THE TRANSFER POLARIZATION OF THE D(d, n)$_3^\text{He}$ REACTION

AND

THE SCATTERING OF POLARIZED NEUTRONS FROM $^4\text{He}$ AND $^3\text{He}$

by

Paul W. Lisowski

Department of Physics
Duke University

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Richard L. Walter, Supervisor
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(Physics)

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1973
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Neutron polarizations produced by inducing the $D(d, n)^3\text{He}$ reaction with polarized deuterons were obtained for deuteron energies from 3.6 to 14.6 MeV in approximately 0.5 MeV steps. Determinations of the polarization were made by scattering the neutrons, produced at a reaction angle of $0^\circ$, from a high pressure $^4\text{He}$ gas scintillator. Neutrons which scattered through $120^\circ$ lab were detected by plastic side scintillators. Backgrounds were minimized by accepting only those helium-recoil pulses which satisfied energy and time-coincidence requirements. In a separate experiment the zero-degree tensor analysing power for the $D(d, n)^3\text{He}$ reaction was obtained from the ratio of the neutron intensity for deuteron beams with transverse spin to the intensity for deuteron beams with longitudinal spin. This analyzing power measurement was made in 0.5 MeV steps for deuteron energies from 1.5 to 15.2 MeV. For all of the above measurements, the quench ratio method was used to determine the deuteron beam polarization.
Zero-degree polarization transfer coefficients for the D(d, n)\(^3\)He reaction were then deduced from the neutron polarization and the zero degree analyzing power values.

In two other sets of measurements, precision angular distributions of the asymmetry for the scattering of 8.0, 12.0, and 17.1 MeV polarized neutrons from \(^3\)He, and 14.0 and 17.1 MeV neutrons from \(^4\)He were determined. A technique similar to that described previously in connection with the measurement of the zero-degree neutron transfer polarization was used. In this case the neutron-helium scattering angles were varied over the range from 40° to about 150° lab, in about 5° increments for the \(^3\)He(n, n)\(^3\)He work and in 10° increments in the \(^4\)He(n, n)\(^4\)He experiment.

An analysis of all of the available \(^3\)He differential cross-section, total cross-section, and polarization data was conducted in terms of phase shifts. Angular momenta of \(l \leq 3\) were included. The resulting set of real phase shift and inelastic parameters provides a convenient parameterization of \(^3\)He data from 1.0 to 23.7 MeV. The possibility of representing the \(^3\)He system by means of a standard optical model was investigated. The resulting parameters provide a reasonable representation of the data and are in most respects similar to those found in optical model analysis of scattering from heavier nuclei.

The \(^4\)He(n, n)\(^4\)He polarization data at 14.0 and 17.1 MeV were incorporated in a multi-energy R-matrix analysis of the p-\(^4\)He and
$n^{-4}$He systems below 20 MeV. The resulting $n^{-4}$He and $p^{-4}$He phase shifts provide an excellent parameterization of the data. The possibility of improving the optical model parameterization of $n^{-4}$He and $p^{-4}$He, particularly at energies above 14 MeV, was investigated. The resulting parameters varied smoothly with energy. The conclusion was reached that substantial improvements in the representation of $n^{-4}$He and $p^{-4}$He are possible and, for the best representation with smoothly varying parameters, that a global analysis of the two systems should be utilized.
ACKNOWLEDGMENTS

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P. W. L.
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Chapter I

INTRODUCTION

A. General

In recent years one of the most fruitful methods of obtaining information about the nuclear interaction, and about the spin dependent part of that interaction in particular, has been from the elastic scattering of polarized nucleons. Chiefly due to the rapid development of intense polarized ion sources, there is a great deal of accurate new information about proton elastic scattering, especially for light nuclei. Unfortunately, considerably less data has been produced by the corresponding neutron measurements, usually because these data must be obtained by the experimentally more difficult double scattering technique. Often the neutron and proton data are of equal significance for demonstrating nuclear phenomena or for testing theoretical predictions; but a detailed comparison of theoretical and experimental results is typically limited by the inaccuracy or lack of neutron data. Perhaps more important for future studies, inaccurate data or the analysis thereof might be used to calibrate new data and in that way lead to a succession of misinformation.
The experimental effort described in this dissertation was undertaken with the objective of obtaining more accurate neutron polarization data for $^3\text{He}(n,n)^3\text{He}$ and $^4\text{He}(n,n)^4\text{He}$. In order to accomplish these goals, a new and important tool in neutron polarization measurements, the use of a polarization transfer reaction as a source of polarized neutrons was investigated. As a result, the following information has been procured. First, the $C_0$ polarization transfer characteristics of the $D(d,n)^3\text{He}$ reaction and its analyzing power have been accurately determined. Second, polarized neutrons produced in the $D(d,n)^3\text{He}$ reaction initiated by polarized deuterons have been used to obtain $^3\text{He}(n,n)^3\text{He}$ and $^4\text{He}(n,n)^4\text{He}$ elastic scattering polarization angular distributions at several energies. Lastly, these data have been parameterized by phase shifts and also used in a new optical model formulation.

B. $D(d,n)^3\text{He}$ As a Source of Polarized Neutrons

One of the chief experimental difficulties in the investigation of the neutron-nucleus spin-orbit interaction has been the availability of good sources of polarized neutrons. Considerable effort has been expended in the investigation of such sources (Walter, 1970). The problem lies in the fact that the neutron is uncharged and cannot be accelerated by electrostatic forces even if some way were devised to develop a "polarized-neutron source" analogous to the recently available "polarized-ion source" for
charged particles. Therefore, the experimenter must rely on a nuclear reaction or scattering for the production of an energetic polarized neutron beam.

As was discussed by Walter (1970), even the best sources of polarized neutrons produced by an unpolarized incident beam are useful only over a restricted energy range and then quite often at an angle at which the differential cross section is at or near its minimum. The D(d, n)\(^3\)He reaction, for example, has been one of the most widely used sources, but the polarized neutrons have their greatest polarization near 45° (c.m.), an angle at which both the cross section and neutron energy are low compared to the corresponding cross section and energy at 0°. (Spalek et al., 1972; Hardekopf et al., 1972.) Hence the experimenter must deal with large unpolarized backgrounds of higher energy than the neutrons of interest. In addition, other choices of polarized neutron producing reactions often have a variation of the angle at which the maximum neutron polarization is produced, as well as a variation of neutron polarization with energy. In some cases the reaction chosen will have excited-state as well as ground-state neutrons, adding to background problems. Usually there must be a compromise between the high counting rate which could be available with a moderately thick target and the dilution and uncertainty of the neutron polarization associated with such a target because of these problems.

Fortunately, using a polarized incident beam to induce the neutron generating reaction changes things drastically. In the last few years,
certain reactions have been shown to transfer the polarization from the incident charged beam to the uncharged neutron with high efficiency. The measure of this exchanged polarization is called the polarization transfer coefficient, and will be discussed later in more detail. In connection with neutron polarization work, the transfer coefficient has been measured for the D(d, n) \(^3\)He, T(d, n) \(^4\)He, and T(p, n) \(^5\)He reactions (Simmons et al., 1971; Blythe et al., 1970; Broste et al., 1970; Donoghue et al., 1971; and Haight et al., 1972). A summary of the information pertaining to these reactions was presented by Simmons et al., (1973). He suggested that the best reaction available for producing beams of polarized neutrons with charged particles of energy less than 16 MeV is the D(d, n) \(^3\)He reaction induced by polarized deuterons.

Although the polarized beam is perhaps 100 times less intense than an unpolarized beam typically employed in gas target experiments, the figure of merit \(P^2I\) can be larger for polarized beams. Here \(I\) is the number of neutrons produced with polarization \(P\). It may be shown that the counting time necessary to attain a given statistical accuracy in a polarization measurement of the type done here is proportional to \(P^2I\). In addition, as is shown in Chapter IV, the transferred polarization at \(0^\circ\) is nearly constant with energy in the D(d, n) \(^3\)He reaction permitting the use of somewhat thicker targets when generating the primary polarized neutron beam with polarized deuterons, as well as permitting a fine gradation of \(E_d\) to get a high polarization for any \(E_n\) above 2.5 MeV. These con-
veniences are not available in any other reaction when unpolarized incident beams are used.

One of the goals of this dissertation has been a careful measurement of the transfer coefficient and the $O^0$ analyzing power of the $D(d,n)\,^3\text{He}$ reaction. This was done with two ideas in mind. First, it would provide sufficiently accurate information about the reaction to allow one to use the polarized neutrons for other experiments. And second, knowledge of the degree of polarization transfer and analyzing power as a function of energy would provide additional experimental information on the mass-4 system as well as on stripping mechanisms in light nuclei.

C. $^3\text{He}(n,n)\,^3\text{He}$

The similarity of neutron and proton elastic scattering from neighboring nuclei has long been recognized (Dodder and Gammel, 1952). In the $A = 4$ system it is possible to compare neutron and proton scattering from the mirror nuclei $T$ and $^3\text{He}$ which have identical structure except that the number of neutrons in $T$ equals the number of protons in $^3\text{He}$. Since the nuclear force is believed to be independent of the charge of the nucleon, the $n$-$n$, $n$-$p$, and $p$-$p$ interactions in the nucleus should be identical, except for restrictions arising from the Pauli exclusion principle. The relatively weak electromagnetic interaction, on the other hand, is additive. Therefore, in light nuclei, where the Coulomb forces are small, there
should be little distinction between the interaction involving \( n - ^3\text{He} \) and \( p - T \) or between \( p - ^3\text{He} \) and \( n - T \), at least at energies sufficiently far from the Coulomb barrier. Yet if one considers comparing \( p - ^3\text{He} \) and \( n - T \) data, the problem arises that the \( n - T \) data is quite scarce due to the experimental difficulties associated with using tritium targets. Heretofore a similar problem existed in the comparison of \( n - ^3\text{He} \) and \( p - T \) data.

In 1971 Hardekopf, Lisowski, Rhea, Walter and Clegg (1972) measured several angular distributions of \( T(p,p)T \) elastic scattering polarizations. They compared their results to the angular distributions of \( ^3\text{He}(n,n)^3\text{He} \) polarization data obtained by Behof et al. (1966), and Büscher et al. (1969), and showed strong differences between the two reactions. Simple calculations with and without the Coulomb interaction included could not explain the differences. In order to determine whether the differences were real, which in fact implies a lack of charge symmetry, we remeasured the \( ^3\text{He}(n,n)^3\text{He} \) polarizations at 8.0 and 12.0 MeV. In the present work we report these results along with data at 17.1 MeV, an energy unexplored previously. All of the available differential cross-section, total cross-section and polarization data were used successively in a complex phase shift analysis and in a concerted attempt to parameterize the scattering with a standard optical model formulation.
D. \( ^4\text{He}(n,n)\ ^4\text{He} \)

Virtually all recent neutron polarization measurements utilize scattering from \(^4\text{He}\) as an analyzer. Because the \(^4\text{He}(n,n)\ ^4\text{He}\) analyzing power has not been measured at the appropriate angles and energies for all experiments, it is usually necessary to rely on a parameterization of the data when particular information about n-\(^4\text{He}\) scattering is needed. The most widely used parameterization for the \(^4\text{He}(n,n)\ ^4\text{He}\) system is that of phase shifts. Unlike the \(^3\text{He} + n\) system, \(^4\text{He} + n\) has been extensively measured, and up to about 14 MeV each of several sets of phases predict very nearly the same result.

Above 14 MeV this agreement deteriorates (Rhea, 1970). An error of nearly 10% could be introduced in a neutron polarization experiment by using phase shift predictions from various authors to calculate the analyzing power. Furthermore, unexpected differences between the p-\(^4\text{He}\) and n-\(^4\text{He}\) systems were present at energies above 14 MeV and one usually tended to suspect the n-\(^4\text{He}\) data rather than to accept the differences as being truly nuclear phenomena.

Therefore, in order to provide more \(^4\text{He}(n,n)\ ^4\text{He}\) polarization data in this energy region we measured \(^4\text{He}(n,n)\ ^4\text{He}\) asymmetry angular distributions at 14.0 and 17.1 MeV with a greater accuracy than had been done previously. Using this new data and all available data for n-\(^4\text{He}\) and p-\(^4\text{He}\), phase shift comparisons and R-matrix analyses were carried out. In addition the data were fit using a standard optical potential model.
Chapter II

EXPERIMENTAL PROCEDURE

A. Introduction

For all of the experiments to be discussed here, polarized neutrons were generated at the reaction angle $0^0$ by bombarding a deuterium filled gas cell with polarized deuterons. The deuterons were produced by the TUNL Lamb-shift polarized ion source and accelerated by an FN tandem Van de Graaff accelerator. The asymmetries for scattering polarized neutrons were measured using a standard neutron polarimeter. The requisite parameters $A_{zz}(0^0)$ for the D(d,n) $^3$He reaction were determined by comparing relative yields measured for different, specified deuteron spin orientations. Presented in the following sections are descriptions of the experimental apparatus utilized in the above measurements, the methods for collecting, storing, and analyzing the data, and some basic definitions of the symbols employed.
E. Lamb-Shift Polarized Ion Source

The operating principles and applications of various types of polarized ion sources were reviewed by Hasberli in 1967. Methods utilizing the metastable 2S state of hydrogen or deuterium, such as are employed in the polarized source at this laboratory, were presented by Cesati et al. (1969). The TUNL and Los Alamos Lamb-shift sources are quite similar in both design and operation. Descriptions of these sources are given by Ohlsen (1970), McKibben et al. (1963), Lawrence et al. (1969), Clegg (1970, 1971), and Hardekopf (1971). Therefore only the salient features of the TUNL source as they apply to deuterons will be presented here. Figure 1 shows a schematic of the TUNL source used in these experiments.

When operating to produce a deuteron beam, the TUNL polarized source uses an intense positive ion source known as a duoplasmatron to provide deuterium ions at an energy of 1100 eV. By means of charge transfer in cesium vapor, neutral deuterium atoms are formed in the metastable D(2S) excited state. A pair of electrostatic deflection plates just after the cesium charge exchange are used to remove any charged component remaining in the beam. The neutral atomic beam then passes into a region of uniform solenoidal magnetic fields which are part of a resonant interference device known as a nuclear spin filter. The magnetic fields produce Zeeman splitting of the Deuterium atomic energy levels. At a magnetic field of 575 gauss, for example, the \( m_1 = -1 \) levels of the \( 2S_{1/2} \) state and the \( m_1 = +1 \) levels of the \( 2P_{1/2} \) state are energy degenerate. Application
Figure 1. Schematic Diagram of Polarized Ion Source
of a small transverse d.c. electric field causes mixing between the two states due to the Stark effect, with the $m_I = -1$ levels decaying quickly to the ground state. This is called quenching. In addition to the d.c. field and magnetic field, an r.f. electric field of 1309 MHz is applied to a carefully designed cavity through which the beam passes. A three-level interaction takes place (Lamb and Retherford, 1950) such that only the $m_I = +1$ level survives, all the others having been quenched to the ground state.

The spin filter may be tuned by adjusting the magnitude of the axial magnetic field to transmit only D(2S) atoms with one of the desired quantum numbers $m_I = +1$, $m_I = 0$, or $m_I = -1$. Figure 2 shows a scan of the ion source current as a function of the magnetic field in the spin filter region. Figures 3 and 4 show the corresponding vector and tensor polarizations as measured by $^4\text{He}(d, d)^4\text{He}$ elastic scattering at 12.0 MeV and $\theta = 30$ degrees lab, where the analyzing powers are accurately known (Ohlsen et al., 1973; Clegg, 1973).

After leaving the spin filter the D(2S) atomic beam is ionized by charge transfer in argon gas, a process which preferentially ionizes the atoms in the D(2S) state. The deuteron spin alignment axis is determined at the time of ionization by a small guide magnetic field in the argon region. As a result, the deuteron alignment axis points along (or opposed to) the axis of the source. By deflecting the beam by 90 degrees using an electrostatic mirror, the alignment axis is left perpendicular to the beam direction and can be precessed by a spin precession solenoid (SRS 1) to a given
Figure 2. Polarized Ion Source Beam Current as a Function of Spin-Filter Magnetic Field

Figure 3. Deuteron Vector Polarization \( (p_z) \) as a Function of Spin-Filter Magnetic Field
Figure 4. Deuteron Tensor Polarization ($p_{zz}$) as a Function of Spin-Filter Magnetic Field
angle. The beam is then deflected 90 degrees onto the tandem accelerator beam tube axis. For the case where the alignment axis is vertical (spin either UP or DOWN), the alignment direction may be changed by 180 degrees by reversing only the polarity of the guide field in the source argon region (and all other magnetic fields in the spin filter region to insure against field inhomogeneity).

An additional advantage of this method is that almost no additional focusing or beam steering will occur when the spin is flipped, as the beam in the spin filter region is largely composed of neutral metastable atoms, and the field in the argon region is small (\(\sim 6 \text{ G} \)) for the selection of \(m_I = \pm 1\) deuterons which we chose. This is important because the spin rotation solenoid acts on the beam as a focusing devices whose effect is different for different current directions. For protons the current required for 90 degree spin precession is approximately 1/5 that required for deuterons, hence the focusing effects are much more serious for deuterons, and tend to drastically reduce beam transmission from the polarized source through the accelerator.

C. Deuteron Beam Polarization

The quench ratio method of determining deuteron polarizations was used for the \(^3\text{He}(n,n)\) \(^3\text{He}\) measurement at 17.1 MeV, and for all of the \(D(d,n)\) \(^3\text{He}\) and \(^4\text{He}(n,n)\) \(^4\text{He}\) experiments. The quench ratio method
was first described by Ohlsen (1971) in a discussion of proton beam polarization determinations. Ohlsen showed that it is possible to accurately determine the proton polarization produced in a Lamb-shift source by atomic beam methods. Experiments conducted at TUNL (Lisowski et al., 1973; Clegg, 1973) confirmed that the quench ratio method is a reliable means for monitoring both proton and deuteron polarizations.

In normal operation the method is straightforward and can be presented simply as follows: The output from the polarized source consists of a polarized component $I$ and an unpolarized background $I_b$ which remains when all of the D(2S) atoms are quenched to the ground state. The polarization is thus determined from the fraction of the total beam which originated from the 100% polarized D(2S) atoms. This number is $P = (I - I_b)/I$. For deuteron output in the $m_I = +1$ spin state, the vector and tensor beam components are equal in polarization, and the magnitude of this polarization is given by $P$. Additional discussion of the quench ratio method is given by Ohlsen (1970) and Trainor (1973).

In the earliest studies, concern existed as to the accuracy which could be achieved with the quench ratio. In fact, for the first studies, the $^3$He(n, n)$^3$He experiments at 8.0 and 12.0 MeV, the deuteron polarization was measured by means of the $^3$He(d, p)$^4$He reaction at 0 degrees. The 0 degree analyzing power, $A_{zz}$, of $^3$He(d, p)$^4$He is large and smoothly varying from 2 to 15.5 MeV (Gruebier et al., 1971; Lisowski et al., 1973). Values of $A_{zz}(0^0)$ were taken from smooth curves through the data obtained
by fitting with a polynomial over a limited energy region.

The deuterón beam polarization was measured before and after each neutron polarization data point by bombarding a gas cell filled with $^3\text{He}$ (located at the center of a scattering chamber on a neighboring beam leg) and taking ratios of the proton yield for two different alignment axis settings. As the $^3\text{He}(d,p)$ reaction has a large positive Q-value (18.4 MeV) it was possible to stop the deuterons in 0.05 mm stainless steel and yet transmit the protons which lost only a small fraction of their energy. The protons were additionally slowed down by means of aluminum absorbers so that they would stop in a 2 mm silicon surface barrier detector located on the deuteron beam axis, i.e., at a $(d,p)$ reaction angle of zero degrees. A sequence of spin UP, spin ALONG, $^1$ spin DOWN measurements were used to determine the deuteron polarization.

D. Neutron Polarimeter

The neutron polarimeter used for these measurements was described in detail by Meier (1969) and Taylor (1971). The only features

\footnote{For experiments in which the beam momentum is not in the same direction at the target as upon entrance to the accelerator, the deuteron alignment axis does not point exactly along $k_{in}$, but deviates a few degrees due to the difference in spin and momentum rotation in the analyzing magnet field. This angle is calculated in Appendix A.}
which were changed were the gas target arrangement and the fact that the neutron spin was flipped by inverting the deuteron spin at the polarized source instead of using the high-current solenoid on the polarimeter.

A schematic of the set-up is shown in Figure 5. Polarized deuterons bombarded a long, cylindrical deuterium-filled gas target. The end of the gas cell was positioned inside the polarimeter solenoid, which for the sake of clarity is not shown in Figure 5. This placement was required in order to decrease the target-to-helium-cell distance without removing the solenoid from the polarimeter stand (a formidable task) as well as providing shielding for the side detectors from the primary neutron flux. Polarized neutrons from the $D(d,n)\, ^3\text{He}$ reaction emitted at 0 degrees were scattered from a high pressure helium scintillator. Details of the helium cell and target gas pressures, gas mixtures and center detector to side detector distances are given in Table 1.

In the elastic scattering experiments a fairly broad neutron energy spread could be tolerated due to the smooth change in energy of each of the experimental polarizations. Deuterium gas pressures for these experiments were adjusted to give a typical deuteron energy loss of 750 keV.

Neutrons which scattered from the $^4\text{He}$ at the correct angle $\theta$ were detected by two 5.0 x 7.5 x 15 cm$^3$ plastic scintillators viewed by magnetically- and electrostatically- shielded 6810A photomultiplier tubes on tapered light pipes. A conical polythene collimator in the solenoid restricted the angular spread in the primary neutron beam to $\pm 2.2$ degrees.
Figure 5. Schematic Diagram of Neutron Polarimeter
<table>
<thead>
<tr>
<th>D(d,n)^3He</th>
<th>A(zz) (O°)</th>
<th>E(d)</th>
<th>Gas Cell Entrance Hauar Foil Thickness (µm)</th>
<th>Gas Cell Length (cm)</th>
<th>Typical Energy Loss to Cell Center (keV)</th>
<th>Helium Cell Pressure (psig)</th>
<th>Helium Cell to Side Detector Distance (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E(d)=3.0 to 7.0 MeV</td>
<td>2.5</td>
<td>7.62</td>
<td>150</td>
<td>2550</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E(d)=7.5 to 15.0 MeV</td>
<td>6.3</td>
<td>5.08</td>
<td>100</td>
<td>2550</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D(d,n)^3He K(y) (O°)</td>
<td>E(d)=4.5 to 7.0 MeV</td>
<td>2.5</td>
<td>7.62</td>
<td>200</td>
<td>2550</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>E(d)=7.5 to 15.0 MeV</td>
<td>6.3</td>
<td>5.08</td>
<td>200</td>
<td>2550</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>^3He(n,n)^3He</td>
<td>P(θ)</td>
<td>E(d)=9.8 MeV E(n)=12.0 MeV</td>
<td>8.3</td>
<td>23.0</td>
<td>450</td>
<td>860</td>
<td>19.0</td>
</tr>
<tr>
<td>E(d)=5.6 MeV E(n)=8.0 MeV</td>
<td>8.3</td>
<td>23.0</td>
<td>450</td>
<td>860</td>
<td>19.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E(d)=14.3 MeV E(n)=17.1 MeV</td>
<td>8.3</td>
<td>3.0</td>
<td>500</td>
<td>860</td>
<td>19.0 for θ≤120°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>24.1 for θ&gt;120°</td>
<td></td>
</tr>
<tr>
<td>^4He(n,n)^4He</td>
<td>P(θ)</td>
<td>E(d)=14.3 MeV E(n)=17.1 MeV</td>
<td>8.3</td>
<td>3.0</td>
<td>500</td>
<td>2650</td>
<td>24.1 for θ≤120°</td>
</tr>
<tr>
<td>E(d)=11.7 MeV E(n)=14.0 MeV</td>
<td>6.3</td>
<td>3.0</td>
<td>330</td>
<td>2000</td>
<td>24.1 for θ≤120°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>29.2 for θ&gt;120°</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6 shows a typical experimental arrangement used in the polarization experiments.

For the measurement of $A_{zz}(0^0)$ for the $D(d,n)\ ^3\text{He}$ reaction, the polarimeter frame was used only to support the helium cell and position it at $\theta = 0^0$. In this experiment precise beam current measurement was necessary over the time span of each data point. Since the quantity of interest was determined from a ratio of cross sections, absolute beam current integration was not really necessary, although the arrangement discussed below probably allowed quite accurate integration. A modification of the gas cell to insure good beam integration included the insertion of a 0.9 cm diameter suppressor ring in front of the gas cell at a potential of -300 V and an overall shortening of the target to be sure that the beam did not spread enough to strike the foil holder or far walls of the gas cell.

The gas cell was positioned outside the solenoid 105 cm from the helium cell center for these determinations. A tapered polyethylene collimator inside the solenoid limited the neutron angular spread to ±1.1 degrees.

E. Neutron Polarization

For nuclear reactions involving a spin 1 projectile and a spin 1/2 ejectile detected at $\theta = 0^0$ there are three general expressions for the intensity and polarization of the outgoing particles (Goldfarb, 1958;
Ohlsen, 1972). For the specific case in which the beam polarization possesses an axis of symmetry oriented along the y-axis, as can be arranged with a polarized ion source, these expressions reduce to

\[ \sigma(\theta^o) = \sigma_0(\theta^o) \left[ 1 + \frac{1}{2} A_{zz}(\theta^o) \ p_{zz}(3\cos^2\beta - 1) \right] \]  
(1)

\[ p_{ny}(\theta^o) = \sigma_0(\theta^o) \left[ \frac{3}{2} K_y(\theta^o) \ p_z \sin\beta \cos\phi \right] \]  
(2)

\( \sigma_0(\theta^o) \) is the zero-degree differential cross section for an unpolarized beam. The quantities \( p_z \sin\beta \cos\phi \) and \( p_{zz}(3\cos^2\beta - 1) \) represent the vector and tensor polarizations of the beam referred to a right-handed coordinate system (xyz) with z along \( \hat{k}_{in} \) and y chosen to be in the vertical direction (the usual choice for \( \theta \neq 0^o \) experiments is y along \( \hat{k}_{in} \times \hat{k}_{out} \). But for \( \theta = 0^o \), \( \hat{k}_{in} \times \hat{k}_{out} \) is undefined; so the choice of y is arbitrary). In (1) and (2) \( \beta \) and \( \phi \) are the angles which give the orientation of the alignment axis (S) of the beam as shown in Figure 7.

\( A_{zz}(\theta^o) \) is the only non-zero analyzing tensor at \( 0^o \). \( K_y(\theta^o) \) is called the polarization transfer coefficient and \( p_{ny} \) is the observed neutron polarization.

For polarization transfer reactions in general it is convenient to choose two coordinate systems, one in which z is along \( \hat{k}_{in} \) (the initial coordinate system for the reaction system which is defined by \( x, y, z \)), and one in which the z' axis is along \( \hat{k}_{out} \) (the final coordinate system for the reaction, which is defined by \( x', y', z' \)). For \( 0^o \) experiments these may be the same as shown in Figure 5, and we may omit the primes on all of the superscripts.
Figure 7. Coordinate System for $D(d,n)^3\text{He}$ Reaction
In a simple view $A_{zz}$ represents that part of the nuclear reaction which is sensitive to the $p_{zz}$ component of the beam ($p_{zz} = \frac{3}{2} k_y (O^0) p_z (3 \cos^2 \beta - 1)$), and $k_y$ represents that fraction of the incident vector polarization which is "transferred" to the ejectile. The limits on $A_{zz}$ and $k_y$ are $-2 \leq A_{zz} \leq +1$ and $-1 \leq k_y \leq +1$, respectively. The ranges for the other parameters for the deuteron beam in the $m_1 = 1$ spin state, are $0 \leq p_z \leq +1$ and $0 \leq p_{zz} \leq +1$.

Solving Equations (1) and (2) for $p_{ny}$ gives

$$p_{ny} = \frac{\frac{3}{2} k_y (O^0) p_z \sin \beta \cos \phi}{1 + \frac{1}{2} A_{zz} (O^0) p_{zz} (3 \cos^2 \beta - 1)} \tag{3}$$

The case of maximum neutron polarization results from spin up ($\beta = \pi/2$, $\phi = 0$) or spin down ($\beta = \pi/2$, $\phi = \pi$). For these two choices we have

$$p_{ny} = \pm \frac{3}{2} k_y (O^0) p_z \tag{4}$$

where the +/- sign applies for spin up/down. Since the second scattering occurs in the plane perpendicular to the $y$ axis the neutron spin direction is determined by the deuteron spin.

The polarized neutron beam has no essential difference from one produced by means of an unpolarized incident beam and therefore the
techniques used in determining the analyzing power or polarization produced in the second reaction are the same. The backgrounds, however, will in general depend on the spin alignment of the deuteron and some different procedures must be adopted to account for this.

F. Electronics

A typical block diagram of the electronics setup is shown in Figure 8. Fast pulses from the right and left phototube anodes triggered fast discriminators producing logic signals which were input to a strobed coincidence unit. By delaying each logic signal by 70 ns and then feeding the signal to the strobed coincidence, accidental coincidences were also measured simultaneously with valid coincidences. A coincidence between the direct or the delayed side detector pulse and the strobe provided by the helium cell fast signal, produced an output at the appropriate terminal of the coincidence unit. These signals were then sent through logic shapers and routed into the computer.

In order to ensure the coincident arrival of the side detector and helium cell signals at the strobe, a time of flight spectrum was generated by starting a time-to-amplitude converter (TAC) with the fast logic signal from the helium cell and stopping it with a fast logic signal from one of the side detectors. This TAC spectrum was stored in a 100 channel block of a multichannel analyzer (MCA) gated by the output of a single
Figure 8. Block Diagram of Neutron Polarization Electronics
channel analyzer whose window was set on the helium-recoil spectrum "knee". In this way the neutron peak was easily distinguished from the background. Another TAC spectrum in which the MCA was gated by the coincidence output from the strobe was stored in a second block. This spectrum indicated the degree of pulse overlap of side detector and helium cell signals in the strobe coincidence unit and took the form of a "window" on the TAC spectrum. This window was made to coincide with the previously obtained neutron peak by adjusting delay cables between the discriminator and strobe coincidence. The overlap or window width was adjusted by changing the width of the output pulse from the discriminator before input to the strobe. Pulse widths were adjusted to give the same number of channels for foregrounds and backgrounds by taking spectra gated by the appropriate signal.

In all of the measurements reported here, the random coincidence events were only a small fraction of the true coincidence counts. This permitted the use of a relatively wide coincidence window. Resolving times for these experiments were 8 to 15 nanoseconds. This broad time interval made it possible to be less cautious about timing changes with neutron energy. A typical linear gated TAC spectrum and the corresponding coincidence window TAC spectrum are shown in Figure 9. For these spectra the neutron energy was 11.1 MeV at $\theta_{\text{lab}} = 120^\circ$. The time calibration was 0.5 nanosecond/channel.
Figure 9. Typical Time of Flight Spectra
G. Data Acquisition

The techniques involved in acquisition of polarization data in experiments utilizing polarization transfer reactions are similar to those in more conventional polarization experiments. A discussion of the latter techniques was recently given by Hardekopf (1971). In the polarization transfer measurements to be reported here, the neutron polarization produced in the initial reaction was measured by scattering from $^4$He. In the elastic scattering experiments the asymmetry $\xi(\theta)$ produced in the scattering of neutrons of known polarization $P_{in}$ (generated through the polarization transfer reaction) was measured, yielding a determination of the polarization $P_{out}(\theta)$. In either case the data to be taken were the left-right asymmetry and the beam polarization.

The measurement of $A_{zz}^{(0)}$ was accomplished without the difficulty of coincidence circuitry. For this measurement only the ratio of counting rates in the helium cell for two known values of the deuteron polarization were necessary.

The data acquisition program PUNT was written by the author for use with experiments involving polarization transfer reactions. The basic features are the same as those of NPOL, the data collection for experiments using unpolarized incident beams. Whereas NPOL provides computer control of the spin precession solenoid on the polarimeter, PUNT sets the polarized neutron spin direction by computer control of the direction of the guide field in the argon region of the polarized ion
source. In addition PUNT provides automatic or manual beam polarization measurement using computer controlled quench ratios.

PUNT stores both coincidence and recoil spectra in a data block of 8 x 128 channels. In addition a SUM spectrum consisting of the RIGHT and LEFT true coincidence counts minus the RIGHT and LEFT accidental counts is periodically calculated and displayed. Asymmetry calculations are made from points selected by light pen in the SUM spectrum. This procedure guarantees that the same channels are selected for each spin direction.

By collecting data in spin UP and spin DOWN sequences and combining the number of counts using geometric means, PUNT calculates the neutron asymmetry in a manner independent of the detector efficiency or current integration (Haeberli, 1963). The usual procedure is to take data in the sequence QUUDQDUQ where Q stands for a deuteron beam polarization measurement by computer controlled QUENCH and U or D stands for deuteron spin incident UP or DOWN. Additional information on PUNT is contained in Appendix B.

For the 0 degree analyzing power data PUNT was used in a manual mode and stored only the helium recoil counts. Different data blocks were used for each of two deuteron spin orientations and the computer controlled quench was used to measure the beam polarization.
Chapter III

DATA REDUCTION

A. Analysis of Spectra--Polarization Experiments

Typical coincidence gated recoil gated spectra from the polarization measurements are shown in Figure 10. These data represent the sum of the four (left and right; spin UP and DOWN) true-coincidence spectra minus the four "accidental" or random-coincidence spectra. In order to obtain reliable asymmetry information from these data, off-line reduction was necessary. The resulting data had to be corrected for finite geometry and multiple scattering effects.

The asymmetries were calculated using the geometric mean of the total number of counts after background subtraction. In the present notation the asymmetry is

\[ \epsilon = \frac{r - 1}{r + 1} \]  \hspace{1cm} (5)

where

\[ r = \sqrt[3]{\frac{N_L^+ N_R^+}{N_L^- N_R^-}} \]  \hspace{1cm} (6)

The \( N_L^+ \) stands for the net number of counts in the left detector obtained with spin UP, etc.
In the transfer coefficient experiment the measured neutron polarization was obtained from the relation
\[ P_{ny}(\sigma^r) = \frac{\varepsilon(\theta)}{\overline{P}(\theta)} \]  
(7)

where \( \overline{P}(\theta) \) was the average polarimeter analyzing power calculated by MOCCASINS.

For the elastic scattering results the quoted polarizations were calculated using the expression
\[ \overline{P}(\theta) = G(\theta) \varepsilon(\theta) / P_{ny}(\sigma^r) \]  
(8)

where the quantity \( G(\theta) \) is taken to be the ratio of the point analyzing power to the average analyzing power from MOCCASINS.

The off-line analysis was carried out by means of a modified version of the data collection program. This code, named PUNT-\( \alpha \), permitted off-line summing and linear-background subtraction. Initial investigations of the spectra obtained in the 12-MeV \( ^3\text{He}(n,n)^3\text{He} \) experiment were made using the "gaussian + unpolarized" background fitting program ASP, (Taylor, 1971). These studies showed that the background near the peak was at least partially polarized. Therefore, it was not possible to assume that the background under the peak itself was unpolarized, as such an assumption would have introduced a systematic error in the asymmetry values.

A number of backgrounds had to be carefully investigated.

The lower half of Figure 11 shows a 12-MeV coincidence sum spectrum
Figure 11. Typical Summed Spectra Taken with Deuterium Filled Target (top) and with Evacuated Target (bottom)
taken with the target cell evacuated. This graph demonstrates that this type of background extended midway under the peak. Analysis showed that it had an asymmetry nearly equal to that of the peak. A linear background chosen by averaging the counts in a region just below the peak and drawing a line from the midpoint of the average to a point on the (pulse height) x-axis was taken to be a reasonable approximation to the true background line shape. By estimating the maximum and minimum extents of the background under the peak, a median value could be obtained. The cross-hatched region of Figure 11 shows typical background levels. Such maximum and minimum choices typically changed the asymmetry by less than 0.004 from the value with a median background. Additional information about the nature of the background was obtained by means of extracting asymmetries calculated channel-by-channel or from the asymmetries of blocks of channels beginning at a low pulse height and extending to beyond the peak. Plots of these results, which will be discussed later, show that the background was indeed polarized.

In the polarization-transfer coefficient experiments, it was possible to examine the dependence of the background polarization on neutron energy. It was found that at the highest energies the channel-by-channel asymmetry was so nearly constant across the coincidence peak that little or no background subtraction was necessary, provided summing limits were carefully chosen. This is a reasonable result
since a polarized background of nearly the same polarization as the peak
cannot be detrimental to the determination of the final asymmetry value
extracted from the data. As the neutron energy became lower, the
unpolarized component in the background grew, until at the lowest
energies, the polarization of the subtracted background was essentially
zero. These results are shown in the lower half of Figure 10. In the
upper half are shown the corresponding sum spectra. The lines are not
fitted curves, but are included as a guide to the eye. The detectors were
at $\theta = 120^\circ$ in the laboratory system when the spectra were recorded.

In the previous experiments the assumption was made that the
accidental-coincidence events as well as the backgrounds were un-
polarized. However in the present experiments with polarized deuteron
beams, the neutron background was definitely polarized. Furthermore,
the neutron flux as a function of $D(d,n)$ $^3$He reaction angle was different
for different deuteron spin directions so that the accidental backgrounds
had to be subtracted taking the possibility of polarized accidental back-
grounds into account. For these reasons the individual accidental back-
ground coincidence spectra were subtracted from the appropriate true
coincidence spectra before making any calculations.

B. Corrections to the Measured Asymmetries

Geometry and Multiple Scattering. -- The $^3$He data were
corrected for finite geometry effects using a modified version of the code MOCCASINS. This code has been employed previously for evaluating geometry and multiple scattering corrections and is based on the Monte Carlo method (Sawers, 1966). In this case a calculation of cross sections and polarizations from spin 1/2 on spin 1/2 phase shifts was substituted for the usual spin 1/2 on spin 0 part of the program. For the 8.0 and 12.0 MeV data these phase shifts were taken from polynomial fits to the T(p,p)T phase shift results of Hardekopf et al. (1972). For the 17.1 MeV $^3$He(n,n)$^3$He data, phase shifts from a smooth curve through the results of single energy fits to cross section and polarization data at several energies were available.

The $^4$He(n,n)$^4$He data were corrected by MOCCASINS for finite geometry and multiple scattering using the Stammbach-Walter (Stammbach and Walter, 1972) phase shifts to generate the appropriate cross sections, polarizations, and in the case of multiple scattering, spin rotation effects. The maximum geometry and multiple scattering corrections were approximately 5%, with a typical correction of less than 3% for 29.2 cm He cell to side detector distance.

**Neutron Scattering from Scintillator Walls.** -- The correction to the asymmetry measurements due to neutron scattering from the iron walls of the scintillation cell was first investigated at this laboratory by Sawers (1966). He concluded that the iron multiple scattering, for
low neutron energies, contributed to a non-subtracting background. An experimental check by Sawers showed that the magnitude of the effect was consistent with the results of a simple calculation and that proper background subtraction made the effect negligible.

Tornow et al. (1973) present the results of an absolute measurement of the \( n^4\text{He} \) polarization at 15 MeV. Included in their result was a calculation of the wall scattering effect. Because the correction for their case was so large (approximately 0.06 out of an asymmetry of 0.44), an investigation of the effect of neutrons scattered from the iron scintillator walls was made.

The code MOCCASINS was used to calculate the effect on the measured asymmetry due to wall scattering. The following assumptions were made.

1) The \( \text{Fe}(n,n)\text{Fe} \) cross section was appreciable only at forward angles, so back-scattering events could be ignored. Inelastic events were also ignored.

2) \( n\)-\( \text{Fe-He} \) and \( n\)-\( \text{He-Fe} \) type events were assumed to be equivalent, so calculations were made from a projection onto the front wall of random points chosen in the helium volume. These projected points were used as the source of wall scattering and were counted twice to account for both types of events.
3) The iron responsible for wall scattering should be the amount in the helium cell wall illuminated by the primary neutron beam for n-Fe-He events. For n-He-Fe events the amount should be that in approximately 1/2 of the scintillation wall area. The iron correction was therefore calculated for a ratio of iron to helium nuclei equal to the average.

4) The effect of D, R, and A (Wolfenstein, 1956), for scattering from iron was assumed to be unimportant and was therefore ignored.

For these investigations, $^{56}$Fe(n,n)$^{56}$Fe cross sections and polarizations were calculated at 4, 8, 12, 16, and 20 MeV from optical model parameters given by Bechetti and Greenlees (1969), with a compound nucleus (CN) contribution. The CN contribution was estimated so as to give minima in the differential cross sections of approximately the correct magnitude by comparison with data taken from BNL-400 (Garber et al., 1970). It was found that the spin-cutoff and fluctuation parameters for the (compound nucleus) Hauser-Feshbach calculation, which are used in the optical model code OPTICS (Eastgate et al., 1973) could be taken as $S = 2.9$ and $H = 1.2 - E/2.0$, to give reasonable agreement with measured differential cross sections. Data at intermediate energies were interpolated from that previously calculated. For the total cross section, smoothed values were taken from a compilation from Karlsruhe (Clerjacks et al., 1968).
It was found that the correction calculated by MOCCASINS scaled in proportion to the ratio of the number of iron nuclei in the scintillator wall to the number of helium nuclei in the helium cell volume. For a typical ratio of iron nuclei/helium nuclei = 0.83, corresponding to 2.2\(^{\circ}\) illumination of a helium cell of pressure of 173 atm, the magnitude of the correction was calculated to be less than 0.01 at 14.0 MeV and 120\(^{\circ}\) lab. The point polarization, geometry averaged polarization, and the geometry and multiple scattering polarization with and without iron scattering is shown for \(^4\text{He}(n,n)^4\text{He}\) in Figure 12. Here the regions around 120\(^{\circ}\) and 80\(^{\circ}\) in the laboratory system have been expanded to amplify the correction. The iron multiple scattering corrections which were based on 10\(^{\circ}\) angle increments in the iron cross-section and polarization data were applied to the 2-1/2\(^{\circ}\) calculations for the point polarization and helium-only multiple scattering in Figure 12.

In order to experimentally investigate the iron scattering effect, \(^4\text{He}(n,n)^4\text{He}\) asymmetries were measured at neutron energies of 11.1 and 16.0 MeV at 120\(^{\circ}\) in the laboratory system, and at 14.0 and 17.1 MeV at 80\(^{\circ}\) in the laboratory system, with and without a 0.23 cm iron cylinder around the helium cell. This amount of iron represented an increase of approximately 150\% of the wall thickness. For all of the measurements made, the asymmetries with and without additional iron agreed to within the statistical error of the measurement.
Figure 12. Average Analyzing Powers Calculated by MOCCASINS

- Point Geometry
- Geometry + Helium Multiple Scattering
- Geometry + Helium and Iron Multiple Scattering
Table 2 presents these results.

<table>
<thead>
<tr>
<th>Neutron Energy (MeV)</th>
<th>$\Theta$ lab</th>
<th>$\epsilon$ Without Iron</th>
<th>$\epsilon$ With Iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.1</td>
<td>120</td>
<td>0.552 + 0.007</td>
<td>0.557 + 0.007</td>
</tr>
<tr>
<td>14.0</td>
<td>80</td>
<td>-0.479 + 0.010</td>
<td>-0.484 + 0.010</td>
</tr>
<tr>
<td>18.0</td>
<td>120</td>
<td>0.525 + 0.009</td>
<td>0.523 + 0.011</td>
</tr>
<tr>
<td>17.1</td>
<td>80</td>
<td>-0.404 + 0.012</td>
<td>-0.408 + 0.015</td>
</tr>
</tbody>
</table>

The chief effect of the iron cylinder seemed to be a slight filling in of the valley below the $n_0$ neutron peak. Usually this background is subtracted out during off-line analysis. For the above reasons, the conclusion was that the iron scattering contribution for 150% increase in iron showed no systematic effect and, in fact, was essentially negligible even with no background subtraction.

C. Analysis of Spectra -- $A_{zz}$ Experiment

The determination of $A_{zz}$ for the reaction $D(d,n)^3$He was made by measuring the counting rate for the recoils in the helium cell for two
different beam alignment axis settings. The experimental spectra in this case did not have a shape which allowed a simple separation of the neutrons of interest from the background. A discussion of how this was done and of how $A_{zz}$ was inferred from the counting rates follows.

In the $A_{zz}$ experiment the deuteron spin was set either at $\beta = 90^\circ$, $\phi = 0^\circ$, or very nearly along the beam momentum direction, i.e. at $\beta = 8.49^\circ$, $\phi = 90^\circ$. Hereafter, these conditions will be referred to as spin UP or as spin ALONG respectively. These beams have two different values of polarization. That this is true can be seen by recalling the formula for $P_{zz}$, the component of the beam affected by the tensor analyzing power $A_{zz}$: $P_{zz} = P_{zz}^{(3)} (3 \cos^2 \beta - 1)$. In order to obtain the two spin orientations, the current through SRS 1 was changed from 0 A (spin ALONG) to approximately 60 A (spin UP). The different focusing effects of the two magnetic fields caused different amounts of unpolarized background to enter the beam, changing its polarization with alignment axis setting. This posed no experimental difficulty since the quench ratio measured the true beam polarization for each spin alignment. It however was necessary to calculate $A_{zz}$ with the correct values of $P_{zz}$:

In order to do this Equation (1) must be written as

\begin{align}
\sigma_1(\phi^*) &= \sigma_0(\phi^*) \left[ 1 + \frac{1}{2} A_{zz}(\phi^*) P_{zz}^{(1)} (3 \cos^2 \beta - 1) \right] \\
\sigma_2(\phi^*) &= \sigma_0(\phi^*) \left[ 1 + \frac{1}{2} A_{zz}(\phi^*) P_{zz}^{(2)} (3 \cos^2 \beta - 1) \right]
\end{align}

(9)
where $P_{ZZ}^{(1)}$ is the measured deuteron tensor polarization for spin UP, and $P_{ZZ}^{(2)}$ gives the same quantity for spin ALONG. These two polarizations differed typically for approximately 0.02. Since the same detector measured the number of counts for each spin direction, and since care was exercised to ensure precise current integration and dead time correction, the cross sections were proportional to the number of counts. Taking a ratio then canceled out the detector efficiency and other effects. If the ratio of counts observed for one spin direction to the other is

$$R = \frac{N_1}{N_2}$$  \hspace{1cm} (10)$$

then

$$A_{ZZ}(\sigma') = \frac{4(R - 1)}{F_1 P_{ZZ}^{(1)} - RF_2 P_{ZZ}^{(2)}}$$  \hspace{1cm} (11)$$

where

$$F_i = (3 \cos^2 \beta_i - 1)$$  \hspace{1cm} (12)$$

Since the recorded data were recoil spectra, there was no convenient way to separate out the ground state $n_o$ neutrons from the breakup neutrons coming from the $D(d,n)$pp reaction and from other background events. *A priori* there is no reason to believe that the breakup and background neutrons would have the same value of $A_{zz}$. It was found however, that a calculation of $A_{zz}$ for blocks of channels, with the high channel fixed, gave a very sensitive indication of any background.

Figure 13 shows two spin UP recoil spectra. The first at 6.2 MeV has no appreciable contaminant, the second at 15.2 MeV deuteron energy shows a sharp drop near channel 60 in the value of $A_{zz}$ (calculated from
Figure 13. Typical $^4$He Recoil Spectra and Calculated $A_{zz}$ Values
the spectrum shown, and the spin ALONG spectrum which is not pictured). This was taken to indicate that any significant background of lower energy neutrons was essentially zero just below the recoil "knee". For spectra such as the first, the value of $A_{zz}$ was calculated from the entire spectra. For the second type, the value of $A_{zz}$ and its statistical uncertainty was calculated from a 10 channel average, using only data from the region of linear $A_{zz}$.

D. Error Analysis

The uncertainty in the final values of the polarizations, transfer coefficients and analyzing powers comes from several sources. Because the accuracy of these experiments was greater than any previous fast neutron polarization results, it was felt that a complete discussion of the error analysis was essential. The following section presents a summary of the known systematic and random errors in the measurements.

Errors due to peak summing and background subtraction. -- The same channels were used for summing all eight spectra. This procedure minimizes errors arising from summing. The back angle coincidence spectra were reasonably clean, and in most cases background subtraction had a very slight effect (for reasons discussed previously). Nevertheless, care was taken to choose the backgrounds
systematically. The forward angle spectra from the $^4\text{He}(n,n)^4\text{He}$ and 17.1 MeV $^3\text{He}(n,n)^3\text{He}$ experiments showed considerable overlap with the break-up neutron peak. Here again the high polarization of the background made negligible changes in the asymmetry for a background subtraction consistent with that polarization. In the lower energy data the partially polarized background was more of a difficulty. In all of these analyses, three choices of background were made and the asymmetry calculated for each. Because of the large statistical errors associated with the 8.0 and 12.0 MeV $^3\text{He}(n,n)^3\text{He}$ asymmetry data (typically 0.015) the error associated with the choice of different backgrounds was quite small (0.003). Within reasonable variations, none of the subtracted backgrounds changed the calculated asymmetries by more than the statistical error of that point.

**Beam polarization uncertainty.** -- The first experiments involved the measurement of the $^3\text{He}(n,n)^3\text{He}$ polarization. For these data the beam polarization was determined to a statistical accuracy of about 0.006 by measurements using the $^3\text{He}(d,p)^4\text{He}$ reaction. The neutron polarizations calculated from these measurements had a typical uncertainty of 0.010. This uncertainty included the statistical uncertainties from 1) the counting uncertainty of the measurement itself, 2) $A_{zz} (0^\circ)$ for the $^3\text{He}(d,p)^4\text{He}$ reaction, and 3) $A_{zz} (0^\circ)$ and $K_y^V (0^\circ)$ for the $D(d,n)^3\text{He}$ reactions.
Later work utilized the quench ratio method to determine beam polarizations. In these measurements the average beam current was obtained for a given time period for the normal and quenched modes of operation. These results gave randomly varying beam polarization values in which the average fluctuation was on the order of 0.005 over the accumulation of counts for one set of data.

Another possible contribution to the uncertainty in the beam polarization would be an uncertainty in the knowledge of the spin direction of the deuteron on target. Fortunately, for all of the experiments described here, there is no first order dependence of the error on any spin precession angle which is not known to a high degree of accuracy. (See Appendix A.) Hence, variations in the spin rotation solenoid current and polarized beam energy in the solenoid field are considered to contribute a negligible amount to the deuteron polarization error.

If the beam polarization is not the same for both spin UP and spin DOWN parts of an asymmetry measurement, there will be an error introduced in the calculation of the asymmetry. When the asymmetry is divided by the beam polarization, as was done in these experiments, the dependence of the result on a spin-UP spin-DOWN polarization difference is very weak. In fact, Trainor (1973) has calculated an expression for this error, which shows that the effect on P(e) is typically less than 0.0001 for these experimental conditions.
Statistical errors. -- The statistical error in the asymmetry was formed from the relation

\[(\Delta E)^2 = \sum \left( \frac{\partial E}{\partial S_i} \right)^2 (\Delta S_i)^2 + \left( \frac{\partial E}{\partial B_i} \right)^2 (\Delta B_i)^2 \]

(13)

Here \(S_i = N_i + B_i\) is the gross number of summed counts in the peak, \(B_i\) is the subtracted background and \(N_i\) is the total after background subtraction.

It follows (see, for example, Hardekopf, 1971) that the asymmetry error may be written as

\[\Delta E = \frac{r}{(r + 1)^2} \sqrt{\sum_i \frac{S_i + B_i}{(S_i - B_i)^2}}\]

(14)

Polarimeter analyzing power. -- The 8.0 and 12.0 MeV \(^3\)He(n,n)\(^3\)He data were taken in two parts. The first used the spin precession solenoid to invert the neutron spin and allow cancellation of detector efficiencies. For these data a correction based on the calibration done by Hardekopf (1971) was used. The largest correction occurred at 12 MeV and was 3.66% with an uncertainty of 0.03%. For the 8.0 MeV data, the spin precession correction factor was nearly unity and was known with sufficient accuracy to affect the uncertainty in the measurement negligibly.

The uncertainty of the calculated analyzing power was determined in part by the number of sample neutrons used in the Monte Carlo calculation in MOCCASINS. For the present experimental
conditions, an investigation of the convergence of $\overline{P}$ as a function of the number of neutrons considered, showed that, in the single scattering case, the final result changed by less than 0.001 for more than 1000 neutrons. For the multiple scattering correction, convergence was more rapid, with the final result changing by 0.0005 after 900 neutrons. Therefore 1000 neutrons were used in each case. The contribution to the uncertainty in $\overline{P}$ due to the number of neutrons used in the calculation was taken to be less than 0.0005.

The Monte Carlo calculation in MOCCASINS utilizes computer generated random numbers for the purpose of determining certain probabilities. Occasionally one random number will be generated which will lead to an unusually large probability for detection of the neutron under consideration. Although no such anomalous numbers were observed in the calculations presented here, there was a variation of $\overline{P}$ ranging from 0.001 to 0.006 for different choices of random starting numbers. The largest variation was observed in angular regions where the corrections were large.

The contribution to the uncertainty in the average analyzing power due to this random effect was taken to be the full width at half maximum of results obtained from a series of starting numbers, averaged over angle. This uncertainty was found to contribute 0.0002 to the uncertainty in $\overline{P}$. 
Another contribution to the error in $\overline{D}_2$ probably comes from the geometry assumption in MOCCASINS. For the calculations presented here, the helium cell geometry was considered to consist of two intersecting cylinders. Another possible choice in the calculation was that of a sphere.

The real geometry is approximated by a combination of the two types. Sets of calculations for the two geometries indicated that the spherical geometry always produced a systematically larger correction than the cylindrical geometry, but that the differences were negligible for the purposes of these results.

**Polarimeter alignment and beam positioning effects.**

Alignment of the polarimeter at $\Theta = 0$ degrees with respect to the momentum axis of the beam as determined by optical alignment was to within $\pm 0.05^\circ$. The scattering angles on the polarimeter itself were determined to about $0.015^\circ$. In the range from $90^\circ$ to $110^\circ$ lab in which the $^4\text{He}(n,n)^4\text{He}$ polarizations change rapidly with angle, no data were taken. The slit geometry allowed a maximum variation of the beam axis of less than $0.1^\circ$. Because of this accurate alignment and slow variation of all of the experimental polarizations, i.e., the $K_y^V$ of $D(d,n)^3\text{He}$ and $P(\Theta)$ for $^4\text{He}(n,n)^4\text{He}$ and for $^3\text{He}(n,n)^3\text{He}$, over most of the range measured, false asymmetries due to alignment and beam movement on target are negligible.
Summary. -- Uncertainties in the measured polarizations, transfer coefficients and analyzing powers may be divided into three categories; statistical errors, systematic scaling errors and systematic non-scaling errors. Errors of the first and third types affect each data point independently. The scaling type errors affect the entire angular distribution or excitation function in the same way and tend to act as a normalization.

Because the error analysis in experiments utilizing transfer polarizations and quench ratio measurements of the beam polarization tends to indicate rather good precision, the scaling errors, which are for the most part independent of the other types, give the data the largest absolute error possible. It is customary in neutron analysis to permit a reasonable renormalization of experimental results for comparison with theory because of the large uncertainties associated in the past with the data. Therefore a summary of the data has been prepared in which all three types of errors have been tabulated as well as a final error which may be taken as the absolute limit of the uncertainties. The summary is presented as Appendix E.

The uncertainties in the values of the corrections to the $^3$He data were not included because the results of the $^4$He analysis showed that the errors in the corrections would be small enough to be ignored when compared to the statistical errors of the $^3$He data.
Chapter IV

\[ D(d,n)^3\text{He} \] RESULTS

A. General

The reaction mechanism involved in the \[ D(d,n)^3\text{He} \] reaction at forward angles for energies above 5 MeV appears to be consistent with \( l_p = 0 \) stripping. This was recognized some time ago and was reported by Goldberg and Le Blanc (1960). In a simple stripping model the loosely bound neutron in the deuteron is only slightly affected by the proton transfer and carries with it much of the polarization which it initially had in the deuteron. Assuming that the outgoing zero-degree neutron polarization is the same as in the incoming deuteron, Simmons et al. (1971) were able to calculate an estimate of the depolarization resulting from the deuteron D-state. Their estimate for the outgoing neutron polarization using a simple model was approximately 9% higher than the measured value, but the reasonable agreement indicated that the interpretation was at least partially correct.
B. Zero Degree Analyzing Power $A_{zz}$

A comparison of the effect of $A_{zz}$ on the calculated neutron polarization (Appendix A) shows that, under typical conditions, a 10% uncertainty in $A_{zz}$ would introduce a 1% uncertainty in the neutron polarization. It is therefore possible to make the error in the neutron polarization which is due to the lack of precise knowledge of $A_{zz}$ quite small. In this experiment $A_{zz}$ was measured to a typical statistical accuracy of $+0.017$. This would normally generate a possible error in the neutron polarization of $+0.002$.

Table 3 lists the values obtained here for $A_{zz}$ as well as certain other experimental quantities of interest. The results of the measurement are shown in Figure 14. Here we show only the statistical errors.

The principal features of the analyzing power are the nearly energy-independent nature, and the possible increase in magnitude for $E_d < 3.5$ MeV. The data are well described by a constant value. The equation for a least squares fit to the data is of the form

$$A_{zz}(E, 0^\circ) = -0.462.$$  

There are two sets of $A_{zz}(0^\circ)$ data for the $D(d, n)^3$He reaction which are available for comparison, both being obtained at Los Alamos. The data of Simmons et al. (1971), and the more recent data of Salzman et al. (1973) are shown in Figure 14. These data show reasonable agreement.
### TABLE 3

**ZERO-DEGREE ANALYZING POWER FOR D(D,N)He3**

<table>
<thead>
<tr>
<th>DEUTERON ENERGY</th>
<th>(A_{zz}(E,\theta))</th>
<th>ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.54</td>
<td>-0.554</td>
<td>0.030</td>
</tr>
<tr>
<td>2.10</td>
<td>-0.499</td>
<td>0.019</td>
</tr>
<tr>
<td>2.56</td>
<td>-0.480</td>
<td>0.018</td>
</tr>
<tr>
<td>3.11</td>
<td>-0.475</td>
<td>0.100</td>
</tr>
<tr>
<td>3.59</td>
<td>-0.474</td>
<td>0.007</td>
</tr>
<tr>
<td>4.12</td>
<td>-0.475</td>
<td>0.011</td>
</tr>
<tr>
<td>4.65</td>
<td>-0.438</td>
<td>0.013</td>
</tr>
<tr>
<td>5.18</td>
<td>-0.456</td>
<td>0.011</td>
</tr>
<tr>
<td>5.68</td>
<td>-0.465</td>
<td>0.013</td>
</tr>
<tr>
<td>6.20</td>
<td>-0.434</td>
<td>0.010</td>
</tr>
<tr>
<td>6.48</td>
<td>-0.461</td>
<td>0.009</td>
</tr>
<tr>
<td>7.01</td>
<td>-0.454</td>
<td>0.008</td>
</tr>
<tr>
<td>7.54</td>
<td>-0.448</td>
<td>0.008</td>
</tr>
<tr>
<td>8.06</td>
<td>-0.457</td>
<td>0.009</td>
</tr>
<tr>
<td>8.58</td>
<td>-0.451</td>
<td>0.009</td>
</tr>
<tr>
<td>9.10</td>
<td>-0.477</td>
<td>0.009</td>
</tr>
<tr>
<td>9.61</td>
<td>-0.466</td>
<td>0.013</td>
</tr>
<tr>
<td>10.12</td>
<td>-0.473</td>
<td>0.010</td>
</tr>
<tr>
<td>10.64</td>
<td>-0.459</td>
<td>0.015</td>
</tr>
<tr>
<td>11.15</td>
<td>-0.458</td>
<td>0.016</td>
</tr>
<tr>
<td>11.78</td>
<td>-0.438</td>
<td>0.014</td>
</tr>
<tr>
<td>12.17</td>
<td>-0.470</td>
<td>0.011</td>
</tr>
<tr>
<td>12.68</td>
<td>-0.468</td>
<td>0.011</td>
</tr>
<tr>
<td>13.19</td>
<td>-0.458</td>
<td>0.016</td>
</tr>
<tr>
<td>13.70</td>
<td>-0.468</td>
<td>0.016</td>
</tr>
<tr>
<td>14.21</td>
<td>-0.470</td>
<td>0.016</td>
</tr>
<tr>
<td>14.82</td>
<td>-0.466</td>
<td>0.016</td>
</tr>
<tr>
<td>15.22</td>
<td>-0.468</td>
<td>0.016</td>
</tr>
<tr>
<td>15.22</td>
<td>-0.468</td>
<td>0.016</td>
</tr>
</tbody>
</table>
Figure 14. Measured Values of $K_Y(0^0)$ and $A_{zz}(0^0)$ of the $D(d, n)^3\text{He}$ Reaction
C. Zero Degree Transfer Coefficient $K^Y_y$

Table 4 lists the values of $K^Y_y$ as well as certain other experimental quantities of interest. The principal feature is the lack of structure as a function of energy. Although an examination of the measured asymmetry presented in Appendix E shows an increase as the neutron energy is lowered, this increase is due to a gradual rise in the 120 degree analyzing power of $^4$He and does not appear in $K^Y_y$. The results of a least squares polynomial fit to the $K^Y_y$ data are $K^Y_y(E, 0^0) = 0.636$.

A comparison of the present data to the earlier results of Simmons et al. (1971) is somewhat more difficult in the case of $K^Y_y$ than for $A^Y_{zz}$. The Los Alamos group used the Satchler et al. (1968) phase shifts to calculate the average analyzing power for their liquid helium polarimeter. Unfortunately, above 12 MeV the predictions of $^4$He observables from the Satchler phase shifts begin to show deviations from those of the Stammbach-Walter (S-W) phase shifts which were used to correct these data. As will be shown in the discussion in Chapter VI, data obtained since the Satchler analysis, and the results of our work, reported later, indicate that the Satchler predictions match experimental observables less well than the S-W predictions. For this reason we chose to use the S-W results and adjust the Los Alamos $K^Y_y$ values for comparison to our data. To first order the adjustment may be made by multiplying by the ratio of point polarizations $(P_{S-W}/P_{Satchler})$. The adjusted
### Table 4

**Zero-Degree Polarization Transfer Coefficients for D(3n) He\textsubscript{3}**

#### A) Present Results

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Deuteron</th>
<th>Neutron</th>
<th>$k'y$</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.59\textdegree</td>
<td>6.35\textdegree</td>
<td>0.639</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>4.11\textdegree</td>
<td>7.37\textdegree</td>
<td>0.632</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>4.65\textdegree</td>
<td>7.73\textdegree</td>
<td>0.654</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>5.08\textdegree</td>
<td>8.32\textdegree</td>
<td>0.649</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>5.64\textdegree</td>
<td>8.86\textdegree</td>
<td>0.661</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>6.12\textdegree</td>
<td>9.33\textdegree</td>
<td>0.599</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>6.59\textdegree</td>
<td>9.78\textdegree</td>
<td>0.529</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>7.10\textdegree</td>
<td>10.27\textdegree</td>
<td>0.646</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>7.50\textdegree</td>
<td>10.65\textdegree</td>
<td>0.642</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>7.97\textdegree</td>
<td>11.10\textdegree</td>
<td>0.643</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>8.50\textdegree</td>
<td>11.60\textdegree</td>
<td>0.625</td>
<td>0.009</td>
<td></td>
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<tr>
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<td>12.10\textdegree</td>
<td>0.638</td>
<td>0.010</td>
<td></td>
</tr>
<tr>
<td>9.54\textdegree</td>
<td>12.59\textdegree</td>
<td>0.653</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>10.06\textdegree</td>
<td>13.08\textdegree</td>
<td>0.638</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>10.57\textdegree</td>
<td>13.57\textdegree</td>
<td>0.643</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>11.09\textdegree</td>
<td>14.06\textdegree</td>
<td>0.631</td>
<td>0.008</td>
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<tr>
<td>11.56\textdegree</td>
<td>14.56\textdegree</td>
<td>0.639</td>
<td>0.011</td>
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</tr>
<tr>
<td>12.11\textdegree</td>
<td>14.98\textdegree</td>
<td>0.641</td>
<td>0.013</td>
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<tr>
<td>12.59\textdegree</td>
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<td>0.010</td>
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<tr>
<td>13.14\textdegree</td>
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<td>13.61\textdegree</td>
<td>16.44\textdegree</td>
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<td>0.011</td>
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<td>16.92\textdegree</td>
<td>0.626</td>
<td>0.012</td>
<td></td>
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<tr>
<td>14.66\textdegree</td>
<td>17.40\textdegree</td>
<td>0.642</td>
<td>0.012</td>
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</tr>
</tbody>
</table>

#### B) Los Alamos Results and Adjustments

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Measured $P(S-W)/P(S)$</th>
<th>Adjusted $P(S-W)/P(S)$</th>
<th>Deuteron</th>
<th>Neutron</th>
<th>$k'y$</th>
<th>Error</th>
<th>Ratio</th>
<th>Adjusted $k'y$</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.06\textdegree</td>
<td>7.33\textdegree</td>
<td>0.629</td>
<td>0.018</td>
<td>0.999</td>
<td>0.628</td>
<td>0.018</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.04\textdegree</td>
<td>9.20\textdegree</td>
<td>0.650</td>
<td>0.016</td>
<td>1.081</td>
<td>0.651</td>
<td>0.016</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.04\textdegree</td>
<td>11.20\textdegree</td>
<td>0.616</td>
<td>0.011</td>
<td>1.005</td>
<td>0.619</td>
<td>0.011</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.02\textdegree</td>
<td>13.00\textdegree</td>
<td>0.651</td>
<td>0.014</td>
<td>1.016</td>
<td>0.661</td>
<td>0.014</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.97\textdegree</td>
<td>14.90\textdegree</td>
<td>0.624</td>
<td>0.011</td>
<td>1.038</td>
<td>0.648</td>
<td>0.011</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.50\textdegree</td>
<td>16.30\textdegree</td>
<td>0.578</td>
<td>0.013</td>
<td>1.065</td>
<td>0.616</td>
<td>0.014</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.08\textdegree</td>
<td>17.80\textdegree</td>
<td>0.608</td>
<td>0.022</td>
<td>1.107</td>
<td>0.673</td>
<td>0.024</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Los Alamos $K^Y_y$ values are plotted in Figure 14. The data and corrections are given in Table 4. Although there are some fluctuations, the adjusted Los Alamos data show good agreement with the present results.
Chapter V

$^{3}\text{He}(n,n)^{3}\text{He}$ RESULTS AND ANALYSIS

A. Results and Comparison to Other Data

Angular distributions of the asymmetry produced in $^{3}\text{He}(n,n)^{3}\text{He}$ elastic scattering were obtained at average neutron bombarding energies of 8.0, 12.0 and 17.1 MeV. Table 5 lists the final $^{3}\text{He}(n,n)^{3}\text{He}$ polarization values as well as other experimental details necessary to permit changes in the neutron polarizations should any of the several parameters involved in the calculation be measured more accurately in the future. The errors listed are statistical.

The asymmetries divided by the calculated neutron polarizations are shown in Figure 15, along with the 3 MeV $^{3}\text{He}(n,n)^{3}\text{He}$ data of Hollandsworth et al. (1972). The solid lines are the results of a set of single-energy phase shift fits which will be discussed later. The graph illustrates the principal features of the distributions. These features are somewhat similar to those observed in $^{4}\text{He}(n,n)^{4}\text{He}$ in that, as the neutron bombarding energy increases, the positive peak

(61)
### Table 5

**HE3(N,N)HE3 Polarization Data**

#### 8.8 MeV

<table>
<thead>
<tr>
<th>LAB</th>
<th>C M</th>
<th>HE3(N,N)HE3</th>
<th>(\Phi)</th>
<th>ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>58.8</td>
<td>66.8</td>
<td>-0.014</td>
<td>p.028</td>
<td></td>
</tr>
<tr>
<td>58.4</td>
<td>66.2</td>
<td>-0.134</td>
<td>p.026</td>
<td></td>
</tr>
<tr>
<td>58.3</td>
<td>76.8</td>
<td>-0.224</td>
<td>p.039</td>
<td></td>
</tr>
<tr>
<td>62.6</td>
<td>79.9</td>
<td>-0.227</td>
<td>p.055</td>
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</tr>
<tr>
<td>68.2</td>
<td>84.8</td>
<td>-0.197</td>
<td>p.057</td>
<td></td>
</tr>
<tr>
<td>111.3</td>
<td>129.9</td>
<td>0.364</td>
<td>p.057</td>
<td></td>
</tr>
<tr>
<td>123.3</td>
<td>139.9</td>
<td>0.356</td>
<td>p.058</td>
<td></td>
</tr>
<tr>
<td>140.2</td>
<td>159.2</td>
<td>0.111</td>
<td>p.053</td>
<td></td>
</tr>
<tr>
<td>148.8</td>
<td>169.2</td>
<td>0.121</td>
<td>p.054</td>
<td></td>
</tr>
</tbody>
</table>

#### 12.8 MeV

<table>
<thead>
<tr>
<th>LAB</th>
<th>C M</th>
<th>HE3(N,N)HE3</th>
<th>(\Phi)</th>
<th>ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>46.8</td>
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<td>-0.141</td>
<td>p.027</td>
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</tr>
<tr>
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<td>64.8</td>
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<td>p.035</td>
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</tr>
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<td>54.1</td>
<td>69.8</td>
<td>-0.126</td>
<td>p.020</td>
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<td>p.025</td>
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<td>p.051</td>
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<td>p.057</td>
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<td>0.580</td>
<td>p.059</td>
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</tr>
<tr>
<td>196.7</td>
<td>158.8</td>
<td>0.280</td>
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<td>0.145</td>
<td>p.031</td>
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</table>

#### 17.4 MeV

<table>
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<tr>
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<th>C M</th>
<th>HE3(N,N)HE3</th>
<th>(\Phi)</th>
<th>ERROR</th>
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<td>133.8</td>
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<td>158.7</td>
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<td>156.3</td>
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**Final Values Calculated Using the D(C,N)He3**

<table>
<thead>
<tr>
<th>XYY</th>
<th>AZZ</th>
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</thead>
<tbody>
<tr>
<td>#.636</td>
<td>-#.462</td>
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</table>
Figure 15. $^3$He($\alpha$,n)$^3$He Polarization Data and Phase Shift Fit
near $120^0$ c.m. moves to larger angles. Also the negative region at forward angles, near $90^0$ c.m. increases in magnitude.

At 17.1 MeV the maximum positive polarization for $^3$He(n,n)$^3$He in this energy region has been passed since the peak is of lower magnitude than at 12.0 MeV.

Figure 16 presents a comparison of the present 8.0 and 12.0 MeV $^3$He(n,n)$^3$He results with the previous $^3$He(n,n)$^3$He data and the T(p,p)T data of Hardekopf et al. (1972) and Kankowsky (1972). The agreement with the old $^3$He(n,n)$^3$He data of Behof et al. (1966) at 7.9 MeV and Büsser et al. (1969) at 12.0 MeV is quite poor. Neither of the older data sets were corrected for finite geometry. Applying a correction of the same shape as that for the present data to the 7.9 MeV Behof results would tend to decrease disagreement at angles near the positive peak, but increase the discrepancy near the negative minimum. No forward angle data were previously available at 12 MeV. The earlier data at 12.0 MeV were taken with a small angular resolution and a correction for finite geometry effects should be negligible here.

The mirror symmetric reaction T(p,p)T, shows good agreement with the present data. Although some slight differences, particularly at forward angles may exist, there is certainly no evidence for strong violation of charge symmetry in these reactions, as comparison of the data before this experiment would have suggested. In fact, if one accounts in a crude way for the Coulomb effects by shifting the
Figure 16. Comparisons with Other $^3\text{He}(n,n)^3\text{He}$ and $T(p,p)T$

Data at 8.0 and 12.0 MeV
energy scale to match energies in the compound system and then compares, these differences are even smaller.

B. Phase Shift Analysis

Spin 1/2 on Spin 1/2 Phase Shift Formalism. -- One method of parameterizing elastic scattering results is by means of phase shifts. Such parameterizations are important in that they provide a convenient way to calculate a representation of observed results at any energy or angle for comparison to other results or to theoretical predictions. The formalism of phase shift parameterization arises from a description of the scattering process using quantum mechanics, and is a natural method for use in this case. The development of phase shift formalism may be found in many introductory quantum mechanics textbooks (Merzbacher, 1970). More general formulas and a description of the theory may be found in Blatt and Biedenharn (1952) and Lane and Thomas (1958).

Expressions for tensor moments arising from reactions induced by polarized projectiles are given by Simon and Welton (1958). An outline and description of the computational techniques involved in programming a computer calculation of phase shifts to describe $^3\text{He}(n,n)^3\text{He}$ is given by Kankowsky and Flick (1971). We shall use the Blatt and Biedenharn (1952) parameterization of the scattering or S-matrix in terms of eigen-phase shifts. Several alternate but equivalent methods of
parameterizing these quantities are given by Stapp (1957) and Detch (1970). The explicit expressions for calculating the cross sections and polarizations for spin 1/2 on spin 1/2 elastic scattering in a form convenient for computer calculation is given by Tombrello (1962; 1965).

For spin 1/2 on spin 1/2 elastic scattering the channel spin (s) can be either 0 or 1 giving rise to sets of singlet (s = 0) and triplet (s = 1) phases. Ignoring tensor interactions results in a diagonal form of the S-matrix, in which we may write the phase shifts

\[
\begin{align*}
\delta_{s0} & \quad \delta_{s5}^{J = \frac{3}{2}} \\
\delta_{s5} & \quad \delta_{s5}^{J = \frac{3}{2}} \\
\delta_{s5} & \quad \delta_{s5}^{J = \frac{3}{2} + 1}
\end{align*}
\]

where there are different phase shifts for all \( |l - s| \leq J \leq |l + s| \). For \( l = 0 \) the only member of the triplet is \( \delta_{01} \).

The most general interaction must include tensor forces. These forces give rise to non-diagonal terms in the scattering matrix, they allow non-zero singlet-triplet spin flip amplitudes and mix states whose \( l \) values differ by two.

Physically these off-diagonal S-matrix terms account for the emergence of an incident partial wave in a different channel. The Blatt and Biedenharn formulation introduces a unitary transformation which may be applied to \( 2 \times 2 \) S-matrix submatrices to diagonalize the S-matrix. The off-diagonal S-matrix components are reformulated in terms of eigen-phase shifts \( \delta_{ij}^{J} \) and mixing parameters \( \epsilon \). For this analysis only the channel spin mixing parameter, denoted by \( \epsilon_{\frac{1}{2}} \).
was included. In general, mixing parameters have been neglected in previous phase shift analyses in the mass-4 system.

In the $^3$He + n system there are open reaction channels as well as the elastic scattering channel. The S-matrix formalism may be generalized to perform simultaneous multichannel analysis (Detch et al., 1971) but the usual practice is to permit complex phase shifts. Then the S-matrix element is of the form

$$\exp \left( 2i(\delta_{s5}^j + iv_{s5}^j) \right) = \exp(-2v_{s5}^j) \exp(2i\delta_{s5}^j) = \eta_{s5}^j \exp(2i\delta_{s5}^j)$$

Here $v_{s5}^j$ is the complex part of the phase shift and $\eta_{s5}^j$ is its equivalent, called the absorption or inelastic parameter.

In order to determine values of the phase shifts which would reproduce the data, a computer code capable of searching for the optimum phase shift values was employed. The phase shift search code CPHASE (Hardekopf, 1971) used in these phase shift fits was capable of dealing with angular momentum values as high as $l = 3$. However, the highest energy n-$^3$He data available was at 23.7 MeV and a classical calculation of the maximum impact parameter corresponding to the sum of a neutron radius of about 0.8 fm and a $^3$He radius of about 1.7 fm yields a maximum $\lambda$-value of 2$\hbar$. Since the $l = 3$ f waves would be expected to be quite insensitive to the phase shift fit at this energy, as they would be quite small, the maximum $\lambda$ value of 2 was chosen. However, even with a maximum of three partial waves the number of parameters involved in this analysis was quite large. There were 10
real phase-shifts, 10 absorption parameters, and 2 mixing parameters at each energy.

**Phase Shift Fits to the Data.** -- There have been several theoretical analyses of $^3$He$(n,n)^3$He reported in the literature (Bransden et al., 1956; Szydlik and Werntz, 1968; Werntz and Meyerhof, 1968; Heiss and Hackenbroich, 1973). These analyses have met with varying degrees of success in describing the experimental results. None however, provide a very good representation of all of the data available.

Parameterization by means of phase shifts has been carried out by Büsser et al. (1967, 1969). The 1969 results of Büsser were done allowing only p-wave splitting with $l \leq 2$. Absorption parameters were fixed at the theoretical estimates of Szydlik and Werntz (1968). The resulting analysis provided a good description of the data available at that time. Since then however, considerably more data has been produced, at least some of which indicates that the earlier experimental results were in error. Therefore a new analysis of all of the $^3$He$(n,n)^3$He data was carried out.

The first step involved in preparation for performing a phase-shift analysis on data covering a large range in energy is the accumulation and subsequent editing of the data to be used. In the case of $^3$He$(n,n)^3$He there was so little data that only the polarization data of Behof et al. (1966) at 7.90 MeV and 3.33 and of Büsser et al. (1969)
at 12.0 MeV were initially discarded as comparison with our data and that of Hollandsworth at 3.0 MeV showed them to be in error.

Differential cross-section data were taken from the work of Sayres et al. (1961) at 2.5, 5.0, 8.0 and 17.5 MeV; Seagrave et al. (1960) at 1, 2, 3.5 and 6 MeV; and Antolkovic et al. (1967) at 14.4 MeV. Data at 7.9, 12.0, 13.6, 14.4 and 23.7 MeV were provided prior to publication by the Los Alamos physics division (Drosog, 1973).

Polarization data were available from Seagrave et al. (1960) at 1.10 MeV (2 angles) and 2.15 MeV (one angle), Behof et al. (1966) at 3.33 and 7.90 MeV (omitted early), Büsner et al. (1969) at 12 (omitted early) and 16 MeV, Hollandsworth et al. (1972) at 3 MeV, and Busse et al. (1972) at 21.9 MeV.

Total cross section data were available in association with all of the differential cross sections except for the 14.4 MeV Antolkovic results and the Los Alamos unpublished work. These results were in fair agreement with the more recent total cross section data from 0.7 to 30 MeV provided by Goulding (1973) which were used in the fits. The $^3$He + n total cross section data of Goulding were provided in the form of a plot, from which points were read and piecewise fit with polynomials. Figure 17 shows a comparison of the present phase shift predictions with the total cross-section data.

Preliminary calculations indicated that a good representation of the data could be obtained regardless of the starting set of phase shifts
Figure 17. Comparison of $n$-$^3$He Total Cross Sections Calculated in the Present Work to Experimental Values.
due to the large number of parameters in the analysis. Two starting sets of phase shifts were chosen since it was obvious that investigation of others would give comparable fits. Set 1 was chosen from $^3\text{He}(p,p)^3\text{He}$ analysis (Tombrello, 1965) because the $^3\text{He} + p$ system has been most thoroughly analyzed and therefore probably has the most nearly unique phase shifts. Also a comparison to the $T + p$ phase shift results of Hardekopf (1971) which used the same starting set provided a ready comparison of the $T + p$ and $^3\text{He} + n$ results. Set 2 was taken from the $T + p$ phase shift results of Hardekopf (1971). Both sets were started at 12.0 MeV and the phases optimized at that energy. The resulting 12.0 MeV $^3\text{He}(n,n)^3\text{He}$ phase shifts were then used at the nearest energy as a starting set there. This procedure was continued until all of the data had been fitted. The results are shown in Figure 18. Table 6 presents a listing of the phase shifts. Figure 19 shows the phase shift fit to the differential cross section data of Seagrave et al. (1980) at 3.5 MeV and to the unpublished Los Alamos data at 7.9, 12.0, 14.4 and 23.7 MeV (Drosy, 1973).

The energy range of the present analysis corresponds to excitation energies in $^4\text{He}$ from 20.4 MeV to 39.3 MeV. No strongly resonant behavior was found for any of the phase shifts. Broad structure appears in the $\ell = 1$ and $\ell = 2$ (singlet) real phase shifts for both set 1 and set 2. For other real phase shifts certain additional characteristics may be pointed out. 1) The $\ell = 1$ and $\ell = 2$ singlet phase shifts have
Figure 18. Phase Shifts for n - $^3$He
### Table 6

**Phase Shifts for N=163**

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<tr>
<th>A) SET 1 (P-WAVE STARTING PARAMETERS)</th>
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<th>Energy (MeV)</th>
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<tr>
<td><strong>Singlet S</strong></td>
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<td><strong>Triplet S</strong></td>
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<td><strong>Singlet P</strong></td>
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<td><strong>Triplet P (J=L+1)</strong></td>
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<td>12.6</td>
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<tr>
<td><strong>Triplet P (J=L)</strong></td>
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<td>19.5</td>
</tr>
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<td><strong>Singlet D</strong></td>
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</tr>
<tr>
<td><strong>Triplet D (J=L+1)</strong></td>
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<td>3.5</td>
</tr>
<tr>
<td><strong>Triplet D (J=L)</strong></td>
<td>-8.6</td>
<td>-3.8</td>
</tr>
<tr>
<td><strong>Inelastic Parameters</strong></td>
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<tr>
<td><strong>Singlet S</strong></td>
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<td>1.0</td>
</tr>
<tr>
<td><strong>Triplet S</strong></td>
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<td>0.7</td>
</tr>
<tr>
<td><strong>Singlet P</strong></td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Triplet P (J=L+1)</strong></td>
<td>1.6</td>
<td>1.0</td>
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<td><strong>Triplet P (J=L)</strong></td>
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<td><strong>Triplet D (J=L)</strong></td>
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<td>1.0</td>
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<tr>
<td><strong>Mixing Parameters (Deg)</strong></td>
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<tr>
<td><strong>D-Wave</strong></td>
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*Note: The table continues with similar entries for other parameters.*
### Table 6 (Cont.)

#### Phase Shifts for n-MES

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<th>8) Set 2 (P-T Starting Parameters)</th>
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<td>Singlet S</td>
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<td>2.1</td>
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<td>TriP D (J=L)</td>
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<td><strong>Inelastic Parameters</strong></td>
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<td>Triplet S</td>
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<td>Singlet P</td>
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<td>1.0</td>
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<tr>
<td><strong>Mixing Parameters (Deg)</strong></td>
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<tr>
<td>D-Wave</td>
<td>1.8</td>
<td>1.8</td>
</tr>
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</table>

### Notes
- The table provides phase shifts for n-MES with energy values in MeV.
- Real phase shifts are given for singlet and triplet states.
- Inelastic parameters are also listed for singlet and triplet states.
- Mixing parameters for P- and D-waves are provided in degrees.

---

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Figure 19. Phase Shift Fits to $^3\text{He}(n,n)^3\text{He}$ differential Cross-Section Data
opposite signs for the two sets. 2) the $\mathcal{Q} = 1$ triplet phase shifts are nearly identical for both sets. 3) For $E_r$ above 5 MeV the $\mathcal{Q} = 3$ triplet phase shifts are quite similar. Below 5 MeV the $\delta_{21}^{1}$ and $\delta_{21}^{2}$ set 2 phase shifts each exhibit fluctuations of opposite sign which level out above 5 MeV.

The inelastic parameters show considerably more absorption in the singlet than in the triplet branches. At low energies only the $\eta_{01}^{1}$ parameter is large, but it quickly approaches unity as the neutron energy increases. These results are similar to those observed by Hardekopf (1971) for the $T + p$ inelastic parameters. Since the $d + d$ reaction products may be formed only through a spin flip for absorption in the triplet state the corresponding inelastic parameter is expected to be near unity.

Although it is highly unlikely that either set of phase shifts and inelastic parameters presented here represents a unique solution, it is nevertheless possible to draw several conclusions from the results. 1) Sets of phase shifts such as these, in which results are based on many energies, make deviations from the general trend easier to detect. Abnormalities may show up in unusual values of phase shifts for one or more phases, as was the case for the 21.9 MeV data of Busse (1972). Repeated attempts to simultaneously fit both the cross section and the Busse polarization data produced either a) unusually large or unusually small phase shifts when compared to ones at neighboring energies, or
b) a very bad fit to the polarization with less unusual phase shifts. These data were therefore not included in the final results. The 16.0 MeV polarization data of Büscher (1969) also gave a poor fit usually, but the large experimental errors produced a reasonable $\chi^2$ value with no abnormal phase shifts. Büscher's data was therefore included in the final results. 2) Additional cross section and polarization data below 8 MeV and above 17.1 MeV would be useful, but unless different types of data are available (i.e. triple scattering or spin correlation parameters) are obtained, the number of possible solutions will remain large.

C. $^3$He(n,n)$^3$He Optical Model Calculations

In order to attempt parameterizations and interpretations of cross-section and polarization data for $^3$He(n,n)$^3$He and $^4$He(n,n)$^4$He scattering, many approaches have been taken. Since the nucleon-nucleon interaction may be expressed phenomenologically in terms of potentials with appropriate radial dependences (Moravcsik, 1963), the hope arises that the general properties of the nucleon-nucleus interaction may be calculated from the nucleon-nucleus starting point. Many-body interactions, detailed nuclear shell structure and other physical problems coupled with the mundane calculational difficulties associated with processing the interaction of a nucleon with a 3-body or N-body system preclude any exact calculations. Approximations which reduce
the complexity of the problem must be made, and compromise calculations which are still quite involved are possible (for example see Heiss and Hackenbroich, 1973).

The phenomenological approach is another method. Here, the average nucleon-nucleus interaction is represented by a potential whose form is determined from simple theoretical arguments (McDonald and Hull, 1966), and whose parameters may be systematically adjusted to represent experimental results. This approach is surveyed in detail by several authors (Feshbach et al. 1953, 1954; Hodgson, 1963, 1967) and is the approach which shall be discussed here.

The basic premise in these analyses is that the nucleon-nucleus interaction is equivalent to a one body potential depending only on the radial separation \( r \) between the nucleon and the nucleus. Such a general potential averages out the complexities of the nucleon-nucleon and many body interaction as well as other properties of the nuclear force which depend on detailed level structure. The hope for such analyses is that a potential may be found which reproduces essential features of experimental observables over reasonable energy and mass ranges, but which ignores individual nuclear characteristics. Historically such representations are known as optical model potentials on the basis of a similarity between the cross sections calculated in this approximation and the pattern observed in the scattering of light from a translucent obstacle.
The applicability of the optical model to nucleon elastic scattering from heavy nuclei has been demonstrated by several authors (Perey, 1963; Bechetti and Greenlees, 1969; Rosen et al., 1965; Hodgsen, 1967). Other investigators have explored the optical model description of light nuclei such as $^4\text{He}$, $^6\text{Li}$, $^{11}\text{B}$, $^{16}\text{O}$ and neighboring $^{1p}$ shell nuclei (Satchler, 1968; Watson, 1969). The use of a potential model in the few nucleon problem has also been tried (Devries et al., 1972). Surveying the results of all of the above studies indicates that the optical model is most generally applicable to heavy nuclei for energies above 10 MeV. Sets of systematically varying parameters obtained from global computer searches of all of the optical model parameters give a reasonable description of nucleon scattering from a wide variety of nuclei (Bechetti and Greenlees, 1969). At lower energies and for lighter nuclei the investigators found worse fits to the data in general and the optical model description as it was originally applied appears to be in some doubt. This is because the detailed nuclear structure effects are not sufficiently averaged out for many light nuclei. Other theoretical difficulties are also present (Watson, 1969), but the fact remains that for all but the lightest nuclei the model seems to be capable of describing the average properties of nucleon scattering.

In point of fact, the optical model as applied to the mass-5 system below 20 MeV bombarding energy reproduces the cross-section, polarization and total cross-section data as well as or better than
applications to many heavy nuclei at higher energies (Satchler et al., 1968). Also, calculations by Devries et al. (1972) and Sherif et al. (1972) have been successful in predicting n-T differential cross sections. In connection with DWBA calculations, optical potentials have been used with reasonable success in p-D differential cross-section calculations from 17.1 to 43.6 MeV (Devries et al., 1972).

In light of these successes the $^3$He-n data seemed to be a logical choice for optical model analysis. But in fact, we found that the parameters reported in the above references do not describe both the cross section and polarization appropriately. We therefore parameterized the $^3$He + n data used in the previously discussed phase shift analysis by means of a standard optical model.

The optical potential used in this work was of a form which has become standard in such analyses. The explicit general form is that of a complex central potential plus a real spin-orbit potential and is defined through

$$V(r) = V_C(r) + V_N(r) + V_{nl}(r) + V_{SO}(r) f_{l-\frac{1}{2}}$$

Where the Coulomb potential acting between the projectile $Z_p$ and the target $Z_t$ was taken to be that of a uniformly charged sphere

$$V_C(r) = Z_p Z_t e^2 / 2 R_c \left[ 3 - \left( \frac{r}{R_c} \right)^2 \right], \quad r \leq R_c$$

$$= Z_p Z_t e / r \quad ; \quad r > R_c$$

the real central nuclear potential was of Woods-Saxon form
\[ V_N = -V_0 f(r, r_0, a_0) \]  

\[ f(r, r_0, a_0) = \left\{ 1 + \exp[\frac{(r - r_0)}{a_0}] \right\} \]  

the imaginary potential was of the volume plus surface-derivative Woods-Saxon form

\[ W_N(r) = -i W_3 f(r, r_1, a_1) + 4i a_1 W_0 \frac{d}{dr} f(r, r_1, a_1) \]  

and the spin-orbit potential was

\[ V_{SO}(r) = -V_{SO} f_{VSO} \frac{d}{dr} f(r, r_{SO}, a_{SO}) \]  

The spin-orbit radial exponent allowed variation of the surface derivative form factor of equation 20.

Calculations were made using the computer code OPTICS (Eastgate et al., 1973). Preliminarily a systematic study of the effect of varying each parameter about its minimum \( \chi^2 \) value was performed. The procedure for finding a set of optical potentials was to start with a set of parameters which other investigators had used, and which were known to reproduce experimental results. Using OPTICS, a grid of single-shot calculations were made in order to obtain a good fit to the 12.0 MeV results. Data at another near-by energy were then fit and this procedure repeated until a fair approximation of the data over the entire energy range was obtained.

The results of this parameter search show that \(^3\)He + n may be represented by a standard optical model with reasonable parameters.
The indication so far is that an accurate description of single energy sets of data is possible, with most of the optical model parameters exhibiting a simple dependence on energy. Table 7 lists optical potential parameters for several sets of experimental results. Also included in Table 7 is a comparison of the present results with those of some other investigators. For neutron energies above 6 MeV the present results may be seen to have a real geometry rather similar to that given by Perey (1963), but with all of the other parameters somewhat different from any previous results. A large real well diffuseness ($a_0 \approx 0.95$) was necessary at low energies. Lower values ($a_0 \approx 0.65$) made simultaneous fits to the cross-section and polarization data at 3 MeV impossible. A possible explanation for this unusual behavior of $a_0$ at low energies is that the effects of the 21.1- and 22.1-MeV states in $^4$He show up as a distortion of the form of the optical potential. In addition, the opening of the $^3$He + n $\rightarrow$ d + d reaction channel at 23.85 MeV in $^4$He could cause some effect near 4 MeV in the $^3$He + n system.

Other optical potential parameters similar to the sets found for $^4$He by Satcher et al. (1968), and in Chapter VI of this work were employed, but did not represent the $^3$He + n data as well as the present results.

The optical potentials presented by Sherif et al. (1972) for T(n,n)T give a good fit to the differential cross section, but overestimate the polarization by nearly a factor of two at 8.0 and 12.0 MeV.
### Table 7

**Optical Model Parameters for N-He3**

<table>
<thead>
<tr>
<th>Neutron Energy</th>
<th>V₀</th>
<th>R₀</th>
<th>A₀</th>
<th>W₀</th>
<th>R₁</th>
<th>A₁</th>
<th>VSO</th>
<th>RSO</th>
<th>ASO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.000</td>
<td>39.12</td>
<td>1.25</td>
<td>0.974</td>
<td>1.900</td>
<td>1.750</td>
<td>0.550</td>
<td>3.600</td>
<td>1.400</td>
<td>0.650</td>
</tr>
<tr>
<td>2.000</td>
<td>41.33</td>
<td>1.25</td>
<td>0.974</td>
<td>1.400</td>
<td>1.750</td>
<td>0.550</td>
<td>3.600</td>
<td>1.400</td>
<td>0.650</td>
</tr>
<tr>
<td>2.600</td>
<td>42.13</td>
<td>1.25</td>
<td>0.974</td>
<td>1.400</td>
<td>1.750</td>
<td>0.550</td>
<td>3.600</td>
<td>1.400</td>
<td>0.650</td>
</tr>
<tr>
<td>3.000</td>
<td>38.50</td>
<td>1.25</td>
<td>0.950</td>
<td>1.400</td>
<td>1.750</td>
<td>0.550</td>
<td>3.000</td>
<td>1.400</td>
<td>0.650</td>
</tr>
<tr>
<td>3.500</td>
<td>43.70</td>
<td>1.25</td>
<td>0.852</td>
<td>1.440</td>
<td>1.750</td>
<td>0.550</td>
<td>2.990</td>
<td>1.400</td>
<td>0.650</td>
</tr>
<tr>
<td>5.000</td>
<td>45.00</td>
<td>1.25</td>
<td>0.800</td>
<td>1.600</td>
<td>1.750</td>
<td>0.550</td>
<td>3.020</td>
<td>1.400</td>
<td>0.650</td>
</tr>
<tr>
<td>6.000</td>
<td>55.70</td>
<td>1.25</td>
<td>0.658</td>
<td>1.720</td>
<td>1.750</td>
<td>0.550</td>
<td>3.050</td>
<td>1.400</td>
<td>0.650</td>
</tr>
<tr>
<td>8.000</td>
<td>57.20</td>
<td>1.25</td>
<td>0.550</td>
<td>1.900</td>
<td>1.750</td>
<td>0.550</td>
<td>3.100</td>
<td>1.400</td>
<td>0.650</td>
</tr>
<tr>
<td>12.000</td>
<td>61.80</td>
<td>1.25</td>
<td>0.465</td>
<td>2.390</td>
<td>1.750</td>
<td>0.550</td>
<td>3.230</td>
<td>1.400</td>
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</tr>
<tr>
<td>13.600</td>
<td>58.80</td>
<td>1.25</td>
<td>0.420</td>
<td>2.520</td>
<td>1.750</td>
<td>0.550</td>
<td>3.240</td>
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<tr>
<td>14.400</td>
<td>58.50</td>
<td>1.25</td>
<td>0.425</td>
<td>2.600</td>
<td>1.750</td>
<td>0.550</td>
<td>3.270</td>
<td>1.400</td>
<td>0.650</td>
</tr>
<tr>
<td>17.100</td>
<td>65.80</td>
<td>1.25</td>
<td>0.310</td>
<td>2.200</td>
<td>1.750</td>
<td>0.550</td>
<td>2.600</td>
<td>1.400</td>
<td>0.650</td>
</tr>
<tr>
<td>23.700</td>
<td>86.73</td>
<td>1.25</td>
<td>0.427</td>
<td>2.180</td>
<td>1.750</td>
<td>0.550</td>
<td>3.500</td>
<td>1.400</td>
<td>0.650</td>
</tr>
</tbody>
</table>

### B) Other Results

1) **Perey**

\[ V₀ = 53.3 - 0.855E + 0.472/E + 27(N-Z)/A \]

\[ W₀ = 13.5 \]

\[ VSO = 7.5 \]

\[ R₀ = 1.25 \]

\[ A₀ = 0.65 \]

\[ R₁ = 1.25 \]

\[ A₁ = 0.47 \]

\[ RSO = 1.25 \]

\[ ASO = 0.65 \]

2) **Bechetti and Greenlees**

\[ V₀ = 56.3 - 0.32E - 24(N-Z)/A \]

\[ W₀ = 13.6 - 0.35E - 12(N-Z)/A \]

\[ Wₛ = 0.22E - 1.56 \]

\[ VSO = 6.2 \]

\[ R₀ = 1.17 \]

\[ A₀ = 0.75 \]

\[ R₁ = 1.26 \]

\[ A₁ = 0.58 \]

\[ RSO = 1.20 \]

\[ ASO = 0.75 \]

3) **Sherif and Podmore** (T(N,N) at 6.0 MeV)

\[ V₀ = 50.3 \]

\[ Wₛ = 0.52 \]

\[ VSO = 1.73 \]

\[ R₀ = 1.488 \]

\[ A₀ = 0.144 \]

\[ R₁ = 1.551 \]

\[ A₁ = 0.378 \]

\[ RSO = 1.849 \]

\[ ASO = 0.289 \]
It was possible to find a set of optical model parameters similar to those given by Sherif et al. which fit the present $^3\text{He}(n,n)^3\text{He}$ polarization data, but which require an unreasonable 20% renormalization of the differential cross section at 8.0 MeV for a good fit.

Further improvements in the optical model fits to the data could come from the use of a search code which automatically varies each of the parameters to minimize the differences between calculation and experiment. Unfortunately, at the present time no such code exists in operating condition at TUNL. Additional investigation of the optical model for $^3\text{He}$ will be carried out as soon as a suitable search code is available.

D. Conclusions

The large differences between the polarizations observed in $T(p,p)T$ and $^3\text{He}(n,n)^3\text{He}$ which existed before the present data were available no longer appear. There is some evidence that the $^3\text{He}(n,n)^3\text{He}$ data has a slightly larger polarization at forward angles than the $T(p,p)T$ data when compared at equal incident energies. In fact, a comparison of the $^3\text{He}(n,n)^3\text{He}$ data and $T(p,p)T$ phase shift predictions at equal energies in the compound system show even smaller differences than when compared at equal incident energies. Until a better theoretical understanding of how such comparisons should be carried out, the conclusion must be that there is no longer a sound basis for suggestion that
charge independence violation is observed in the polarizations of $T(p,p)T$ and $^3\text{He}(n,n)^3\text{He}$. 
Chapter VI

$^4$He(n,n)$^4$He RESULTS AND ANALYSIS

A. Results and Comparison to Other Data

Angular distributions of the asymmetry were measured in the $^4$He(n,n)$^4$He experiment at 14.0 and 17.1 MeV. Table 8 lists the final $^4$He(n,n)$^4$He polarization values and other information of interest, as was done previously for the $^3$He data. The errors listed are statistical.

The asymmetries divided by calculated neutron polarizations are plotted in Figure 21. The solid lines are the results of single energy phase shift fits to differential cross-section, polarization, and total cross-section data. While these fits may not be the best choices for an energy dependent set of phases, they illustrate the smoothness and consistency of the polarization angular distributions at each energy.

Figure 22 shows a comparison of the present 17.1 MeV results to the 17.7 MeV data of Broste (1971). Here we see that there is in general quite good agreement between the two sets, although the
<table>
<thead>
<tr>
<th>LAB ANGLE</th>
<th>CM ANGLE</th>
<th>HE4(N, N)HE4 P(θ)</th>
<th>ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.0</td>
<td>49.3</td>
<td>-θ.321</td>
<td>0.014</td>
</tr>
<tr>
<td>50.0</td>
<td>61.1</td>
<td>-θ.414</td>
<td>0.014</td>
</tr>
<tr>
<td>60.0</td>
<td>72.6</td>
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<td>0.017</td>
</tr>
<tr>
<td>70.0</td>
<td>83.7</td>
<td>-θ.676</td>
<td>0.016</td>
</tr>
<tr>
<td>75.0</td>
<td>89.1</td>
<td>-θ.755</td>
<td>0.017</td>
</tr>
<tr>
<td>80.0</td>
<td>94.4</td>
<td>-θ.797</td>
<td>0.018</td>
</tr>
<tr>
<td>115.0</td>
<td>128.2</td>
<td>θ.984</td>
<td>0.017</td>
</tr>
<tr>
<td>120.0</td>
<td>132.6</td>
<td>θ.887</td>
<td>0.013</td>
</tr>
<tr>
<td>130.0</td>
<td>141.1</td>
<td>θ.681</td>
<td>0.019</td>
</tr>
<tr>
<td>140.0</td>
<td>149.3</td>
<td>θ.486</td>
<td>0.019</td>
</tr>
<tr>
<td>148.0</td>
<td>155.7</td>
<td>θ.366</td>
<td>0.018</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LAB ANGLE</th>
<th>CM ANGLE</th>
<th>HE4(N, N)HE4 P(θ)</th>
<th>ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.0</td>
<td>49.3</td>
<td>-θ.274</td>
<td>0.016</td>
</tr>
<tr>
<td>50.0</td>
<td>61.1</td>
<td>-θ.383</td>
<td>0.018</td>
</tr>
<tr>
<td>60.0</td>
<td>70.6</td>
<td>-θ.537</td>
<td>0.016</td>
</tr>
<tr>
<td>70.0</td>
<td>83.7</td>
<td>-θ.649</td>
<td>0.014</td>
</tr>
<tr>
<td>75.0</td>
<td>89.1</td>
<td>-θ.702</td>
<td>0.013</td>
</tr>
<tr>
<td>80.0</td>
<td>94.4</td>
<td>-θ.742</td>
<td>0.018</td>
</tr>
<tr>
<td>115.0</td>
<td>128.2</td>
<td>θ.957</td>
<td>0.023</td>
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<tr>
<td>120.0</td>
<td>132.6</td>
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<td>141.1</td>
<td>θ.676</td>
<td>0.020</td>
</tr>
<tr>
<td>140.0</td>
<td>149.3</td>
<td>θ.486</td>
<td>0.021</td>
</tr>
<tr>
<td>148.0</td>
<td>155.7</td>
<td>θ.317</td>
<td>0.017</td>
</tr>
</tbody>
</table>

FINAL VALUES CALCULATED USING THE D(D,N)HE3

<table>
<thead>
<tr>
<th>KYY</th>
<th>AZZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.636</td>
<td>-0.462</td>
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</tbody>
</table>
Figure 21. Comparison of $^4\text{He}(n,n)^4\text{He}$ Polarization Data and Single Energy Phase Shift Fits at 14.0 and 17.1 MeV
Figure 22. Comparison of Present Results to Other $^4\text{He}(n,n)^4\text{He}$ Results at 17.7 MeV
older data seems to have too large a polarization at angles beyond $140^\circ$. This problem with the older data showed up earlier in attempts to parameterize the data with phase shifts. The data plotted here are each normalized to polarizations calculated using the set of phases which gave the best fit to the 17.1 MeV data. No other polarization data is available for comparison with the 14.0 MeV results. For energies below 14.0 MeV, the results of previous phase shift analyses do a reasonable job of describing the data. In particular, the results of Stammbach and Walter (1972) provide the best representation of all, when the phase shifts of Satchler et al. (1968), Hoop and Barshall (1966), Arndt and Roper (1970), and Stammbach and Walter are considered.

B. Phase Shift Analysis

General. -- The phase shift formalism for $n - {}^4\text{He}$ or $p - {}^4\text{He}$ involves a "spin 1/2 - spin 0" system and is considerably less complicated than that for $n - {}^3\text{He}$ which was discussed in the previous chapter. The general references to phase shift formalism in Chapter V apply here also.

For $^4\text{He}(n,n)^4\text{He}$ in the energy region covered by this analysis, 0.2 MeV to 20.0 MeV, there are no open reaction channels; therefore, all of the phase shifts are real. In addition, with a spin 0 target there are no spin-spin terms in the S-matrix. As a result there are only 7
phase shift parameters at each energy for the case here where \( l = 3 \) is the highest angular momentum value required. In this work, the principal focus was on developing better energy-dependent \(^4\text{He}(n,n)^4\text{He} \) phase shifts in the 10 - 20 MeV region.

In addition, a set of single-energy phase shifts was obtained at 14.0 and 17.1 MeV. These phase shifts were useful because they give the best possible parameterization of the data in the sense that they have the minimum \( \chi^2 \)/point at each energy. Unfortunately, single-energy fits do not always provide a smooth set of phase shifts from which one may conveniently derive \(^4\text{He}(n,n)^4\text{He} \) observables. The single-energy phase shifts found in the present analysis are listed below.

<table>
<thead>
<tr>
<th>Neutron Energy</th>
<th>s 1/2</th>
<th>p 1/2</th>
<th>p 3/2</th>
<th>d 3/2</th>
<th>d 5/2</th>
<th>f 5/2</th>
<th>f 8/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.0</td>
<td>97.55</td>
<td>58.93</td>
<td>101.00</td>
<td>2.07</td>
<td>3.19</td>
<td>0.66</td>
<td>0.83</td>
</tr>
<tr>
<td>17.1</td>
<td>92.58</td>
<td>57.23</td>
<td>97.41</td>
<td>3.57</td>
<td>5.34</td>
<td>1.21</td>
<td>1.73</td>
</tr>
</tbody>
</table>

These results were obtained using the computer code SHOSZ. This program was written by the author to fit differential cross-section, polarization, and total cross-section data with spin 1/2 on spin 0 phase shifts. A gradient search similar to the one in the code LEVEL (see Appendix D) was used.
Because there is no differential cross-section data at 14.0 and 17.1 MeV, differential cross sections were calculated from the R-matrix fit to the \(^4\text{He}(n,n)^4\text{He}\) data which is described later. The total cross section data were taken from the results of Goulding (1973). Relatively insensitive d and f wave phase shifts were not searched on, but rather were fixed at the values obtained by Stammbach and Walter (1972).

There have been several analyses of \(^4\text{He}(n,n)^4\text{He}\) data in terms of phase shifts in recent years. Below 20 MeV, phase shift calculations and summaries of the available data have been given by Satchler et al. (1968), Morgan and Walter (1968), Arndt and Roper (1970), and Stammbach and Walter (1972). Other phase shift analyses, not so comprehensive as the previous ones, have been presented by Broste et al. (1972), Stammbach et al. (1970), Niller et al. (1970), and Gammel et al. (1958). An older analysis, but one which covered the 6 - 30 MeV energy range was presented by Hoop and Barshall (1963). This analysis was based on the p - \(^4\text{He}\) phase shifts of Weitkamp and Haeberli (1966) above 17 MeV with the Coulomb amplitudes set to zero and the energy scale shifted so as to match up mirror states in \(^5\text{Li}\) and \(^5\text{He}\). This prescription for obtaining n - \(^4\text{He}\) phase shifts from the relatively more accurately p - \(^4\text{He}\) phases worked reasonably well but suffered from the lack of accurate n - \(^4\text{He}\) data for comparison.
Using charge symmetry arguments, an early analysis by Dodder and Gammel (1952) parameterized both p - $^4$He and n - $^4$He data by means of R-matrix theory. They were able to predict the energy dependence of n - $^4$He phase shifts from p - $^4$He R-matrix parameters. The 1968 analysis of Morgan and Walter followed much the same approach for neutron energies less than 8 MeV. By fitting single-energy phase shifts with resonance parameters, an energy dependent set of phase shifts was found. In 1972, Stammbach and Walter presented a comprehensive analysis of n - $^4$He and p - $^4$He results for energies below 20 MeV. Using R-matrix formalism, they chose to fit the neutron and proton data itself rather than phase shifts, in order to avoid uncertainties due to correlations between phase shifts of different partial waves.

The R-matrix or dispersion technique has certain advantages in producing energy dependent sets of phase shifts. For example, if a prescription is used for deriving the n - $^4$He R-matrix parameters from the p - $^4$He parameters, such as was largely done by Stammbach and Walter, one may rely more heavily on p - $^4$He data, especially at higher energies where accurate neutron data is hard to obtain. It is also possible to base such a prescription to some extent on the physics involved. In this way the energy dependence of the phase shifts arises from the approximate model of physical reality which was set up initially.
**R-matrix Formalism.** -- The formal basis of R-matrix theory has been established by several authors (Lane and Thomas, 1958; Breit, 1959). Essentially the formalism is straightforward, but a complete presentation is complicated by considerable algebraic manipulation. Fortunately, for the cases of \( n - ^4\text{He} \) and \( p - ^4\text{He} \), the results simplify greatly. In the following discussion an introductory outline will be presented with the idea that it will tend to unify the description of the calculations which will be discussed later.

The most general form of R-matrix theory is rigorous and hence applies to reactions proceeding by both compound nucleus and direct reaction mechanisms (Lane and Thomas, 1958). Hence R-matrix theory is more of a framework for describing nuclear reactions than a formal theory in its own right. The basic concept is that the configuration space about a nucleus may be divided into two parts, an internal and an external region. Internally the theory does not restrict the interaction, and hence considers the nucleus as a "black box". External to the interaction region, beyond the range of the nuclear force, the wave functions are merely the free particle coulomb wave functions. At any point in configuration space, the wave functions and their radial first derivatives must be continuous; hence, the "external" wave functions must join smoothly onto the "internal" wave functions at any arbitrary boundary radius \( a \). A suitably chosen value for \( a \) should be one beyond which the nuclear interaction has a negligible effect on the Coulomb wave
functions. At the boundary radius the wave function has a radial derivative given by

\[
\left[ \frac{r}{u_{ij}} \frac{d u_{ij}}{d r} \right]_{r=a} = \frac{1}{R_{ij}} + B_{ij}
\]

where \( \frac{1}{R_{ij}} + B_{ij} \) is a function which defines the slope of the radial wave function at \( r = a \). \( R_{ij} \) is the \( R \) function of Lane and Thomas (1958) and \( B_{ij} \) are boundary values which define the particular eigenfunctions which will be used here. This equation must hold on a spherical surface of radius \( a \) surrounding the nucleus. At certain real energies, the wave functions of the internal region, which must be solutions to the Schrodinger equation, will satisfy Equation 21. These energies, denoted by \( E_{R_{ij}} \) are energy eigenvalues satisfying the derivative boundary condition at \( r = a \). The utility of \( R \)-matrix formalism is that the unknown and possibly complicated internal region may be treated in terms of a logically more simple derivative function or matrix which itself is defined in terms of this arbitrary boundary.

Matching the logarithmic derivatives of the wave functions of the two regions at \( r = a \) allows us to find the nuclear phase shifts

\[
\tan \delta_j = \left[ \frac{\left( \frac{1}{R_{ij}} + B_{2j} \right) F_{\ell}(r) - r F'_{\ell}(r)}{\left( \frac{1}{R_{ij}} + B_{2j} \right) G_{\ell}(r) - r G'(r)} \right]_{r=a}
\]

where \( F_{\ell}(r) \) and \( G_{\ell}(r) \) are the regular and irregular coulomb wave functions of the free particle, with primes indicating differentiation.
with respect to $r$.

By definition, the phase shifts $\delta_k^j$ do not depend on the choice of $a$ and $B_{qj}$. The resonance parameters of the internal region however are left as variables to be optimally chosen or specified in order to reproduce the data. In this analysis, as in the earlier work of Stammbach and Walter, the choice of $a = 3.0$ fm, corresponding to $r_o = 1.9$ fm was made.

In the single level approximation the function $R$ is chosen as the form

$$R_{qj} = \frac{\gamma^2_{qj}}{E_{qj} - E} \quad (23)$$

where $\gamma^2_{qj}$ and $E_{qj}^R$, denote the reduced width and characteristic energy of an R-matrix state in the internal region. In this approximation the assumption is made that only the characteristic energy and reduced width of the state under consideration are important.

In the event that distant levels produce a non-zero contribution the $R_{qj}$ may be chosen

$$R_{qj} = \frac{\gamma^2_{qj}}{E_{qj}^R - E} + \frac{\gamma^2_{Bqj}}{E_{Bqj}^R - E} \quad (24)$$

where the effect of the other levels is contained in the "background" term parameterized by $\gamma^2_{Bqj}$ and $E_{Bqj}^R$. This form gives the distant levels an energy-dependent structure.
In the limit that \( E_{\beta\ell j} \gg E \) we see that

\[
R_{\ell j} \approx \frac{\delta_{\beta\ell j}^2}{E_{\beta\ell j}^R - E} + R_{\ell j}^\infty
\]

where the identification \( R_{\ell j}^\infty \approx \delta_{\beta\ell j}^2 E_{\beta\ell j}^R \) has been made. This is the energy independent "distant pole" contribution employed in the earlier work of Stammbach and Walter (1972).

The nuclear phase shift \( \delta_{\ell j}^j \) may be written in two parts

\[
\delta_{\ell j}^j = \delta_{\ell j}^H + \delta_{\ell j}^R
\]

where

\[
\tan \delta_{\ell j}^R = \frac{P_\ell R_{\ell j}}{1 - (S_{\ell j} - B_{\ell j}) R_{\ell j}}
\]

\[
\tan \delta_{\ell j}^H = -\left[ \frac{F_\ell}{G_\ell} \right]_{r=a}
\]

where \( \delta_{\ell j}^H \) is the potential scattering hard sphere phase shift and \( \delta_{\ell j}^R \) is resonant phase shift. Here \( P_\ell \) and \( S_\ell \) are the penetrability and shift functions defined by Lane and Thomas (1958). The \( \delta_{\ell j}^H \) may be interpreted as the phase shift associated with a perfectly reflecting nucleus. The \( \delta_{\ell j}^R \) resonates at the characteristic \( E_{\ell j}^R \), reaching a value of \( \pi/2 \).
Considering Equation 22 it may be seen that the choice of \( B_{ij} = S_{i}^{R}(E) \) is the condition which forces the phase shift \( \delta_{ij}^{R} \) to resonate at the energy given by \( E = E_{ij}^{R} \). If the boundary condition were chosen in some other way, the resonance in \( \delta_{ij}^{R} \) would not occur at \( E_{ij}^{R} \). This may be seen by rewriting Equation 27 as

\[
E_{S} = \delta_{ij}^{2} (S_{i}(E) - B_{ij})
\]

unless

\[
B_{ij} = S_{i}(E)
\]  

Therefore with the boundary condition (30), the characteristic energies and reduced widths obtained by fitting experimental cross sections and polarizations correspond to equivalent resonance energies and reduced widths in \(^5\text{He} \) and \(^5\text{Li} \) for which the nuclear potential has been approximated by an equivalent square well (Voigt, 1962).

Michaud et al. (1970) demonstrated that although the resonance energies and reduced widths which are obtained in this manner do not correspond exactly to the states and widths of the corresponding compound nucleus, the effect of a more realistic well shape may be calculated. In particular, the result would be a resonance energy shift accompanied by a reduction of the reduced widths. References for additional discussion and interpretation may be found in Michaud et al. (1970).
If the assumption is made that the wave functions of mirror R-matrix states are similar, the possibility of inferring phase shifts for \( n - ^4He \) from an R-matrix fit to \( p - ^4He \) arises. In a simple model the \( \varphi_{\alpha j}^2, \varphi_{\beta \epsilon j}^2 \), and \( E^R_{\alpha \epsilon j} \) should be identical, while the \( E^R_{\alpha j} \) should differ by approximately the ground-state coulomb energy difference of \( ^5Li \) and \( ^5He \). The \( E^R_{\alpha j} = S_j (E^R_{\epsilon j}) \) will differ for the two systems due to the difference in \( E^R_{\epsilon j} \) and the charge dependence of the shift function, but the matching radius \( r = a \) may be kept the same. This prescription is similar to that followed by Stammbach and Walter (hereafter referred to as S-W) except that they assumed in addition that the \( \varphi_{\alpha j}^2 \) and \( E^R_{\alpha j} \) were \( j \)-independent. In their analysis these restrictions on parameters describing the \( p \)-waves (which resonate in the energy region of interest) were too severe and, in order to obtain a good fit to both \( p - ^4He \) and \( n - ^4He \) data, their restrictions on \( E^R_{\alpha j} \) and \( \varphi_{\alpha j}^2 \) were relaxed.

Because the earlier (S-W) search for R-matrix parameters had been conducted as a series of grid calculations there was the possibility that a simultaneous fit to both \( n - ^4He \) and \( p - ^4He \) data using a computer fitting procedure might be able to locate a minimum in \( \chi^2 \) space which had been missed. In order to accomplish this purpose the computer program LEVEL was written. LEVEL uses a gradient search procedure similar to that given by Bevington (1969). A description of LEVEL is given in Appendix D.
The method used by S-W for calculating the $\chi^2$ for the data and fit was adopted for use in LEVEL. That is, an angular distribution consisting of differential cross sections or polarization was weighted as one point by dividing the total $\chi^2$ by the number of points in the distribution. Therefore the total $\chi^2$ for all of the energies considered was expected to be approximately equal to the number of energies considered for $p - {}^4\text{He}$. In the case of $n - {}^4\text{He}$ the total $\chi^2$ included an additional $\chi^2$ term from the fit to an experimental total cross-section value at each energy; therefore, a $\chi^2$ of approximately twice the number of energies considered was expected for the neutron data.

Initially a search on the $n - {}^4\text{He}$ and $p - {}^4\text{He}$ data set used by S-W was conducted. This search coupled the resonance energies and fixed the reduced widths for corresponding R-matrix states. The d- and f-wave phase shifts, which are only weakly defined in the energy region below 20 MeV, were calculated using the S-W R-matrix parameters. Unfortunately, even after extensive investigation this procedure failed to give a $\chi^2$ comparable to that obtained by S-W. The restrictions on $\mathcal{J}_{q,i}$ were next relaxed and although the $\chi^2$ improved further, the best fit gave a $\chi^2$ per energy of approximately 3.2 as compared with an average of about 1.5 for S-W. A comparison of the phase shifts from this fit with the S-W $n - {}^4\text{He}$ phase shifts showed good similarity, but the p-wave phase shifts both tended to be several degrees higher than
the S-W values at energies above 14 MeV. In fact, this difference was 
hoped for and justified by the results of phase shift fits to recent high 
energy p - 4\(^He\) data (Plattner et al., 1972). That is, the results of 
Plattner et al. indicated that the S-W p - 4\(^He\) phase shifts upon which 
the n - 4\(^He\) phase shifts relied, were several degrees too low at 20 MeV.

An investigation was conducted to determine which R-matrix 
parameter should be further adjusted to give better agreement to the 
p - 4\(^He\) phase shifts near 20 MeV. The conclusion was that greater 
energy dependence was needed and could be provided by permitting the 
background resonances, previously held at E\(_R\) = \infty , to move to lower 
ergies.

Another search similar in scope to the first was then carried 
cut. For this fit, it was decided that the p - 4\(^He\) and n - 4\(^He\) data sets 
should be more evenly matched. Whereas a great deal of weight was 
given to the low energy neutron fit by utilizing all of the n - 4\(^He\) data of 
Morgan (1968) in the S-W case and in the previous search, a new neutron 
data set was formed by removing alternate sets of low energy 
4\(^He\)(n, n) 4\(^He\) differential cross-section data. In addition, the n - 4\(^He\) 
total cross-section data previously used were replaced by more accurate 
results (Goulding, 1973) which just became available. The p - 4\(^He\) 
differential cross-section and polarization data of Bacher et al. (1972) 
at 19.34 MeV were also included. Table 9 gives a summary of the 
p - 4\(^He\) and n - 4\(^He\) data used in the calculations.
Table 5
Summary of n- and p-\(^4\)He Data Used in R-Matrix Analysis

a) n-\(^4\)He differential cross-section data

<table>
<thead>
<tr>
<th>Energies (MeV)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.222, 0.404, 0.599, 0.796, 1.098, 1.700, 2.200, 2.96, 5.03, 5.99, 6.52</td>
<td>Morgan and Walter, Phys. Rev. A68 (1968) 1114</td>
</tr>
<tr>
<td>20.0, 21.0</td>
<td>Shamy and Jenkin, Phys. Rev. 135 (1964) 899</td>
</tr>
<tr>
<td>17.6, 20.9</td>
<td>Miller et al., Phys. Rev. 64 (1972) 36</td>
</tr>
</tbody>
</table>

b) n-\(^4\)He polarization data

<table>
<thead>
<tr>
<th>Energies</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.02, 2.44</td>
<td>Sayers et al., Phys. Rev. 168 (1968) 1102</td>
</tr>
<tr>
<td>6.0, 10.0, 16.4</td>
<td>Ray et al., Nucl. Phys. A45 (1963) 17</td>
</tr>
<tr>
<td>11.0, 17.7</td>
<td>Brocke et al., Phys. Rev. 54 (1972) 761</td>
</tr>
<tr>
<td>20.7</td>
<td>I.S. Trost et al., ZETF 42 (1962) 524</td>
</tr>
<tr>
<td>14.0, 17.1</td>
<td>Present Results</td>
</tr>
</tbody>
</table>

c) n-\(^4\)He total cross-section data

<table>
<thead>
<tr>
<th>E_n (MeV)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_n &lt; 0.700</td>
<td>Vaughan et al., Phys. Rev. 118 (1960) 603</td>
</tr>
<tr>
<td>E_n &gt; 0.700</td>
<td>Goulding, private communication (1973)</td>
</tr>
</tbody>
</table>

d) p-\(^4\)He differential cross-section data

<table>
<thead>
<tr>
<th>Energies (MeV)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.94</td>
<td>Bacher et al., Phys. Rev. 118 (1960) 603</td>
</tr>
</tbody>
</table>

e) p-\(^4\)He polarization data

<table>
<thead>
<tr>
<th>Energies (MeV)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.940, 1.140, 1.35, 1.56</td>
<td>Brown and Träschlin, Nucl. Phys. A60 (1967) 334</td>
</tr>
<tr>
<td>1.705, 1.97, 2.18, 2.59</td>
<td>3.00, 3.20</td>
</tr>
<tr>
<td>19.94</td>
<td>Bacher et al., Phys. Rev. 69 (1972) 1147</td>
</tr>
</tbody>
</table>
The result of the second search was an improved fit to the data, but was still lacking in overall quality. Finally it was decided to conduct an additional search in which the $p - ^4He$ data alone were fit. The $p - ^4He$ results were then taken as a starting set for a fit to the $n - ^4He$ data in which the R-matrix parameters were to be restricted as much as possible to the original conditions. This procedure proved to be successful provided the $p$-wave resonance energies and reduced widths were not tied together. All other parameters were constrained as was previously mentioned.

The resulting R-matrix parameters are given in Table 10. A comparison of phase shifts generated from the final fit with the phase shifts of Stammbach and Walter and with the phase shifts of Hoop and Barshail are shown in Figure 23 for the $n - ^4He$ case. The chief difference between the present results and those of S-W are the larger values (by 1-1/2 -- 2°) of the $s$- and $p$-wave phase shifts at higher energies.

Comparison of the $p - ^4He$ phase shifts of this work with the results of an effective range parameterization of single energy fits to data below 13 MeV (Schwandt et al., 1971) may be seen in Figure 24. The effective range $p_{3/2}$ phase shift presented by Schwandt et al. does not appear to have a single-level shape around 3 MeV. The single-energy phase shift results of Plattner et al. (1972) are also shown in Figure 21.
### TABLE 10

**R-MATRIX PARAMETERS USED TO DESCRIBE N- AND P-HE4**

#### A) N-HE4 PARAMETERS

<table>
<thead>
<tr>
<th></th>
<th>S 1/2</th>
<th>P 1/2</th>
<th>P 3/2</th>
<th>D 3/2</th>
<th>D 5/2</th>
<th>F 5/2</th>
<th>F 7/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_a$</td>
<td>36.170</td>
<td>6.423</td>
<td>0.972</td>
<td>33.500</td>
<td>31.500</td>
<td>69.000</td>
<td>61.000</td>
</tr>
<tr>
<td>$v_a$</td>
<td>3.412</td>
<td>12.055</td>
<td>7.811</td>
<td>8.000</td>
<td>8.000</td>
<td>20.000</td>
<td>20.000</td>
</tr>
<tr>
<td>$E_b$</td>
<td>-195.00</td>
<td>195.00</td>
<td>195.00</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>$v_b$</td>
<td>7.827</td>
<td>62.000</td>
<td>52.000</td>
<td>80.000</td>
<td>80.000</td>
<td>40.000</td>
<td>40.000</td>
</tr>
<tr>
<td>B</td>
<td>$0.000$</td>
<td>$-0.310$</td>
<td>$-0.748$</td>
<td>$-0.295$</td>
<td>$-0.315$</td>
<td>$-0.339$</td>
<td>$-0.394$</td>
</tr>
</tbody>
</table>

**BOUNDARY RADIUS = 3.00**

#### B) P-HE4 PARAMETERS

<table>
<thead>
<tr>
<th></th>
<th>S 1/2</th>
<th>P 1/2</th>
<th>P 3/2</th>
<th>D 3/2</th>
<th>D 5/2</th>
<th>F 5/2</th>
<th>F 7/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_a$</td>
<td>37.170</td>
<td>8.000</td>
<td>2.072</td>
<td>34.500</td>
<td>32.500</td>
<td>70.000</td>
<td>62.000</td>
</tr>
<tr>
<td>$v_a$</td>
<td>8.605</td>
<td>11.434</td>
<td>8.065</td>
<td>8.000</td>
<td>8.000</td>
<td>20.000</td>
<td>20.000</td>
</tr>
<tr>
<td>$E_b$</td>
<td>-195.00</td>
<td>195.00</td>
<td>195.00</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>$v_b$</td>
<td>7.827</td>
<td>62.000</td>
<td>62.000</td>
<td>80.000</td>
<td>80.000</td>
<td>40.000</td>
<td>40.000</td>
</tr>
<tr>
<td>B</td>
<td>$0.005$</td>
<td>$-0.311$</td>
<td>$-0.709$</td>
<td>$-0.303$</td>
<td>$-0.323$</td>
<td>$-0.344$</td>
<td>$-0.399$</td>
</tr>
</tbody>
</table>

**BOUNDARY RADIUS = 3.00**
Figure 23. Comparison of s- and p-Wave Phase Shifts for n-^4^He
Figure 24. Comparison of s- and p- Wave Phase Shifts for p-^4He.
It may be noted that the resonance parameter predictions were extended beyond the energy limit of 20 MeV used in fitting data to show the trend. It is clear that all but the \( p_{3/2} \) phase shifts of this work reproduce the Plattner results quite well. The S-W \( s_{1/2} \) and \( p_{1/2} \) phase shifts tend to have too low a value whereas the Plattner calculation falls between the S.W and the present results for the \( p_{3/2} \) phase shift.

A comparison of the R-matrix fit to \( n - ^4\text{He} \) differential cross-section data is given in Figure 23. Here the 0.202, 1.008, 2.98, and 6.523 MeV results of Morgan and Walter (1968), the 17.6 MeV data of Niller et al. (1971) and the 20.0 MeV values of Shamu and Jenkin (1964) are shown. Figure 26 shows polarizations obtained at this laboratory at 1.015, 2.435 (Sawers et al., 1968) and 7.80 MeV (Stammbach et al., 1970), along with results of this experiment at 14.0 and 17.1 MeV.

Figure 27 shows a comparison of the total cross-section fit to the experimental results of Goulding (1973) and Vaughn et al. (1960). The \( \chi^2 \) of the total cross-section fit was about 0.5 per point. Overall, the quality of the fits was quite good with an average \( \chi^2 \) per energy of 1.3 (compared to the expected 2.0) for all of the cross-section, polarization, and total cross-section data considered.

A comparison of R-matrix results with \( p - ^4\text{He} \) differential cross sections is presented in Figure 28. Here the data of Barnard et al., (1964) at 1.997, 3.006, 5.011, 7.967 and 11.957 MeV, the data of Garetta et al. (1969) at 14.23 MeV and the data of Plattner et al., (1972) at
Figure 25. Comparison of n-^4_He Differential Cross-Section

Data with R-Matrix Fit
Figure 26. Comparison of $n-^4\text{He}$ Polarization Data with R-Matrix Fit
Figure 27. Comparison of $n$-$^4$He Total Cross-Section Data with R-Matrix Fit
Figure 28. Comparison of p-^4\text{He} Differential Cross-Section Data with R-Matrix Fit
Figure 29. Comparison of p-$^4$He Polarization Data with R-Matrix Fit
19.94 MeV is shown. A similar comparison of polarization data and fit is given in Figure 28 with the results of Brown et al. (1967) at 1.970 MeV, Schwardt et al. (1971) at 4.58 and 9.83 MeV, Garreta et al. (1969) at 14.23 MeV and Plattner et al. at 19.94 MeV. Once again the fit is excellent, resulting in an average $\chi^2$ per energy of 0.83 for the complete data set (compared to an expected 1.0).

**Conclusions.** -- The new 14.0 and 17.1 n - $^4$He polarization data reported here have supplied useful information in generating phase shifts which can now be heavily relied upon for comparisons to theory and in calculating analyzing powers for use in other experiments.

The set of phase shifts resulting from the present work provides the best available parameterization of n - $^4$He (and possibly the best for p - $^4$He as well). The R-matrix parameters produced in this work avoid the difficulty of predicting phase shifts which are too small at higher energies, i.e., near 20 MeV, and therefore produce a better fit to the $^4$He(n,n)$^4$He data in that region. At lower energies the fit to the $^4$He(n,n)$^4$He provided by these results equals that of the S-W fit in quality, with a $\chi^2$ per energy below 2 in most cases for both total cross-section and other differential cross-section or polarization data.

From the success encountered in reproducing n - $^4$He observables starting from an R-matrix fit which describes p - $^4$He observables, it appears that perhaps the best way to connect the p - $^4$He and n - $^4$He systems is indeed through R-matrix formalism. Although the n - $^4$He
phase shifts calculated from p - $^4$He R-matrix parameters shifted by a 1 MeV coulomb energy difference are not in complete agreement with the best fit n - $^4$He values, the differences are rather small, especially in view of the assumptions discussed in the previous section. It is in fact quite likely that the appropriate Coulomb energy difference for states in $^5$Li and $^5$He is not 1 MeV, and also that the $p_{1/2}$ and $p_{3/2}$ levels may have different widths due to differences in the Coulomb interaction in the two systems. In view of the fact that the discrepancy is at most 600 keV for the $E^R_{l,j}$ and the $\gamma^2_{2j}$, one may be tempted to say that the differences arise due to the lack of sufficiently accurate data, although this probably is not the case.

Possibly the only shortcoming of the current parameterization could be the lack of $^4$He(n,n)$^4$He differential cross-sections. An examination of the currently available data shows that there are no reliable measurements between the low-energy work of Morgan and Walter (1968) below 8 MeV and the 17.6 MeV results of Nilier et al. (1970).

D. $^4$He(n,n)$^4$He Optical Model Calculations

Of all of the nuclei between $A = 3$ and $A = 40$, elastic scattering of neutrons and protons from $^4$He have been the most thoroughly investigated experimentally. In terms of optical model calculations for light nuclei, these two systems have certainly been the most carefully
analyzed.

Summaries of attempts to represent the n - $^4$He interaction by various potentials have been given by Morgan (1968), and Satchler et al. (1968). Among the investigations were the optical model calculations done by Morgan and Walter (1968) and Owen (ORNL-3904). Utilizing the standard potential form of Chapter V, Morgan and Walter (1968) found average parameters for the n - $^4$He optical model which worked well for energies up to 8 MeV. The Morgan and Walter parameters led to very good fits to both p - $^4$He and n - $^4$He "data" generated from phase shifts. In an unpublished report, Owen (ORNL-3904) found that a fair representation of the n - $^4$He and p - $^4$He experimental results below 20 MeV could be attained using a set of potentials somewhat different from those of Morgan and Walter.

In 1968 Satchler, Owen, Elwyn, Morgan and Walter presented an extensive analysis of most of the available n - $^4$He and p - $^4$He data below 20 MeV. The object of the study was to reproduce experimental results and at the same time obtain phase shifts as nearly identical as possible to those from phase shift analyses of the p - $^4$He and n - $^4$He systems. Satchler et al. chose to vary the real-well radius and spin-orbit depth as a function of energy to fit the data. Their final choice of parameters produced reasonable agreement with the known phase shifts and very good agreement, particularly below 14 MeV, with the p - $^4$He and n - $^4$He differential cross-section, polarization, and total cross-
section data available at that time.

Since the Satchler et al. analysis, no further optical model work has been done on the $n - ^4\text{He}$ and $p - ^4\text{He}$ systems below 20 MeV. However, we have found that for the region above 14 MeV the Satchler et al. optical model tends to predict values for the cross section and polarization which are substantially different from the results of the experiments reported here and from the 19.94 MeV $^4\text{He}(p,p) ^4\text{He}$ results of Plattner et al. (1972).

A reanalysis of the $n - ^4\text{He}$ and $p - ^4\text{He}$ optical model was therefore carried out as part of the present project with the intent of finding parameters which best describe the experimental observations. In this aspect, it was expected that the predicted phase shifts would deviate from the usual values, in part due to the inadequacy of the model.

The procedure used in this analysis was much the same as that described previously. The experimental values which were used in the optical model fit were taken from the data set used in the previous $R$-matrix investigation. Data at energies from 0.2 to nearly 20.0 MeV, in roughly 2.0 MeV steps, were used because the method which had to be employed in obtaining the optical model parameters was too time consuming to fit all of the available experimental results. At each energy there was a set of differential cross-section or polarization data, but usually not both. It was discovered that having both cross-section and polarization data at each energy was an aid in finding a
smooth set of parameters. Therefore, a set of cross-section or polarization "data" were generated from the previously discussed R-matrix parameterization to be used in connection with the experimental results. In this way both cross-section and polarization data were used in the fitting procedure.

The above data were first fit starting from each of the three sets of optical model parameters previously reported. A grid search using OPTICS was used to indicate which parameters would allow the best fits at higher energies, and a smooth set of parameters was generated. It was decided to let $V_o$ and $V_{so}$ vary with energy, meanwhile leaving the well geometries fixed if possible, as this has become the standard procedure in more recent analyses. Table 11 gives the potential parameters found in the above way, along with the results of Morgan and Walter, Owen, and Satchler et al.

The abundance of $^4\text{He}(n,n)^4\text{He}$ and $^4\text{He}(p,p)^4\text{He}$ data preclude using a grid search to give the best overall fit at all energies due to the calculation time involved. But the results in Table 11 provide a fit at lower energies which is similar in quality to the best results of Satchler et al. At energies above 12 MeV the present results are clearly a better representation, for example the $\chi^2$ per point from the Satchler et al. fit to the present 17.1 MeV results is 19.6, and from the fit using the parameters in Table 11, $\chi^2$ is 4.1 per point.
### Table II
Optical Model Parameters for n- and p-^4^He

#### a) n-^4^He

<table>
<thead>
<tr>
<th></th>
<th>$V_o$</th>
<th>$r_o$</th>
<th>$a_o$</th>
<th>$V_{so}$</th>
<th>$r_{so}$</th>
<th>$a_{so}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satchler et al.</td>
<td>41.8</td>
<td>1.50-0.01$E_n$</td>
<td>0.25</td>
<td>3.0+0.1$E_n$</td>
<td>1.000</td>
<td>0.250</td>
</tr>
<tr>
<td>Morgan and Walter</td>
<td>45.0 -0.43$E_n$</td>
<td>1.809</td>
<td>0.325</td>
<td>3.95+0.14$E_n$</td>
<td>1.235</td>
<td>0.435</td>
</tr>
<tr>
<td>Owen</td>
<td>53.3 -0.60$E_n$</td>
<td>1.350</td>
<td>0.250</td>
<td>2.3 + 0.60$E_n$</td>
<td>1.200</td>
<td>0.250</td>
</tr>
</tbody>
</table>

Present Results:

<table>
<thead>
<tr>
<th>Energy</th>
<th>$V_o$</th>
<th>$r_o$</th>
<th>$a_o$</th>
<th>$V_{so}$</th>
<th>$r_{so}$</th>
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</tr>
<tr>
<td>5.00</td>
<td>46.52</td>
<td>1.350</td>
<td>0.220</td>
<td>2.82</td>
<td>1.000</td>
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</tr>
<tr>
<td>7.80</td>
<td>47.00</td>
<td>1.350</td>
<td>0.220</td>
<td>3.30</td>
<td>1.000</td>
<td>0.220</td>
</tr>
<tr>
<td>11.0</td>
<td>46.00</td>
<td>1.350</td>
<td>0.220</td>
<td>3.40</td>
<td>1.000</td>
<td>0.220</td>
</tr>
<tr>
<td>14.0</td>
<td>45.00</td>
<td>1.350</td>
<td>0.220</td>
<td>4.90</td>
<td>1.000</td>
<td>0.220</td>
</tr>
<tr>
<td>16.4</td>
<td>42.00</td>
<td>1.350</td>
<td>0.220</td>
<td>4.20</td>
<td>1.000</td>
<td>0.220</td>
</tr>
<tr>
<td>17.1</td>
<td>41.60</td>
<td>1.350</td>
<td>0.220</td>
<td>4.40</td>
<td>1.000</td>
<td>0.220</td>
</tr>
</tbody>
</table>

#### b) p-^4^He

<table>
<thead>
<tr>
<th></th>
<th>$V_o$</th>
<th>$r_o$</th>
<th>$a_o$</th>
<th>$V_{so}$</th>
<th>$r_{so}$</th>
<th>$a_{so}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satchler et al.</td>
<td>43.0</td>
<td>1.59-0.01$E_p$</td>
<td>0.25</td>
<td>2.7 + 0.1$E_p$</td>
<td>1.000</td>
<td>0.250</td>
</tr>
<tr>
<td>Morgan and Walter</td>
<td>(same values as for n-^4^He optical potential values given above)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Owen</td>
<td>(same values as for n-^4^He optical potential values given above)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Present Results:

<table>
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<tr>
<th>Energy</th>
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<th>$r_o$</th>
<th>$a_o$</th>
<th>$V_{so}$</th>
<th>$r_{so}$</th>
<th>$a_{so}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.02</td>
<td>52.40</td>
<td>1.350</td>
<td>0.220</td>
<td>2.40</td>
<td>1.000</td>
<td>0.220</td>
</tr>
<tr>
<td>4.00</td>
<td>50.60</td>
<td>1.350</td>
<td>0.220</td>
<td>2.65</td>
<td>1.000</td>
<td>0.220</td>
</tr>
<tr>
<td>5.95</td>
<td>49.25</td>
<td>1.350</td>
<td>0.220</td>
<td>2.80</td>
<td>1.000</td>
<td>0.220</td>
</tr>
<tr>
<td>9.89</td>
<td>46.5</td>
<td>1.350</td>
<td>0.220</td>
<td>3.20</td>
<td>1.000</td>
<td>0.220</td>
</tr>
<tr>
<td>12.94</td>
<td>45.0</td>
<td>1.350</td>
<td>0.220</td>
<td>3.50</td>
<td>1.000</td>
<td>0.220</td>
</tr>
<tr>
<td>19.94</td>
<td>39.8</td>
<td>1.350</td>
<td>0.220</td>
<td>4.20</td>
<td>1.000</td>
<td>0.220</td>
</tr>
</tbody>
</table>
As Satchler et al. pointed out, the proper procedure for fitting \( p - ^4\text{He} \) and \( n - ^4\text{He} \) would be to use a global search code such as the one successfully applied by Bechetti and Greenlees (1969) in optical model analyses for heavier nuclei. On the basis of the work done here, it appears that further reanalysis of the data using a fixed geometry and including the more accurate, higher-energy data from the results of this and other recent work, will definitely produce a better optical model parameterization, particularly at higher energies. This should however wait for the application of a global search program. Present plans call for obtaining such a program for use at T. U. C. C. in the near future and applying it to the \( n - ^4\text{He} \) and \( p - ^4\text{He} \) systems using the optical model parameters given here as one set of starting parameters.
APPENDIXES
Appendix A

SUMMARY OF NEUTRON TRANSFER POLARIZATION FORMALISM

The formalism necessary to calculate all of the possible polarization transfer observables in a general experiment is quite complicated. It is possible however, to extract simple expressions which describe the neutron polarization produced at the reaction angle of $0^\circ$ when using a polarized deuteron beam. The purpose of this appendix is to summarize the expressions that were needed in the experiments described in this work. Additional presentations of general polarization transfer phenomena may be found in the work of Ohlsen (1970, 1973) and Gammel (1970).

In the discussion to follow there will be three coordinate systems defined. The first of these systems is called the "initial coordinate system for reaction" in Figure 7, and is labelled by the right-handed set $(x, y, z)$. The $z$ axis is taken along the incident deuteron momentum $\hat{k}_{in}$ with the $y$ axis perpendicular to $\hat{k}_{in}$ and in the vertical direction. In cartesian tensor notation the neutron intensity and

(122)
polarization at \(0^\circ\) are

\[
\sigma(0^\circ) = \sigma_0(0^\circ) \left[ 1 + \frac{1}{2} p_{zZ} A_{zZ}(0^\circ) \right]
\]

(31)

\[
p_{x}^{(0)} \sigma(0^\circ) = \sigma_0(0^\circ) \left[ \frac{3}{2} p_x K_{xZ}(0^\circ) + \frac{2}{3} p_{yZ} K_{yZ}^{x}(0^\circ) \right]
\]

(32)

\[
p_{y}^{(0)} \sigma(0^\circ) = \sigma_0(0^\circ) \left[ \frac{3}{2} p_y K_{yZ}(0^\circ) + \frac{2}{3} p_{yZ} K_{yZ}^{y}(0^\circ) \right]
\]

(33)

\[
p_{z}^{(0)} \sigma(0^\circ) = \sigma_0(0^\circ) \left[ \frac{3}{2} p_z K_{zZ}(0^\circ) \right]
\]

(34)

In these expressions the primed quantities refer to the second coordinate system or "final coordinate system for reaction." This system may be chosen to be different from the unprimed or "initial coordinate system for reaction." In the rest of the presentation given here however, it will be assumed that the final coordinate system is chosen with the \((x',y',z')\) axes in the same directions as the \((x,y,z)\) axes, and the primes will be dropped.

In Equations 31-34 the \(\sigma(0^\circ)\) is the cross section for neutron production by means of a polarized beam at the reaction of angle of zero degrees. \(A_{zZ}(0^\circ)\) is the zero degree analyzing power. The quantities of the form \(K_{ij}^{h}\) and \(K_{ij}^{h}\) refer to the various non-zero polarization transfer coefficients. The \(p_{ij}\) give the outgoing neutron polarizations. The \(p_{i}\) and \(p_{ij}\) refer to the beam vector and tensor polarizations given in the reaction initial coordinate system.
The relation between the initial coordinate system for the reaction and a coordinate system convenient for use at the polarized source, in which \( Z \) is chosen along the axis of symmetry of the polarized ion source (the quantization axis \( \hat{s} \)) is specified by two angles. These angles, denoted as \( \beta \) and \( \phi \) in Chapter II, specify the orientation of \( \hat{s} \) with respect to the \((x,y,z)\) system. Together with the magnitude of the beam polarizations in the \((X,Y,Z)\) system, the angles \((\beta, \phi)\) characterize the beam on target. The expressions for the beam polarization in the reaction system \((x,y,z)\) in terms of the \((X,Y,Z)\) system are given by

\[
\begin{align*}
\rho_x &= -\rho_z \sin \beta \sin \phi \\
\rho_y &= \rho_z \sin \beta \cos \phi \\
\rho_z &= \rho_z \\
\rho_{xz} &= \frac{1}{2} \rho_{zz} (3 \cos^2 \beta - 1) \\
\rho_{yz} &= \frac{3}{2} \rho_{zz} (\sin \beta \cos \beta \cos \phi) \\
\rho_{xz} &= \frac{1}{2} \rho_{zz} (3 \sin^2 \beta \cos^2 \phi - 1)
\end{align*}
\]

In the experiments being discussed here, only the component of the neutron polarization perpendicular to the final scattering plane formed by the helium cell and side detectors (the component along the \( y' \) or \( y \) axis) is effective. Therefore the only two expressions which are needed are 36 and 38. Equations (31) and (33) then become

\[
\mathcal{U}(0) = \mathcal{U}_0(0) \left[ 1 + \frac{1}{4} \rho_{zz} A_{zz}(0, (3 \cos^2 \beta - 1)) \right]
\]
\[ p_{n_y}^{(0^\circ)} = J_d^{(0^\circ)} \left[ \frac{3}{2} p_{Z} K_{y}^{(0^\circ)} \sin \beta \cos \phi + p_{ZZ} K_{y}^{(0^\circ)} \sin \beta \cos \phi \cos \phi \right] \tag{42} \]

Producing polarized neutrons with spin along \(+y\) requires deuteron alignment axis settings of \((\beta = 90^\circ, \phi = 0^\circ)\) or \((\beta = 90^\circ, \phi = 180^\circ)\). In either case the term in \(K_{yZZ}^{V}\) vanishes and Equations 31 and 33 may be solved for \(K_{y}^{V}\) giving

\[ K_{y}^{V}(0^\circ) = \frac{2}{3} \frac{p_{ny}(0^\circ)}{p_{Z}} \left( 1 - \frac{1}{4} p_{ZZ} A_{ZZ}(0^\circ) \right) \tag{43} \]

or for \(p_{ny}\) giving

\[ p_{ny}(0^\circ) = \frac{\frac{3}{2} p_{Z} K_{y}^{V}(0^\circ)}{\left( 1 - \frac{1}{4} p_{ZZ} A_{ZZ}(0^\circ) \right)} \tag{44} \]

where the +/- signs refer to spin UP/ DOWN for the incident deuterons.

The uncertainty in \(K_{y}^{V}\) as a function of each of its parameters may be expressed in the standard way

\[ (\Delta K_{y}^{V})^2 = \left( \frac{\partial K_{y}^{V}}{\partial p_{ny}} \right)^2 (\Delta p_{ny})^2 + \left( \frac{\partial K_{y}^{V}}{\partial p_{Z}} \right)^2 (\Delta p_{Z})^2 + \]

\[ \left( \frac{\partial K_{y}^{V}}{\partial p_{ZZ}} \right)^2 (\Delta p_{ZZ})^2 + \left( \frac{\partial K_{y}^{V}}{\partial A_{ZZ}} \right)^2 (\Delta A_{ZZ})^2 + \]

\[ \left( \frac{\partial K_{y}^{V}}{\partial \beta} \right)^2 (\Delta \beta)^2 + \left( \frac{\partial K_{y}^{V}}{\partial \phi} \right)^2 (\Delta \phi)^2 \tag{45} \]
The complete expression for $\Delta R_y^y$ is given on the following page in Equation 46. It may be seen that measurements taken with spin UP $(\beta = 90^\circ, \phi = 0^\circ)$ and spin DOWN $(\beta = 90^\circ, \phi = 180^\circ)$ have no first order dependence on the deuteron alignment at the target. In addition, the dependence on a knowledge of $A_{zz}$ is quite weak. It is such that a 10% uncertainty in $A_{zz}$ contributes to only about 1% of the uncertainty in $k_y^y$.

In order to determine $k_y^y (0^\circ)$ or $p_{ny}(0^\circ)$, the value of $A_{zz}(0^\circ)$ must be known. This may be measured as discussed in Chapter II. In this measurement $A_{zz}$ is calculated using

$$A_{zz}(0^\circ) = \frac{4}{F_1 P_{zz}(0^\circ) - R F_2 P_{zz}^{(2)}}$$

(11)

The uncertainty in $A_{zz}$ as a function of each of its parameters may be expressed in the standard way

$$
\left(\Delta A_{zz}(0^\circ)\right)^2 = \left(\frac{\partial A_{zz}}{\partial P_{zz}(0^\circ)}\right)^2 \left(\Delta P_{zz}(0^\circ)\right)^2 + \left(\frac{\partial A_{zz}}{\partial P_{zz}^{(2)}}\right)^2 \left(\Delta P_{zz}^{(2)}\right)^2 +
\left(\frac{\partial A_{zz}}{\partial F_1}\right)^2 \left(\Delta F_1\right)^2 + \left(\frac{\partial A_{zz}}{\partial F_2}\right)^2 \left(\Delta F_2\right)^2 + \left(\frac{\partial A_{zz}}{\partial R}\right)^2 \left(\Delta R\right)^2
$$

(48)

The complete expression for $\Delta A_{zz}$ is given in Equation 49 on page 127.

The procedure used in measuring $A_{zz}(0^\circ)$ in these experiments was to choose $\beta_1 = 90^\circ$, $\phi = 0^\circ$ (spin UP) or $\beta_2 = 8.49^\circ$, $\phi = 80^\circ$ (spin ALONG). For the above choices there is no first order dependence
\[ \Delta K_y(0^\circ) = \frac{\frac{2}{3} P_{ny}(0^\circ)}{P_z \sin \beta \cos \phi} \left\{ \left[ 1 + \frac{1}{4} P_{zz} A_{zz}(0^\circ)(3 \cos^2 \beta - 1) \right]^2 \left( \Delta P_{ny} \right)^2 + \left[ \frac{1}{4} P_{zz} A_{zz}(0^\circ)(3 \cos^2 \beta - 1) \right]^2 \left( \Delta P_z \right)^2 + \left[ \frac{1}{4} P_{zz} (3 \cos^2 \beta - 1) \right]^2 \left( \Delta A_{zz}(0^\circ) \right)^2 + \left[ 1 + \frac{1}{4} P_{zz} A_{zz}(0^\circ)(3 \cos^2 \beta - 1) \right]^2 \left( \Delta \phi \right)^2 + \right. \]
\[
\left. \left[ \frac{1}{4} P_{zz} A_{zz}(0^\circ)(\cos \beta \cos \phi) - (1 + \frac{1}{4} P_{zz} A_{zz}(0^\circ)(3 \cos^2 \beta - 1) \cos \phi \sin \phi) \right]^2 \left( \Delta \beta \right)^2 \right\}^{\frac{1}{2}} \] (46)

\[ \Delta A_{zz}(0^\circ) = A_{zz}^2 (0^\circ) \left\{ R_z F_z^2 (\Delta P_{zz})^2 + F_1^2 (\Delta P_{zz}^{(2)})^2 + R_z (P_{zz}^{(3)})^2 \Delta F_z^2 + (P_{zz}^{(1)})^2 (\Delta F_z)^2 + \right. \]
\[
\left. \left[ F_1 P_{zz}^{(1)} - F_z P_{zz}^{(2)} \right]^2 (\Delta R_z) \right\}^{\frac{1}{2}} \] (47)

\[ \Delta F_z = 6 \sin \beta \cos \beta \Delta \beta \quad \text{and} \quad (\Delta R_z)^2 = R_z^2 \left[ \frac{1}{N_1} + \frac{1}{N_2} \right] \]
on the spin orientation of $\beta_1$ as $\Delta F_1 = 0$. The first order dependence on $\beta_2$ is quite weak. In addition $\beta_2$ is known to better to 0.1° from optical alignment and is constant in magnitude because the spin precession solenoid is turned off for those measurements.

The 8.49° value of $\beta$ which results when the spin is left pointing $\perp$ along the momentum direction upon entrance to the tandem accelerator comes from a difference of spin and momentum precession in the transverse field of the bending magnet. Taking a ratio of the Larmour to Cyclotron frequencies gives the result (Ohlsen, 1970).

$$\Delta \Theta = \Delta \Theta_k - \Delta \Theta_s$$

$$\Delta \Theta = \left( \perp - 9 \frac{M}{M_p} \right) \Delta \Theta_k$$

The quantity $\Delta \Theta$ is the difference between initial and final spin ($\Delta \Theta_s$) and momentum ($\Delta \Theta_k$) angles after traversing the magnet. Here $\perp$ is the gyromagnetic moment of the particle, $M$ is its mass and $M_p$ is the mass of the proton. These effects may be summarized for the 52° and 59° beam ports in our laboratory as follows

<table>
<thead>
<tr>
<th>BEAM PORT (degrees)</th>
<th>MOMENTUM DEFLECTION (degrees)</th>
<th>$\Delta \Theta$ (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
<td>52.6</td>
<td>7.52</td>
</tr>
<tr>
<td>59</td>
<td>59.4°</td>
<td>8.49</td>
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</tbody>
</table>
Appendix B

DATA ACQUISITION AND ANALYSIS PROGRAMS

1. General

With the advent of the use of the TUNL polarized source in neutron polarization experiments the need for a set of specialized data acquisition and analysis programs arose. Two programs, PUNT and PUNT-\(\infty\) were written to fulfill these needs. In this appendix a general description of each program and its operation is given. The programming mechanics of each is best explained by the comment cards in the program listings and will not be covered here. Both programs are written in Fortran IV and are similar to others at TUNL, involving assembly language (DAP) subroutines taken from the systems library. The details of these subroutines need not be of concern to the program user, but a general understanding of the function and usage of each may be obtained by reading the systems library documentation.
2. PUNT

The program for neutron polarization data acquisition using a polarized incident beam is PUNT. The method of data acquisition and polarized source control is basically the same as that of the program NPOL, which is described by Hardekopf (1971). As shown in Figure 8, Chapter II, the computer must store four true- and four accidental-coincidence spectra as well as a helium recoil spectrum. These are stored in what is known as the DATA block, in 128 channel arrays. A SUM spectrum made up from the difference of true and accidental coincidence spectra is also calculated and stored.

A second set of 10 identical arrays which do not process incoming data make up the ANALYSIS block. This space is available for storing previous data for further analysis while accumulating additional data for re-reading data for analysis, or for performing on-line subtractions or additions using spectra contained in the DATA block. Because the spectra are stored in 2560 words (20 x 128) the remainder of the computer is available for control and monitoring of the experiment.

Using the GROUP, BLOCK and 1D-2D switches, any of the spectra may be displayed on the oscilloscope. The SUM spectrum is recalculated approximately every 5 seconds during its display. Light penning a pair of points in the SUM spectrum automatically chooses the same channels in each of the other spectra. The light penned channel
numbers, asymmetry, and number of counts may be displayed by
flipping the 1D-2D switch. Other PUNT program features include
window setting by typewriter input as well as by light pen, type out
of asymmetries between any number of pairs of light penned points in
the SUM spectrum, and protection from accidentally dumping over
previous data by only writing on tape once a double set of file marks
are encountered during tape dump operations.

The part of the program which governs data acquisition and
polarized-beam spin direction is contained in subroutine CONTRL.
This routine is called each pass through the display loop and during any
lengthy analysis routine. The usual method of data collection takes
place in what is called a SEQUENTIAL RUN (SR), which is initialized
by the operator using an interrupt sense switch on the interface panel.
CONTRL returns immediately to the main program if a SEQUENTIAL
RUN is not in progress.

Once in a SR, data is collected in the order QUDQDUQ, where
Q stands for quench ratio measurement of the beam polarization, and U
or D indicate incident beam spin UP or DOWN respectively. One set
of these sequences is called a GROUP. GROUPS may be combined in
any number, in which case the computer takes a quench ratio measure-
ment after each UD pair. Collection of a preset amount of charge sig-
nals the end of an U or D segment, and up to five scalars which may be
setup to read coincidence counts are read in to the computer and typed out. The beam spin is then inverted by means of a control pulse (OCP), a 30 second interval is waited by the computer to permit polarized source stabilization, and a sense line indicating the spin polarity is checked to ensure correct data handling before the other part of the UD segment is begun. During a SR the limits on beam current are checked as well as spin direction, and any fault condition will stop data collection until the problem is corrected.

At the conclusion of a QUDQDUQ group, the data is dumped automatically on magnetic tape, the number of groups is incremented, and if less than the number set by typewriter input, another group starting with a U segment is begun. Data is dumped on tape from the DATA block, but data read from tape is put in the ANALYSIS block.

ANALYSIS block operations are possible for each function available in the DATA block. Operations such as adding, subtracting, transferring, and exchanging the DATA and ANALYSIS blocks are possible under operator control. In addition to the data, the energy and angle identifying each run are included in each tape dump, and must be entered or set by sense switch at the start of each SEQUENTIAL RUN.
3. PUNT - $\alpha$

PUNT - $\alpha$ is the analysis program for data taken using PUNT. It is capable of all of the previously described operations in PUNT, except for data collection, as well as additional line printer output. Plotting and analysis routines and spectra printout are optional in PUNT - $\alpha$ exactly as in NPOL - $\alpha$ (Hardekopf, 1971), and will not be described here.

The principal difference between PUNT - $\alpha$ and NPOL - $\alpha$ is the inclusion of a linear background subtraction routine. This linear background is chosen by averaging an optional number of a counts below the peak and extending a line from the midpoint of the averaged channels to a chosen zero background level or to another midpoint of averaged channels. Details of the options available are described in PUNT - $\alpha$.

Using this technique, as well as the correct accidental background subtraction described previously, permits the backgrounds to be chosen with a polarization the same as the background extending below the peak.
Appendix C

SPIN 1/2 ON SPIN 1/2 VERSION OF MOCCASINS

The program MOCCASINS (Sawers, 1966) was originally designed to calculate geometry and multiple scattering corrections for a spin 1/2 on spin 0 elastic scattering. In order to generate a geometry correction for the $^3\text{He}(n,n)^3\text{He}$ data, this program was modified by replacing all of the calculation of spin 1/2 - spin 0 observables with a spin 1/2 - spin 1/2 calculation similar to that in CPHASE (Hardekopf, 1971). The calculation of cross sections, polarizations, and total cross sections is made using a set of real phase shifts and inelastic parameters which are input by means of cards at a series of energies. Multiple scattering corrections may also be calculated, but the code ignores the effect of triple-scattering spin-rotation parameters (which are expected to have a small effect) that are normally included in the spin 1/2 - spin 0 version of MOCCASINS.

With the exception of the input of the phase shifts, the spin 1/2 - spin 1/2 version of MOCCASINS takes the same set of input cards.
as the spin 1/2 - spin 0 version. The input of phase shifts to the program should be made at each energy increment as follows (the notation is the same as that used the spin 1/2 - spin 0 version for variables other than phase shifts)

<table>
<thead>
<tr>
<th>CARD</th>
<th>CONTENTS</th>
<th>FORMAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ENERGY, AMASS, BMASS</td>
<td>3F10</td>
</tr>
<tr>
<td>2</td>
<td>δ₀, δ₂, δ₄, δ₂₀, δ₂₁, ε²⁺</td>
<td>4F10</td>
</tr>
<tr>
<td>3</td>
<td>δ₁₀, δ₁, δ₂, δ₁₁, δ₁₂, δ₁₀, δ₁₁</td>
<td>8F10</td>
</tr>
<tr>
<td>4</td>
<td>δ₂₀, δ₂, δ₃, δ₂₁, δ₂₂, δ₂₁, δ₁₂, δ₁₁</td>
<td>8F10</td>
</tr>
<tr>
<td>5</td>
<td>δ₃₀, δ₃, δ₄, δ₃₁, δ₃₂, δ₃₁, δ₁₂, δ₁₁</td>
<td>8F10</td>
</tr>
<tr>
<td>6</td>
<td>ε⁻, ε²⁺</td>
<td>2F10</td>
</tr>
<tr>
<td>7</td>
<td>ENERGY, SGTNP</td>
<td></td>
</tr>
</tbody>
</table>

Here the ENERGY must be entered in equal energy steps up to an energy which is greater than that at which the correction is to be calculated. The δᵢ, γᵢ and εᵢ are real phase shifts, inelastic parameters, and mixing parameters respectively. On card 7 SGTNP denotes the n-p total cross section, and must be input in barns. All other input is the same as that in the standard version of MOCCASINS. Additional details
of other forms of input and output are given by Rhea (1973), in terms of input to the spin 1/2 - spin 0 version.
Appendix D

THE COMPUTER CODE LEVEL

The program LEVEL was written for the analysis of spin 1/2 on spin 0 elastic scattering data in terms of R-matrix parameters. The program runs on the TUNL 8-K computer and minimizes chi-square for data sets consisting of the total-elastic cross section as well as differential cross sections and polarizations. LEVEL will simultaneously fit up to sixty data sets each with as many as sixty experimental angles. It uses a simultaneous gradient search on single-level resonance energies and widths as well as background energies and widths for s, p, d, and f waves.

For single energy use LEVEL will accept data from cards. In a multi-energy mode of operation, data input is from magnetic tape. Search parameters and results are output on the line printer.

The formalism for spin 1/2 on spin 0 elastic scattering was referenced in Chapter V. Comparisons of the results calculated from phase shifts were made using OPTICS, which does either an optical
model or phase shift calculation of cross sections and polarizations. The calculation of the phase shifts themselves were compared to the results of Stammbach and Walter (1971). There was satisfactory agreement in all cases.

The gradient search routine used in LEVEL was a modified version of the one described by Bevington (1969), and used by Hardekopf (1971). Basically, the search works by stepping each R-matrix parameter being investigated by a small increment and determining the change in chi-square. From these results the gradient of chi-square is calculated.

All parameters being searched on are simultaneously increased in the direction of decreased chi-square until the chi-square passes through a minimum. The minimum is then found by parabolic interpolation. The procedure is then repeated until the minimum is localized so well that the gradient is smaller than some operator-determined limit, or chi-square is changing less than some specified amount, usually 0.1%.

Sense switch options are used for leaving the search, renormalizing the input data for best fit, and outputting results on the printer. In addition, to speed convergence, the increment step size may be automatically decreased as the chi-square minimum is approached, or parameters whose gradient is less than 0.05 may be dropped from the search. Other sense switches provide for card input of individual
R-matrix parameters, card data input at one energy, changes in search parameters, or search continuation. Each of these options is described by means of comment cards contained in LEVEL.

A separate program named DUMP is available to write the data set on magnetic tape for input to LEVEL. DUMP is documented by a series of comment cards contained at the beginning of the program. Other input/output formats are given in the listing of LEVEL.

The time necessary to fit a set of data depends to a large extent on the particular data set involved, the starting parameters, and a great many other factors. A single calculation by LEVEL takes about 1s per energy, not including tape spacing operations. Typical calculation times for one iteration in the gradient search are between 30s and 1 minute for a data set with 30 energies. For the fits presented in this work total calculation time is estimated at approximately 10 hours per set.
Appendix E
DATA SUMMARY

Identification of column headings...

RUN... specifies the identification of the particular measurement
THETA... specifies the lab angle of the measurement
THCM... specifies the center of mass angle of the measurement
ASYM... the final value of the measured asymmetry after off-line analysis
\( G(\ \text{THETA}) \)... the geometry and multiple scattering correction
    used in angular distribution measurements
\( G(\ \text{ENER}) \)... the geometry and multiple scattering correction
    used in the \( \chi^2(0^\circ) \) measurements
P(NEUT)... the calculated incident neutron polarization
F(DEUT)... the incident deuteron polarization
ENER... the average bombarding energy
DASYM... the statistical error associated with the asymmetry measurement
SYSCAL... the systematic scaling error associated with the measurement as specified in Chapter II (see note below)
SYSNS... the systematic non-scaling error associated with the measurement as specified in Chapter II
P(THET)... the asymmetry divided by the incident neutron polarization
DP(THET)... the final error associated with a quadratic combination of the statistical and systematic errors in the measurement
\( KYY(E,0) \)... the zero-degree polarization transfer coefficient
\( DKYY(E,0) \)... the error in the above coefficient determined as for DP(THET)

Because the quench ratio method for determining beam polarizations is a new technique at this laboratory, all of the possible sources of deviation of the quench ratio polarization from the true polarization have not been determined. Until more experience in this matter has been attained, a scaling error of 2% is considered to be associated with the deuteron quench ratio value. This scaling error was combined in SYSCAL.
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M.S. University of Mississippi, 1969

Positions: Research Assistant, University of Mississippi, 1966-1969
Research Assistant, Duke University, 1969-1973

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