,-1\rangle + \sqrt{\frac{2}{3}} |\frac{1}{2}, -\frac{1}{2}\rangle |1,0\rangle
\end{align*}
\]
A beam which is partially polarized, with polarization $P$, can be considered as a fraction $P$ of completely polarized spin states and a fraction $1-P$ of unpolarized spin states. The proton polarization $P_p$ for a $^3$He beam of polarization $P_B$ is then $P_B$ multiplied by the proton polarization for a 100% polarized beam. Furthermore, if the beam is considered to be completely polarized with spin up (i.e. parallel with the beam axis)—all $^3$He nuclei being in the $\left| \frac{1}{2}, \frac{1}{2} \right\rangle$ state—then the only incoming states which participate in the reaction are those which are enclosed in the box.

Again using Clebsh-Gordan coefficients we decompose the states, $\left| \frac{3}{2}, \frac{3}{2} \right\rangle$, $\left| \frac{3}{2}, \frac{1}{2} \right\rangle$, $\left| \frac{3}{2}, -\frac{1}{2} \right\rangle$ of the compound nucleus (weighted by the probability amplitude of their formation from the incoming states, i.e. the coefficients of the boxes incoming states of (2)), into the states $\left| l, m \right\rangle_{\text{proton}}\left| s, m_s \right\rangle_{\text{spin}}$ proton of the outgoing proton, making use of the information from the analysis of the reaction (1) that $l = 2$ and $s = 1/2$.

$$\left| \frac{3}{2}, \frac{3}{2} \right\rangle = \left[ \frac{4}{5} \right| \frac{2}{2}, \frac{1}{2} \rangle - \frac{1}{5} \right| \frac{2}{2}, -\frac{1}{2} \rangle - \sqrt{\frac{1}{5}} \right| \frac{2}{2}, 1 \rangle \right| \frac{1}{2}, \frac{1}{2} \rangle \right]$$

$$\sqrt{\frac{2}{3}} \left| \frac{3}{2}, \frac{1}{2} \right\rangle = \left[ \sqrt{\frac{3}{5}} \right| \frac{2}{2}, 1 \rangle \right| \frac{1}{2}, \frac{1}{2} \rangle - \frac{1}{5} \left| \frac{2}{2}, 0 \rangle \right| \frac{1}{2}, \frac{1}{2} \rangle \right] \sqrt{\frac{2}{3}}$$

$$\sqrt{\frac{1}{3}} \left| \frac{3}{2}, -\frac{1}{2} \right\rangle = \left[ \frac{2}{5} \right| \frac{2}{2}, 0 \rangle \right| \frac{1}{2}, \frac{1}{2} \rangle - \frac{1}{5} \left| \frac{2}{2}, -1 \rangle \right| \frac{1}{2}, \frac{1}{2} \rangle \right] \sqrt{\frac{1}{3}}$$

The states on the right-hand side of (3) are composed of mixtures of spin up, $\left| \frac{1}{2}, \frac{1}{2} \right\rangle$, protons and spin down, $\left| \frac{1}{2}, -\frac{1}{2} \right\rangle$, protons with coefficients representing their...
respective amplitudes. The states $|l,m\rangle$ are the orthonormal spherical harmonics $Y^m_l$

$Y^2_2 = \left(\frac{15}{16}\right)^{1/2} (1-\cos^2\theta)$

$Y^1_2 = \left(\frac{15}{4}\right)^{1/2} (1-\cos^2\theta)^{1/2} \cos \theta$ \hspace{1cm} (C4)

$Y^0_2 = \left(\frac{5}{8}\right)^{1/2} (3 \cos^2\theta-1)$

$Y^{-1}_2 = -\left(\frac{15}{4}\right)^{1/2} (1-\cos^2\theta)^{1/2} \cos \theta$

where $\theta$ is the polar angle measured from the axis of positive spin orientation, i.e. along the direction of the incoming beam. The probability of the proton's being emitted with spin up, $\frac{d\sigma}{d\Omega} \text{ (up)}$ is given by:

$$\frac{d\sigma}{d\Omega} \text{ (up)} = -\left| \left[ \frac{1}{5} \right] Y^1_2 \right|^2 + \left| \left[ \frac{2}{3} \right] Y^0_2 \right|^2 + \left| \left[ \frac{1}{3} \right] Y^{-1}_2 \right|^2$$

$$= \frac{1}{2} \cos^2\theta + \frac{1}{6} \hspace{1cm} (C5a)$$

For emission of protons with spin down:

$$\frac{d\sigma}{d\Omega} \text{ (down)} = \left| \left[ \frac{4}{5} \right] Y^2_2 \right|^2 + \left| \left[ \frac{2}{3} \right] Y^1_2 \right|^2 - \left| \left[ \frac{1}{3} \right] Y^{-1}_2 \right|^2$$

$$= -\frac{1}{2} \cos^2\theta + \frac{5}{6} \hspace{1cm} (C5b)$$

The polarization of the outgoing protons, $P_P$ (for 100% polarized beam) is:

$$P_P = \frac{\frac{d\sigma}{d\Omega} \text{ (up)}}{\frac{d\sigma}{d\Omega} \text{ (up)} + \frac{d\sigma}{d\Omega} \text{ (down)}} = \frac{\cos^2\theta - \frac{2}{3}}{\frac{1}{3}} = \cos^2\theta - \frac{2}{3} \hspace{1cm} (C6)$$

For beam polarization, $P_B$,

$$P_P = P_B \left( \cos^2\theta - \frac{2}{3} \right) \hspace{1cm} (C7)$$
For the present experiment, protons which enter the helium polarimeter are emitted from an angle of 90°, i.e. perpendicular to the axis of the $^3$He polarization. Thus

$$P_p = P_B \left( -\frac{2}{3} \right) = -0.67 \ P_B$$  \hspace{1cm} (C8)
APPENDIX D

Proton Yield of a Deuterium Target Stopping $^3\text{He}^+$ Ions of Energy $\leq 300$ keV

The proton yield of a deuterium target thick enough to stop $^3\text{He}$ ions of energy, $E$, is given by

$$Y = \int_{E}^{0} \frac{1}{\epsilon(E)} \sigma(E) \, dE$$

where $\epsilon$ is the stopping cross section per atom:

$$\epsilon = \frac{1}{N} \frac{dE}{dx}$$

where $N$ is the number of stopping atoms per cc of material. $\epsilon$ is measured in units of ev-cm$^2$. $\sigma(E)$ is the total cross section of the $^2\text{H}(^3\text{He},p)^4\text{He}$ reaction. Stopping cross sections, $\epsilon$, are not available for $^3\text{He}$ ions. Therefore, the following assumptions are made:

1. $\epsilon_p$ in hydrogen $\approx \epsilon_p$ in deuterium, where $\epsilon_p$ is the atomic stopping cross section for protons.

2. $\epsilon_\alpha(E) = \epsilon_\text{He} \frac{^3\text{He}}{^4\text{He}}(E) = R \epsilon_p \frac{1}{^4\text{He}}(E)$

where $\epsilon_\alpha$ is the atomic stopping cross section for alpha particles and $R$ is the ratio $\epsilon_\alpha \epsilon_p$ found tabulated as a function of energy in Ref. 43.$^p$

The integration is approximated by a summation

$$Y = \sum_{i=1}^{\Delta E} \frac{1}{\epsilon_i} \sigma_i$$

Since $\epsilon_p$ in ref. 43 is given in steps of 10 keV, $\Delta E$ will be 30 keV, and the summation will be over 30 keV increments from $E_{\text{initial}}$ (keV) to zero.
<table>
<thead>
<tr>
<th>$^{3}$He energy (keV)</th>
<th>$^{4}$He energy (keV)</th>
<th>Proton Energy (keV)</th>
<th>$\varepsilon_p$ ev-cm$^2$</th>
<th>$\varepsilon_a$ ev-cm$^2$</th>
<th>$\varepsilon_{^{3}}He$ ev-cm$^2$</th>
<th>$\frac{1}{\varepsilon_{^{3}}He} \text{ev}^{-1} \text{cm}^{-2}$</th>
<th>$\sigma_{\text{rel}} \frac{\varepsilon_{^{3}}He}{\varepsilon_{^{3}}He}$ ev$^{-1} \text{cm}^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>40</td>
<td>10</td>
<td>3.8x10$^{-15}$</td>
<td>1.3</td>
<td>4.9x10$^{-15}$</td>
<td>0.202x10$^{15}$</td>
<td>----</td>
</tr>
<tr>
<td>60</td>
<td>80</td>
<td>20</td>
<td>5.0</td>
<td>1.6</td>
<td>8.0</td>
<td>0.125</td>
<td>0.00166</td>
</tr>
<tr>
<td>90</td>
<td>120</td>
<td>30</td>
<td>5.8</td>
<td>1.8</td>
<td>10.4</td>
<td>0.096</td>
<td>0.0166</td>
</tr>
<tr>
<td>120</td>
<td>160</td>
<td>40</td>
<td>6.2</td>
<td>1.9</td>
<td>11.8</td>
<td>0.085</td>
<td>0.053</td>
</tr>
<tr>
<td>150</td>
<td>200</td>
<td>50</td>
<td>6.4</td>
<td>2.0</td>
<td>12.8</td>
<td>0.078</td>
<td>0.12</td>
</tr>
<tr>
<td>180</td>
<td>240</td>
<td>60</td>
<td>6.5</td>
<td>2.2</td>
<td>14.3</td>
<td>0.070</td>
<td>0.22</td>
</tr>
<tr>
<td>210</td>
<td>280</td>
<td>70</td>
<td>6.4</td>
<td>2.4</td>
<td>15.4</td>
<td>0.065</td>
<td>0.36</td>
</tr>
<tr>
<td>240</td>
<td>320</td>
<td>80</td>
<td>6.2</td>
<td>2.5</td>
<td>15.5</td>
<td>0.0645</td>
<td>0.54</td>
</tr>
<tr>
<td>270</td>
<td>360</td>
<td>90</td>
<td>6.0</td>
<td>2.5</td>
<td>15.0</td>
<td>0.067</td>
<td>0.75</td>
</tr>
<tr>
<td>300</td>
<td>400</td>
<td>100</td>
<td>5.8</td>
<td>2.6</td>
<td>15.1</td>
<td>0.066</td>
<td>1.00</td>
</tr>
</tbody>
</table>

$\Sigma = 2.06x10^{14} \text{ev}^{-1} \text{cm}^{-2}$

The cross sections above are measured relative to $\sigma_t = 150 \text{mb at } E_{^{3}}He = 300 \text{keV}$. 49
\[ Y = [30 \text{ keV} \times 10^3 \text{ ev/keV} \times 150 \times 10^{-27} \text{ cm}^2] (\sum_{i} \frac{1}{\varepsilon_i} \sigma_{i,\text{rel}}) \]  
\hspace*{1cm} \text{(D4b)}

\[ = 4.5 \times 10^{-21} \times 2.06 \times 10^{14} = 9.3 \times 10^{-7} \]  
\hspace*{1cm} \text{(D4c)}

protons per $^3\text{He}$ incident

\[ 1 \mu \text{ amp } ^3\text{He}^+ = 6.25 \times 10^{12} \text{ sec}^{-1}, \text{ hence} \]  
\hspace*{1cm} \text{(D5)}

\[ Y = 5.8 \times 10^6 \text{ protons sec}^{-1} \mu \text{ amp}^{-1} \]  
\hspace*{1cm} \text{(D6)}

To find the proton yield for $^3\text{He}$ energies less than 300 keV, we multiply the yield for 300 keV by the ratio of the summation in Eq. (D4b) for the energy $E < 300$ keV to that for $E = 300$ keV.

In this way, we find:

\[ Y(90 \text{ keV}) = 0.01 Y(300) \quad Y(210) = 0.26 Y(300) \]  
\hspace*{1cm} \text{(D7)}

\[ Y(150) = 0.08 Y(300) \quad Y(240) = 0.43 Y(300) \]

The results D7 are plotted in Fig. 4 along with the cross section for the reaction $^2\text{H} \rightarrow ^3\text{He,p} \rightarrow ^4\text{He}$. 
APPENDIX E

Calculation of Analyzing Power and Scattering Efficiency of the Polarimeter

1. Calculation of Analyzing Power for the Polarimeter

a. General Considerations. Because of the great variety of proton trajectories and scatterings which are possible in most polarimeters, calculation of the analyzing power is no simple matter. For those applications in which a high degree of accuracy is required, Monte Carlo calculations have been used. However, since the primary aim of our experiment is to demonstrate polarization in the \(^3\)He beam and to make an estimate of its magnitude, a highly precise determination of the polarimeter analyzing power is not required. The analyzing power will be calculated for the simplest case: a proton beam which undergoes scattering along the polarimeter axis. Departures from this idealized case due to multiple scattering in the entrance foil and off-axial entry will be discussed along with other effects of finite scattering geometry.

The following three sections will be devoted to finding the distribution of proton energies and scattering angles in the polarimeter. These distributions will be used to weight the analyzing power of the reaction in calculating its average over the possible detectable scatterings in the polarimeter.

b. Proton Energy Losses Between Target and Polarimeter Scattering Volume. Table E-1 lists the energy losses of a proton traveling the 5 inches from the deu-
terium target to the scattering volume of the polarimeter through various media. Distances are measured along a line colinear with the polarimeter cylinder axis. These energy loss calculations are based on tabulated proton stopping powers and ranges found in Refs. 8 and 43.

TABLE E-1 Proton Energy Losses in Various Media Between Target and Polarimeter Scattering Volume

<table>
<thead>
<tr>
<th>MEDIUM</th>
<th>THICKNESS IN INCHES</th>
<th>ENERGY LOSS (KEV)</th>
<th>RESIDUAL ENERGY (MEV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>deuterium target material</td>
<td>--</td>
<td>≤ 25</td>
<td>14.7</td>
</tr>
<tr>
<td>aluminum foil</td>
<td>0.0008</td>
<td>100</td>
<td>14.6</td>
</tr>
<tr>
<td>Pilot B plastic scintillator</td>
<td>0.014</td>
<td>1300</td>
<td>13.3</td>
</tr>
<tr>
<td>aluminum foil</td>
<td>0.0005</td>
<td>100</td>
<td>13.2</td>
</tr>
<tr>
<td>air (1 atm., dry)</td>
<td>3.75</td>
<td>400</td>
<td>12.8</td>
</tr>
<tr>
<td>aluminum entrance window</td>
<td>0.006</td>
<td>1300</td>
<td>11.5</td>
</tr>
</tbody>
</table>

c. Proton Energy Losses in Helium Gas. The protons entering the helium gas in the polarimeter have an energy of approximately 11.5 MeV and travel in the gas for a distance of approximately 19 centimeters before striking the rear wall of the polarimeter. Since the pressure of the gas in the scattering volume is 35 atmospheres, the effective target thickness is 665 cm of one atmosphere helium.

The residual energy of a proton which has traveled a distance $s$ in the gas is found by subtracting $35s$ from the range of 11.5 MeV protons. The proton energy corresponding to this residual range is the residual energy. Using proton ranges from Ref. 43, we find, for example, that the residual
energy of protons striking the rear wall of the polarimeter after having traveled along the polarimeter axis is 6.0 MeV.

Taking into account those portions of the polarimeter axis which are not viewed by the detectors because of the vanes, we find that the range of energies over which protons are scattered and then detected is from 6.5 to 11.1 MeV.

d. Calculation of solid angle for polarimeter detectors. The surface of the scintillator in the A or B detector is divided into 19 identical portions by the brass vanes in the polarimeter. The solid angle as a function of angle has been calculated for scattering from the polarimeter axis onto one of these portions:

$$\Omega(\theta) \approx 0.092 \sin^2 \theta - 0.345 \sin^2 \theta \sin[60^\circ - \theta] \text{ steradian} \quad (E1)$$

The scattering situation as well as the approximations used in calculating $$\Omega(\theta)$$ are shown in Fig. 17. $$\Omega(\theta)$$ is used to average the analyzing power over the angular acceptance of the polarimeter. It is easy to show that the solid angle goes to zero for $$\theta = 48^\circ$$ and $$\theta = 75^\circ$$; these are the extreme scattering angles.

The average solid angle for scattering from the axis onto the detector along the 2.8 cm of the axis seen by this portion of the detector is

$$\frac{1}{19} \left\langle \Omega_t(\theta) \right\rangle = 0.025 \text{ steradian} \quad (E2a)$$

or, for the entire scintillator surface,

$$\left\langle \Omega_t(\theta) \right\rangle = 0.48 \text{ steradian} \quad (E2b)$$

The average solid angle will be used in calculating the
scattering efficiency of the polarimeter.

e. Calculation of $P_D$ from $P_P(\theta, E)$ for $^4\text{He}(p,p)$.

$P_D$ will be calculated for the axial beam. Values used for analyzing power and cross section are furnished us by Prof. W. Haeberli\textsuperscript{46}.

For a given energy and angle the polarization, $P_P(\theta, E)$, is weighted first by the laboratory cross section and relative detector solid angle for the energy and angle at which it is evaluated. Choice of angle is limited to those between $48^\circ$ and $75^\circ$, for which the solid angle is non-zero. For each energy interval, the average polarization $\langle P \rangle_E$ is computed:

$$\langle P \rangle_E = \sum_\theta P_A(\theta) \frac{\Omega(\theta)}{\Omega(0)} \frac{\sigma_L(\theta)}{\sigma_L(0)}$$

(E3)

where the summation is over those angles for which the analyzing power $P_A(\theta)$ is furnished and $\sigma_L(\theta)$ is the laboratory differential cross section for elastic scattering at proton energy $E_p$ and laboratory angle $\theta$.

Table E-2 illustrates the computation of $\langle P \rangle_E$ for $E_p = 7$ MeV. For the other energies involved, $\langle P \rangle_E$ is listed in table E-3.
Table E-2

Computation of average polarimeter analyzing power \( \langle P \rangle_E \) for protons of energy \( E_p = 7 \) MeV.

<table>
<thead>
<tr>
<th>( \theta_{\text{Lab}} )</th>
<th>( \theta_{\text{cm}} )</th>
<th>( \sigma(\theta_{\text{cm}}) )</th>
<th>( \sigma(\theta_{\text{Lab}}) )</th>
<th>( \sigma(\theta_{\text{Lab}}) )</th>
<th>( P ) (3)</th>
<th>( P ) (7)</th>
<th>( P ) (8)</th>
<th>( P ) (9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>66.9</td>
<td>0.50</td>
<td>173</td>
<td>1.29</td>
<td>223</td>
<td>-0.59</td>
<td>112</td>
<td>-66.1</td>
</tr>
<tr>
<td>60</td>
<td>72.6</td>
<td>1.00</td>
<td>143</td>
<td>1.24</td>
<td>177</td>
<td>-0.64</td>
<td>177</td>
<td>-113</td>
</tr>
<tr>
<td>65</td>
<td>78.2</td>
<td>0.73</td>
<td>116</td>
<td>1.20</td>
<td>139</td>
<td>-0.67</td>
<td>102</td>
<td>-68.3</td>
</tr>
<tr>
<td>70</td>
<td>83.7</td>
<td>0.40</td>
<td>93.1</td>
<td>1.15</td>
<td>107</td>
<td>-0.68</td>
<td>42.8-29.1</td>
<td></td>
</tr>
</tbody>
</table>

\[ \langle P \rangle_7 = \frac{\text{summation (9)}}{\text{summation (8)}} = -0.65 \]

Table E-3

Average polarimeter analyzing power \( \langle P \rangle_E \) for protons of energy \( E_p \).

<table>
<thead>
<tr>
<th>( E_p ) (MeV)</th>
<th>( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>-0.64</td>
</tr>
<tr>
<td>8</td>
<td>-0.65</td>
</tr>
<tr>
<td>9</td>
<td>-0.64</td>
</tr>
<tr>
<td>10</td>
<td>-0.63</td>
</tr>
<tr>
<td>11</td>
<td>-0.61</td>
</tr>
</tbody>
</table>

Next, the average polarization for energy \( E_p \) is weighted by the path length along that part of the beam axis viewed by the detectors on which the proton energy before scattering (6.5 to 11.1 MeV) is \( E_p + 0.5 \) MeV—which except for the case \( E_p = 11 \) MeV, where the upper limit is 11.1 MeV. Equivalently, we weight, for example, \( \langle P \rangle_7 \) by the differ-
ence in range $\Delta R_p$ of protons of energy 6.5 MeV and 7.5 MeV in $^4$He gas, NTP (the actual path length in the polarimeter along which the energy is $E_p + 0.5$ MeV is $\frac{\Delta R_p}{35}$, since the pressure in the polarimeter is 35 atmospheres), and similarly for the other $\langle P \rangle_E$. Proton ranges in helium are given in Table E-4, and the weights assigned $\langle P \rangle_E, W_E$, are given in Table E-5.

Table E-4
Ranges of protons of energy $E_p$ in $^4$He gas, NTP.

<table>
<thead>
<tr>
<th>$E_p$ (MeV)</th>
<th>$R_p$ (cm)</th>
<th>$R_p$ (cm)</th>
<th>$\Delta R_p$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>330</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7.5</td>
<td>430</td>
<td>100</td>
<td>2.9</td>
</tr>
<tr>
<td>8.5</td>
<td>540</td>
<td>110</td>
<td>3.1</td>
</tr>
<tr>
<td>9.5</td>
<td>660</td>
<td>120</td>
<td>3.4</td>
</tr>
<tr>
<td>10.5</td>
<td>795</td>
<td>135</td>
<td>3.9</td>
</tr>
<tr>
<td>11.1</td>
<td>828</td>
<td>83</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table E-5
Average analyzing power $\langle P \rangle_E$ for protons of energy $E_p$ weighted by the probability, $W_E$, that the proton energy before scattering is $E_p + 0.5$ MeV (for 11 MeV the upper limit is 11.1 MeV).

<table>
<thead>
<tr>
<th>$E_p$ (MeV)</th>
<th>$W_E$ (cm)</th>
<th>$W_E \cdot \langle P \rangle_E$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>100</td>
<td>-64</td>
</tr>
<tr>
<td>8</td>
<td>110</td>
<td>-71.5</td>
</tr>
<tr>
<td>9</td>
<td>120</td>
<td>-76.8</td>
</tr>
<tr>
<td>10</td>
<td>135</td>
<td>-85.1</td>
</tr>
<tr>
<td>11</td>
<td>83</td>
<td>-50.6</td>
</tr>
</tbody>
</table>
The mean analyzing power of the polarimeter for an axial beam, \( P_D \), is then
\[
P_D = \frac{\sum E P W_E \cdot \langle P \rangle_E}{\sum E W_E} = -0.64 \quad (E4)
\]

In the calculations leading to (E4) we have ignored attenuation of the beam intensity along the length of the polarimeter. In order for a proton to be removed from the beam before reaching a certain energy interval it would have to be scattered through an appreciable angle in a previous energy interval. Since the probability of these large angle scatterings is small, we can safely assume that the beam flux is very nearly constant for each of the proton energy intervals in the polarimeter.

A factor which has been neglected to this point and which will be discussed in the next section is the azimuthal dependence of the analyzing power which arises because some of the protons which are detected have been scattered in a direction which is not perpendicular to the axis of spin polarization.

f. Effects of Cff-Axial Entry and of Variations in Azimuthal Angle on the Preceding Calculation of \( P_D \).

Because of collimation of the proton beam by the trigger detector light-pipe and the polarimeter entrance slits, the beam can enter the polarimeter a maximum of 0.33 inches off the polarimeter axis and will travel nearly parallel to the axis regardless of the position of entry. Multiple scattering in the aluminum entrance window due to proton-electron encounters is found to be small, the rms angle is \( \sim 2^\circ \). Multiple scattering in the helium gas is also small \( \sim 3^\circ \). Because of the small multiple scattering and because
the beam enters the polarimeter nearly parallel to the polarimeter axis in any case (the mean angle of deviation is about $3^\circ$) the maximum divergence of the beam at the rear of the polarimeter is only about 0.75 inches off the axis.

Although the solid angle is increased almost two-fold for the protons which approach nearest the detector over those which travel along the beam axis, the angular acceptance is approximately the same for the high protons as for the on-axis protons. The same arguments apply to the protons which enter below the beam axis and detector—except for the solid angle, which is reduced two-fold from the on-axis situation. Therefore, the averaged analyzing power for off-axis protons is very nearly equal to that calculated for protons entering along the polarimeter axis.

There is a further geometrical factor which has an effect on the analyzing power, the azimuthal scattering angle $\phi$. The azimuthal angle is defined in the following manner: if the incoming proton beam in the polarimeter is incident along the $-z$ axis (incoming wave vector $k_\perp$ points in $+z$ direction) of a right-handed cartesian coordinate system, the polar scattering angle $\theta$ is the angle between $k_\perp$ and the wave vector $k_o$ of a scattered proton; the azimuthal angle $\phi$ is then the angle between the $+x$ axis and the projection of $k_o$ on the $xy$ plane. If we choose the $-y$ axis to be the direction of proton polarization for positive $^3$He beam polarization, $\phi = 0$ corresponds to scattering onto the midline of the A detector and $\phi = \pi$ to scattering onto the midline of the B detector.

$\left\langle \mathcal{F} \right\rangle$ in the preceding section (d) was evaluated $\phi = 0$. For an azimuthal angle $\phi$ the analyzing power of a
reaction is $P_D \cos \theta$. Therefore, for a detector which subtends a finite azimuthal angle about $\theta = 0$ (or $\theta = \pi$), the average value of $\cos \theta$ over the width of the detector, $\langle \cos \theta \rangle$, must be evaluated. The experimentally measured asymmetry is then divided by $\langle \cos \theta \rangle$ to correct for the effect of the azimuthal part of the finite scattering geometry.

Figure 18 shows the azimuthal angles for scattering from the polarimeter axis as well as from the extreme positions when the proton beam is at its highest (or lowest) approach to a scintillator and when it is at its farthest distance to the right (or left) of the axis. For protons scattered from along the polarimeter axis, the distance from the axis to the center of the detector is about 2.2 inches at an angle of 60°. $\theta$ varies from -25° to +25° over the 2 inch width of the detector. $\langle \cos \theta \rangle$ in this case is 0.97.

For the high-left beam, $\theta$ varies between -15° and +44°; $\langle \cos \theta \rangle = 0.91$. For the low-right beam, $\theta$ varies between -31° and 9°; $\langle \cos \theta \rangle = 0.96$. The solid angles of high, on-axis, and low beams are roughly in the ratio 1.7, 1.0, 0.65. Weighting the values of $\langle \cos \theta \rangle$ by these ratios gives the average value of $\langle \cos \theta \rangle$ over the polarimeter as 0.94.

The expression for the $^3$He beam polarization as a function of the experimentally measured asymmetry $\mathcal{A}$ is:

$$P_B = \frac{\mathcal{A}}{-0.67 \langle \cos \theta \rangle P_D} = \frac{\mathcal{A}}{0.67 \times 0.94 \times 0.64}$$

$$P_B = + 2.5 \mathcal{A} \quad (E5)$$
If the beam polarization is positive, the asymmetry will also be positive; for the arrangement of target and polarimeter shown in Figure 3, more counts will be observed in the upper counter than the lower counter when $^3$He nuclear spins are polarized along the direction of acceleration.

B. An Estimate of the Scattering Efficiency of the Polarimeter

The scattering efficiency, $E$, is defined to be the probability that a proton entering the polarimeter will be detected in either detector A or detector B. The scattering efficiency is given by the product of the number density of the helium gas, the scattering cross section at the scattering energy and angle, and the total detector solid angle. This product must, of course, be averaged over the energies and scattering angles of detected protons.

An approximate calculation of the scattering efficiency will be useful for comparing the polarimeter with other existing or hypothetical polarimeters. Also, the scattering efficiency is necessary to give an estimate of the time required for data acquisition.

The mean energy of the protons in the polarimeter is about 9.0 MeV, and the mean scattering angle is 60°. The laboratory cross section is about 172 mb/sr at this energy and angle. The average solid angle of each of the 38 sections of the two detectors is 0.025 sr for a target thickness of 2.8 cm (see p. 53). The atomic density of helium gas at a pressure of 35 atmospheres and a temperature of 20°C is $8.7 \times 10^{20}$ cm$^{-3}$. Using this information we find:

$$E = 4 \times 10^{-4} \quad (E6)$$
Since the solid angle subtended at the polarimeter entrance foil by the target is approximately $1.6 \times 10^{-2}$ sr, the counting rate $Y$ in the polarimeter is given by

$$Y = E \times \frac{1.6 \times 10^{-2} \text{sr}}{4\pi \text{sr}} \times n$$

$$= 5.1 \times 10^{-7} n$$  \hspace{1cm} (E7)

where $n$ is the rate of production of protons in the target.

In Appendix D, $n$ for a pure deuterium target is shown to be $5.8 \times 10^6 \text{ sec}^{-1} \mu \text{ amp}^{-1}$ at $^3\text{He}$ energy of 300 keV. Therefore, the counting rate will never be higher than $3 \text{ sec}^{-1} \mu \text{ amp}^{-1}$ for 300 keV $^3\text{He}$ ions and the geometries used in this experiment.
$V_1 = V_2 = 4C \times 300A$

$L_1 = 2$ turns #10 copper wire on $1\frac{1}{4}''$ form, center tapped
Calculating average cosine of azimuthal scattering angle.

\[ \langle \cos \phi \rangle = \frac{1}{\phi_j - \phi_i} \int_{\phi_i}^{\phi_j} \cos \phi \, d\phi \]

Figure 18.
REFERENCES AND NOTES

1. The spin dependence of the neutron-proton force, which was the first to be detected experimentally (J. Halpern, I. Estermann, O. C. Simpson, and O. Stern, Phys. Rev. 52, 142 (1937)), is discussed by S. DeBenedetti in Nuclear Interactions (John Wiley and Sons, New York, 1964, p. 42).


6. For example, it can be shown that the left right scattering asymmetry of the scattered particle in elastic scattering from a polarized target is equal to the spin polarization of the recoil particle in the same reaction with an unpolarized target. The argument used to establish this relationship is based on time reversal invariance [see G. Shapiro, in Progress in Nuclear Techniques and Instrumentation, F. J. M. Farley, ed., V. 1 (North Holland, Amsterdam, 1965) p. 175]. Use has been made of this relation to test $^3$He + p elastic scattering phase shifts by measuring proton scattering asymmetries from a polarized $^3$He target (D. H. McSherry, S. D. Baker, D. O. Findley, and C. C. Phillips, Bull. Am. Phys. Soc. 12, 189 (1967); also D. H. McSherry, M. A. Thesis, Rice University, May 1967).


18. Certain refinements in the theoretical description of optical pumping in $^3$He are discussed by W. A.


25. G. K. Walters, private communication.

26. The latest cell cleaning procedure is to include a small portion of hydrogen gas with the helium gas when the microwave discharge is struck to clean the cell. Otherwise the cleaning procedure remains as Stockwell described it (Ref. 23).

27. We are grateful to R. L. Gamblin for furnishing details and a photograph of the lamp used in Ref. 19.


38. G. J. Lush, T. C. Griffith, and D. C. Imrie [Nuclear Instruments and Methods 27, 229 (1964)] describe a helium filled proton polarimeter used on line at the 50 MeV Proton Linear Accelerator at the Rutherford Laboratory, Harwell. This polarimeter is very similar in design to the one to be used at Rice University on the polarized $^3$He ion source.


46. W. Haeberli, private communication. We are grateful to Prof. Haeberli for supplying these polarization and cross section data, which form the basis for the contour plot $P(\theta, E)$ for $^4\text{He}(p,p)$ in Fig. 7. The phase shifts from which $P_p$ and the cross sections are derived are fits to cross section data and to the experimental values of polarization from Ref. 32.
ACKNOWLEDGMENTS

Professors G. C. Phillips and G. K. Walters have not only marshalled the manpower and resources for the polarized ion source project but have also facilitated progress on the experiment by many fruitful suggestions. The author thanks these two men for serving on his thesis examination committee, also.

The polarimeter was designed by Dr. E. B. Carter, formerly of Rice University; his foresight in the design has been confirmed by experience.

Diana McSherry and Rus Simpson provided assistance for the polarimeter detector tests.

For financial assistance in the form of fellowships, the author is grateful to the Woodrow Wilson Foundation, Rice University, and the Atomic Energy Commission.

Lastly, the author expresses his heartfelt gratitude to his thesis advisor, Professor S. D. Baker, a teacher, for patient guidance, instruction, and friendship.