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Polarization of Neutrons from the $^{14}\text{(d, n)}^{15}\text{O}$ Reaction at 1.32 Mev

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by

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CHAPTER I

INTRODUCTION

Any particle with intrinsic spin other than zero can align its spin axis relative to an axis of quantization. If all of the spin directions are represented with equal probability in a beam of particles, the beam is unpolarized. However, if all of the particle spins are aligned in the same direction, the beam is completely polarized. Beams of identical particles will in general be completely unpolarized unless some sorting mechanism has been employed. If a beam contains \( N_+ \) particles in states with spin aligned in the positive \( z \) direction and \( N_- \) particles in states with spin aligned in the negative \( z \) direction, a natural definition for polarization is

\[
P_z = \frac{N_+ - N_-}{N_+ + N_-} \quad [1]
\]

With this definition, \(-1 \leq P_z \leq 1\). In general \( P_z \) alone is not sufficient to describe the polarization state unless \(|P_z| = 1\). If
$|P_z| \neq 1$, the polarization components in 3 independent $\vec{n}_i$ are needed.

$$\vec{P} = P_x \vec{n}_x + P_y \vec{n}_y + P_z \vec{n}_z$$ \hfill [2]

where $P_x$ and $P_y$ are defined in the same manner as $P_z$ (1).

Important information on nuclear structures and nuclear interactions can be obtained from the study of polarization in nuclear processes. The present investigation of the $^14N(d,n)^15O$ reaction was undertaken for the following purposes:

(1) to furnish some information on the interaction mechanism. The shape and degree of polarization to be expected from the compound nuclear process may be quite different from that expected from a direct interaction. Explanations of the reaction by a few level compound nucleus model, and by a stripping model have been suggested, but not established.

(2) to see if information can be obtained about states in $^16O$ above 20 Mev excitation. If the reaction can be explained by a few-level compound-nucleus model, data on polarization will help define the excited states. Several theoretical and experimental investigations which have been carried out on the $^16O$ nucleus in the excitation energy range corresponding to the present experiment give rise to many questions. In particular, any information
on the presence and isotopic spin of a giant dipole resonance at an O^{16} excitation level of about 22 Mev is of major interest.

(3) to investigate this reaction as a possible source of polarized neutrons. The N^{14}(d, n_0)O^{15} reaction produces neutrons in an energy region which might help fill a gap in the energies of available polarized neutron sources. The known polarized neutron sources available from 0.2 to 15 Mev are shown in Figure 1. It can be seen that for low-energy accelerators, for which the application of the T(p, n) reaction is limited, polarized neutron sources yielding neutrons more energetic than those from the D(d, n) reaction are not available. The N^{14}(d, n) reaction has a Q value 2 Mev greater than the D(d, n) reaction and might be a useful source for low energy accelerators.

The first suggestions for the polarization of fast neutron beams by scattering were made by Schwinger (2, 3). He predicted that polarization should be expected in elastic scattering from helium due to the P-level splitting in the compound nucleus He^5. Helium scattering is commonly used for analyzing polarization. Schwinger also suggested an alternate method of analyzing the polarization of fast neutrons. The motion of a neutron in the coulomb field of a nucleus results in a spin-orbit coupling between
the spin of the neutron and the magnetic moment of the coulomb field expressed by the following term in the Hamiltonian:

$$H' = \frac{g e \hbar}{2M^2C^2} \vec{\sigma} \cdot \vec{E} \times \vec{P}$$  \[ \text{[3]} \]

where $g$ is the gyromagnetic ratio, $\vec{P}$ is the neutron momentum, $\frac{e \hbar}{2MC}$ is the nuclear magneton and $\vec{E}$ is the electric field. The advantage of coulomb scattering is that it does not depend on the phase shifts which enter into resonance scattering, and thus, is more easily calibrated. Unfortunately, the polarization from nuclear coulomb scattering has appreciable values only for very small scattering angles, on the order of a few degrees, from a heavy target.

Wolfenstein (4, 5) suggested that the prominence of spin-orbit coupling in nuclear interactions may result generally in the polarization of the reaction products. This suggestion was primarily based on a paper by Konopinski and Teller (6) showing that the interpretation of the d-d reaction requires a sizeable p-wave interaction with strong spin-orbit coupling. Both the protons and neutrons were soon proven to be polarized by observation of the left-right asymmetry when they were scattered from helium, carbon or oxygen as an analyzer (7, 8, 9, 10).

Since these early experiments a number of other reactions have been found to produce polarized particles. Thorough
Experimental evaluations have been carried out for many reactions
which have application as sources of polarized neutrons. The
polarization of neutrons from the \( D(d, n)He^3 \) reaction has been
studied in experiments by Pasma (11), Meier (12), Levintov (13),
Baicker and Jones (14, 15), McCormac (16), and Dubbeldam (17).
The \( Li^7(p, n)Be^7 \) reaction which has a threshold of 1.88 Mev has
been studied by Adair (18), Willard (19), Darden (20, 21), Cran-
berg (22), and Baicker and Jones (14, 15). Artermov et al. (23)
used the inverse reaction technique suggested byBarschall (24)
to analyze the neutron polarization from the \( T(p, n)He^3 \) reaction.
The \( T(d, n)He^4 \) reaction has been investigated as a source of high
energy neutrons. Pasma (11) detected no polarization for
deuteron energies up to 300 Kev. However, measurements with
1.8 Mev deuterons by Levintov et al. (25) showed a maximum
polarization of 0.12. Haeberli (26) and Roland showed that
neutrons emitted near the forward peak of the angular distribution
for the \( C^{12}(d, n)N^{13} \) stripping reaction have a relatively high
polarization.

The general conclusion from these experiments is that
polarization in reactions is not an uncommon phenomenon. Since
spin-orbit coupling is a necessary condition for polarization, the
polarization experiments afford direct evidence of the importance
of spin-orbit coupling in nuclear reactions. In addition, sources of polarized neutrons for use in scattering experiments are now available, with a few blank areas, over an energy range from 0.2 to 16 Mev (27).
CHAPTER II
THEORY OF POLARIZATION

It was previously shown that the spin properties of a beam of spin 1/2 particles can be completely described by the polarization vector $\bar{P}$. Each directional component of this vector is defined as the difference between the number of particles having their spins parallel and anti-parallel to that direction divided by the sum. In a quantum mechanical description the wave function for a particle consists of a scalar function $\psi(r)$ and a spin function $\chi$

$$\psi(r, \hat{s}) = \psi(r) \chi(\hat{s}) \quad [4]$$

For a spin 1/2 particle (nonrelativistic), the spin state is a superposition of the two base states

$$\psi = a_1 \psi + a_2 \psi \quad [5]$$

and normalizing

$$|a_1|^2 + |a_2|^2 = 1 \quad [6]$$

In Pauli spinor notation

$$\chi = \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \quad [7]$$

$|a_1|^2$ represents the probability of finding the particle in the
state $S = 1/2$ and $|a_2|^2$ the probability of finding it in a $S = -1/2$
state.

Thus

$$P_z = \frac{|a_1|^2 - |a_2|^2}{|a_1|^2 + |a_2|^2} = \frac{|a_1|^2 - |a_2|^2}{|a_1|^2 + |a_2|^2}$$

In terms of the Pauli spin matrixes

$$\langle \sigma_z \rangle = \langle \chi^+ , \sigma_z \chi \rangle = \langle a_1^* , a_2^* \rangle \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

$$= \langle a_1^* , a_2^* \rangle \begin{pmatrix} a_1 \\ -a_2 \end{pmatrix} = a_1^* a_1 - a_2^* a_2$$

and from [8]

$$P_z = \langle \sigma_z \rangle = \langle \chi^+ , \sigma_z \chi \rangle$$

with the spin matrixes defined

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

This leads to the definition of $P$ as the expectation value of the

$$P = \langle \chi^+ , \sigma_z \chi \rangle$$

or

$$P_x = a_1^* a_2 + a_1 a_2^* = 2 \text{Re} a_1^* a_2$$

$$P_y = \frac{1}{i} (a_1^* a_2 - a_1 a_2^*) = 2 \text{Im} a_1^* a_2$$

$$P_z = |a_1|^2 - |a_2|^2$$

Each of the spin $1/2$ particles can be considered as being

in a state given by a Pauli spinor. If all of the particles are in
the same state, the beam is completely polarized and may be
specified in the above formulation. However, if the beam has
mixed spin states, the question arises as to whether it is necessary
to specify the spin states of all the particles in order to completely
determine the results of any experiment involving the beam.

The polarization for a beam is defined as

$$P_z = \frac{\sum_n (|a_1(n)|^2 - |a_2(n)|^2)}{\sum_n (|a_1(n)|^2 + |a_2(n)|^2)}$$

with the other components defined similarly. The sum over "n"
includes all particles in the beam. This formal averaging proce-
dure can be avoided by introducing the concept of the density
matrix.

Density Matrix

The wave function of a pure state $\psi$ can be expanded in a
complete set of functions $\phi_n$,

$$\psi = \sum_n C_n \phi_n \quad \text{with} \quad \sum_n |C_n|^2 = 1$$

and the expectation value of the operator $A$ is given as

$$\langle A \rangle = \langle \psi^+, A \psi \rangle = \int \sum_n C_n^* \phi_n^+ A \sum_m C_m \phi_m \, d\tau$$

$$= \sum_{nm} C_n^* C_m \int \phi_n^+ A \phi_m \, d\tau = \sum_{nm} A_{nm} C_n^* C_m$$

The observable $A$ in a mixed state is the statistical mechanical
average over the expectation values of the pure states.
\[ \langle \tilde{A} \rangle = \sum_{\alpha} g^{(\alpha)} \langle A^{(\alpha)} \rangle = \sum_{nm} A_{nm} \sum_{\alpha} g^{(\alpha)} C_n^{\alpha} C_m^{\alpha} \quad [17] \]

where \( g^{(\alpha)} \) is the statistical weight of the pure state \( \langle \alpha \rangle \).

\[ \sum_{\alpha} g^{(\alpha)} = 1 \quad [18] \]

The density matrix is defined as

\[ \rho_{mn} = \sum_{\alpha} g^{(\alpha)} C_n^{\alpha} C_m^{\alpha} \quad [19] \]

and \([17]\) becomes

\[ \langle \tilde{A} \rangle = \sum_{mn} A_{nm} \rho_{mn} = \text{Tr}(\rho A) \quad [20] \]

Thus, the expectation value of any operator \( \mathcal{A} \) is given as the trace of the matrix \( \rho \). Now if one defines

\[ \rho_{\alpha\nu} = \sum_n \frac{1}{n} g^{(n)} a_\alpha^{(n)} a_\nu^{(n)*} \quad (\alpha, \nu = 1, 2) \quad [21] \]

with \( \sum_n g^{(n)} = 1 \)

then

\[ \bar{P} = \langle \bar{\sigma} \rangle = \text{Tr}(\bar{\rho} \bar{\sigma}) \quad [22] \]

Since rotational invariance is required the \( P \) matrix must be Hermitian and any 2 x 2 Hermitian matrix can be expressed as a linear combination of the unit matrix and the Pauli spin operators.

\[ \rho = a I + b \sigma_x \sigma_1 + b \sigma_y \sigma_2 + b \sigma_z \sigma_3 = a + b \cdot \sigma \quad [23] \]

From \([21]\) \( \text{Tr} \rho = 1 \). With \( \text{Tr}(I) = 1 \) and \( \text{Tr}(b \bar{\sigma}) = 0 \), \( a \), is determined to be 1/2. Setting operator, \( A \), in \([20]\) equal to \( \sigma_j^* \)

and noting that

\[ \text{Tr}(\sigma_j^* \alpha_{ij}) = \delta_{ij} \]

yields

\[ \rho = 1/2(I + \bar{P} \bar{\sigma}) \quad [24] \]
For a beam completely polarized in the z direction the density matrix becomes
\[ \rho_{\text{pol}} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \]
and for an unpolarized beam
\[ \rho_{\text{unpol}} = \begin{pmatrix} 1/2 & 0 \\ 0 & 1/2 \end{pmatrix} \]
If the z axis corresponds to the axis of polarization
\[ \rho = P \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} + (1 - P) \begin{pmatrix} 1/2 & 0 \\ 0 & 1/2 \end{pmatrix} \]
Thus, a partially polarized beam is equivalent to a combination of two beams, one completely polarized and one completely unpolarized.

**Scattering From a Spin 0 Target**

For the He\(^4\) analyzer used in the present experiment, the scattering matrix can be restricted to a spinless target. The total wave function for neutron scattering can be written
\[ \psi = \psi_{\text{in}} + \psi_{\text{out}} = e^{i\mathbf{k}_\| \cdot \mathbf{r}} + e^{i\mathbf{k}_\perp \cdot \mathbf{r}} M(\Theta, \Phi) \]
As in \[\text{[23]}\], the scattering matrix \(M\) is expressed as a linear combination of the unit operator and Pauli spin operators.
\[ M = g I + \mathbf{\vec{h}} \cdot \mathbf{\vec{\sigma}} \]
Since the Pauli spin operator transforms like an axial vector, \(\mathbf{\vec{h}}\) must also transform like an axial vector. The only physical vectors available are \(\mathbf{\vec{k}}_{\text{in}}\) and \(\mathbf{\vec{k}}_{\text{out}}\) which can combine as an
axial vector only in the form $\mathbf{n} = \mathbf{r}_{\text{in}} \times \mathbf{r}_{\text{out}}$. Thus $\mathbf{h} = h(\varepsilon) \mathbf{n}$ and equation \[29\] becomes

$$M(e, \phi) = g(\varepsilon) + h(\varepsilon) \mathbf{\sigma} \cdot \mathbf{n}$$  \[30\]

The density matrix formulation used previously can be conveniently applied to the expression of the cross section

$$\sigma(e, \phi) = \xi g^{(\varepsilon)} \chi^{(\varepsilon)}_{1}^{\tau} M \chi^{(\varepsilon)}_{2}$$  \[31\]

$$= \text{Tr}(\rho M M) / \text{Tr} \rho = \text{Tr}(\rho M M)$$

and by suitable algebra:

$$\sigma(e, \phi) = \left| g(\varepsilon) \right|^2 + \left| h(\varepsilon) \right|^2 + 2 \text{Re} g^{*} h(\mathbf{P} \cdot \mathbf{n})$$  \[32\]

The asymmetry with $P = 1$ becomes

$$A = \frac{\sigma(e, 0) - \sigma(e, 180^\circ)}{\sigma(e, 0) + \sigma(e, 180^\circ)} = \frac{2 \cdot 2 \text{Re} g^{*} h}{2 \left[ \left| g(\varepsilon) \right|^2 + \left| h(\varepsilon) \right|^2 \right]}$$  \[33\]

with

$$\sigma_{\text{unpol}}(\theta) = \left| g(\theta) \right|^2 + \left| h(\theta) \right|^2$$  \[34\]

It can be verified that the polarization given to an unpolarized beam is equal to the asymmetry $A$ from a polarized beam

$$P_2(\varepsilon) = A_2(\varepsilon)$$  \[35\]

From a phase shift analysis the functions

$$g(\varepsilon) = \frac{1}{k} \xi \sum_{l} e^{i \delta_{l}^{+} \sin \delta_{l}^{-}} e^{i \delta_{l}^{-} \sin \delta_{l}^{+}} P_{l}^{1}(\cos \varepsilon)$$  \[36\]

$$h(\varepsilon) = \frac{1}{k} \xi \sum_{l} e^{i \delta_{l}^{+} \sin \delta_{l}^{-}} e^{i \delta_{l}^{-} \sin \delta_{l}^{+}} P_{l}^{1}(\cos \varepsilon)$$

Substituting these functions into \[33\] yields the analyzing power of He$^4$. The curves of polarization used here were those calculated from the phase shifts derived by Seagrave (28).
Polarization in Compound Nucleus Reaction

A theoretical analysis which generalizes the expression for polarization in compound nucleus reactions has been made by Simon and Welton (29). The term reaction includes elastic scattering, and the case of elastic scattering by $\text{He}^4$ was specifically treated in this formulation. Since the elements of the nuclear scattering matrix are independent of all magnetic quantum numbers, these sums are eliminated and the final results are expressed in terms of the reaction matrix and Racah coefficients. From the properties of Racah coefficients, Simon and Welton list several selection rules.

(a) If only $S$ waves are effective in this reaction, for either the incident or the final states, there can be no polarization.

(b) If only levels of the compound nucleus having $J = 1/2$ and a single parity (or $J = 0$ with any parity) are effective, there will be no polarization.

(c) If only channel spin 0 is effective for the final channel spin, the polarization vanishes.

(d) Polarization results from the interference of different subchannels (i.e., partial waves or final channel spins) contributing to the reaction. (The state of the residual nucleus must always be the same, of course.) Hence, if there is only a single nonzero element of the scattering matrix, the polarization will vanish.
(e) If there is no spin orbit coupling, the polarization is zero.

(f) If there is a largest effective incident orbital wave $\ell$, final orbital wave $\ell'$, or total angular momentum $J$, there will be a largest value of $L''$ (in the angular distribution $P_{L''}^i$) given by the simultaneous conditions

$$L \leq 2\ell; 2\ell'; 2J$$

In addition, one must remember that $L$ must be even if the interfering states have the same parity.

The symmetry properties which were applied to the polarization of neutrons scattered by helium also apply to the polarization of neutrons produced in nuclear reactions. These require that the polarization vector be normal to the reaction plane, and that there be symmetry about the direction of the incident beam. Following the Simon and Welton derivation which utilizes the Blatt and Biedenharn (30) notation, differential polarization is defined to be

$$dP_{\alpha'\alpha} = \langle \langle \psi_{\alpha'\alpha} \mid i' \psi_{\alpha'\alpha} \rangle \rangle \cdot \hat{v}_{\alpha'\alpha}^{-1} \hat{v}_{\alpha'\alpha} \rangle_{\text{ave}} \tag{38}$$

where an average is taken over initial states and a sum over final states. The polarization is then defined to be

$$P(\theta) = \left( \frac{1}{i} + \frac{1}{i} \right)^{1/2} \left( \frac{dP(\theta)}{\sigma(\theta)} \right) \tag{39}$$
The final polarization expression with the sum over $J_1 J_2 \ell_1 \ell_2$

$$\sum_{\ell_1, \ell_2, s_1, s_2}$$

and $L$ is

$$dP_{q'q} = \frac{2}{\pi} \frac{(2i_1 + 1)^{1/2}}{(2i + 1)(2i + 1)} \sum_{i} \langle \ell_2^{-\ell_1 + \ell_1' - \ell_2'} \rangle$$

$$\times R.P. \left\{ \frac{1}{2} \left[ \delta(\ell_1' s_1') \delta(\ell_2' s_2') \langle s_1' s_2' \rangle - S(q' \ell_1' s_1'; q' \ell_1; J_1 \ell_1') \right] \right\}$$

$$\times \left\{ \delta(q_1' q_2) \delta(\ell_1' \ell_2') \langle s_1' s_2' \rangle - S(q_1' \ell_1' s_1'; q_2 \ell_2; J_2 \ell_2') \right\} \right\}$$

$$\times (-1)^{I_1 - I_2} \pi^{I_1 + J_1 - s_1 + \ell_1 + 1} \pi^{I_2 + J_2 - s_2 + \ell_2 + 1}$$

$$\times (2J_1 + 1)(2J_2 + 1)(\ell_1 L_1 \ell_2 L_2 00) \times (\ell_1' \ell_2' 00 \ell_1' \ell_2' L_1 L_2 00)$$

$$\times \left( \frac{1}{2} \right) \langle \ell_1' \ell_2' 00 \ell_1' \ell_2' L_1 L_2 00 \rangle$$

$$\times W (i_1' s_1' i_2' s_2'; I_1 I_2) \times W (\ell_1 \ell_2 \ell_2' \ell_1'; SL)$$

$$\times X (J_1 \ell_1' i_1' s_1' J_2 \ell_2' s_2'; LL L) \times P_{\ell_1}(\ell_1) d \ell_1$$

Some correlations of the polarization results of this experiment were carried out using this formulation and are discussed in Chapter VI.

**Polarization in Direct Reactions**

Whether the $N^{14}(d, n)O^{15}$ reaction or its mirror reaction $N^{14}(d, p)J^{15}$ at 1.3 Mev bombarding energy can best be described by a compound nucleus or a deuteron stripping model is open to some question. W. M. Jones (31) studied the proton angular distribution from the reaction and concluded that this data could probably be described in terms of a few-level compound-nucleus reaction. However, not enough information was available to yield a strong conclusion. On the other hand, Gorodetsky (32) gave
evidence for direct interaction in the $N^{14}(d,p)$ reaction, and Weil and Jones (33) fit the angular distribution of the $N^{14}(d,n)$ reaction at one energy with plane wave exchange stripping.

Recent developments in the theory of direct reaction (34) and in methods of calculation (35) permit evaluation of the polarization of reaction products. The Butler stripping theory (36) and similar plane wave theories neglect the interaction of the deuteron as well as the outgoing neutron with the nucleus. Thus no polarization is predicted. Newns (37) showed semiclassically that polarization of the outgoing neutron could be expected if distortion effects of the nucleus on the entering and exiting wave are considered. Referring to Figure 2, it can be seen that protons captured in hemisphere 1 have their orbital angular momentum directed out of the page, while those captured in hemisphere 2 will have oppositely directed orbital angular momentum. Thus, the spins of the neutrons emitted from hemisphere 1 will be opposite from those emitted from hemisphere 2. If there is no interaction between either the deuterons or the neutrons and the nucleus, spin up and spin down neutrons will emerge with equal probability, as is assumed in the Butler theory. However, if the neutrons are attenuated by the nucleus, fewer neutrons will emerge from hemisphere 1 than from hemisphere 2, and the beams will be partially polarized. The sign of the polarization depends on whether the
total angular momentum \( j \) is equal to \( \ell + 1/2 \) or \( \ell - 1/2 \). If \( j = \ell - 1/2 \) and only the neutron wave is distorted, the spin up neutrons from hemisphere 2 will predominate and the neutron polarization will be positive (Basel convention). For \( j = \ell + 1/2 \) the signs are opposite. If, however, the predominant distortion is on the incoming deuteron, more neutrons will originate from hemisphere 1 than from hemisphere 2, and the polarization will be negative for \( j = \ell - 1/2 \). For \( \ell = 0 \), obviously no polarization can occur. In any real nucleus, of course, deuteron and neutron interactions can both occur, giving rise to polarizations of varying sign and magnitude. However, the general results of deuteron stripping experiments in the medium energy range show that, with the exception of 2 reactions, deuteron central distortion effects predominate over proton distortion in producing polarization (38). The two exceptions are \( B^{10}(d,p)B^{11} \) and \( Ca^{40}(d,p)Ca^{41} \). The anomalous \( B^{10}(d,p)B^{11} \) polarization may be explained on the basis of a spin flip following the normal \( \ell = 1 \) transition, requiring non-central proton interaction. An alternate suggestion is that exchange stripping may occur.

Direct reaction theory can be considered as an extension of the optical model with an additional interaction which gives rise to non-elastic processes. This perturbation affects some internal degree of freedom of one of the nuclei. The simplest type of
interaction is the case where one nucleus is regarded as consisting of two nuclides held in a bound state by their mutual attraction. In deuteron stripping reaction, for example, the incident deuteron consists of two particles, the proton and neutron, while the target nucleus is considered as a single core particle.

The distorted-wave Born approximation for the transition amplitude assumes that elastic scattering is the most important process which occurs, that non-elastic events can be treated as perturbations and that the interaction can be described by a one step process. Relative motion before and after the collision is described by distorted waves, which include the elastic scattering. These waves are usually calculated with an optical model approximation.

The complexity of the calculations involved in distorted wave theory make the use of a high-speed computer desirable. The ORNL code Sally (35) has been used for these calculations. The "zero-range" approximation is applied in Sally. That is, the effective interaction is evaluated assuming that the separation vectors \( \mathbf{r}_{bB} \) and \( \mathbf{r}_{aA} \) are parallel, \( \mathbf{r}_{bB} = \frac{M_A}{M_B} \mathbf{r}_{aA} \) where "a" refers to the incident particle, "b" refers to the emitted particle, and "A" and "B" are the target and residual nuclei. Spin orbit coupling is also neglected. With these approximations the maximum allowable polarization is 1/3. However, the
polarization in some stripping experiments has been shown experimentally to be greater than 1/3. This discrepancy can be explained by the assumption of a small amount of spin-orbit coupling (34). Heavy particle stripping can also lead to complete polarization (39). Because of the zero range approximation, Sally cannot treat heavy particle stripping.
CHAPTER III

MEASUREMENT OF POLARIZATION

Several possible experiments are available for the determination of the polarization of neutrons. In the present investigation of the $^{14}_N(d, n)^{15}_O$ reaction a left-right scattering experiment was performed using liquid helium as an analyzer. It can be seen from the following description that scattering of a polarized beam can result in azimuthal asymmetry.

The cross-section for elastic scattering of polarized neutrons is

$$
\sigma(\theta_2) = \sigma_u(\theta_2) \left[ 1 + P_1 P_2(\theta_2) \hat{n}_1 \cdot \hat{n}_2 \right]
$$

$P_1$ = Degree of polarization of the incident neutron

$\theta_2$ = The angle between the incident and scattered neutrons

$\sigma_u(\theta_2)$ = The elastic scattering cross-section for unpolarized neutrons

$P_2(\theta_2)$ = The analyzer efficiency of the scatterer

$= \text{The degree of polarization of the scattered neutron if the incident beam is unpolarized}$

$\hat{n}_1$ and $\hat{n}_2$ are normals to the reaction and scattering planes respectively
if the reaction and scattering are coplanar. The primes refer to the outgoing particle.

\[ \sigma^+(\theta_2) = \sigma_u(\theta_2)[1+P_1P_2(\theta_2)] \]
\[ \sigma^-(\theta_2) = \sigma_u(\theta_2)[1-P_1P_2(\theta_2)] \]

and from the ratio \( r = R/L = \sigma^+(\theta_2)/\sigma^-(\theta_2) \) the value of \( P_1P_2 \) follows:

\[ P_1P_2 = \frac{r-1}{r+1} \]

Helium was chosen for this investigation for several reasons. It has been extensively studied by previous workers; its efficiency is high and relatively well known, and varies reasonably smoothly with energy. Also it can be used as a liquid scintillator which was required in the present experiment. Other fairly commonly used analyzer material includes carbon and oxygen.

Mott-Schwinger scattering has been used by Voss and Wilson (40) at Harwell to measure neutron polarization by scattering at 0.3° from uranium. This method, which was discussed in the previous section, provides almost 100 per cent analyzer efficiency. A modified Stern-Gerlach experiment has been considered for analyzing fast neutron polarization, but the small magnitude of the magnetic moment makes the experiment impractical.
Another mechanism for analyzing polarization, which was first discussed by Barschall (24) is the use of the inverse reaction. This method has been used by Artemov (23), et al., in studying the polarization of neutrons from the T(p,n)He\textsuperscript{3} reaction by measuring the right-left asymmetry of the proton produced in the inverse reaction He\textsuperscript{3}(n,p)T. It is possible to choose an angle of emission for the neutron such that the compound nucleus He\textsuperscript{4} is formed with the same excitation energy in the original as in the inverse reaction. If the same center of mass angle between neutrons and protons is chosen for both reactions, the polarization of the neutron can be determined by measuring the left-right asymmetries of the protons. The importance of the method is that the asymmetry depends only on the square of the polarization, with no knowledge of phase shifts required. The proper Barschall angles yield

\[
\frac{R}{L} = \frac{1 + P^2}{1 - P^2}
\]

[45]

In a reaction \( a + b \rightarrow c \rightarrow d + e \) the Barschall angle is given by

\[
\cos\theta = \frac{E_a \left( m_b + m_e \right) + Q \left( m_c + m_e \right)}{2 \left( m_a m_e \times E_a (E_a m_b + Q m_e) \right)^{1/2}}
\]

[46]

where Q is the reaction energy.

All of the experimental methods for analyzing polarization require the measurement of left-right asymmetries. In the usual
method, the one used for the present experiment, the detector is turned from \((+\phi_2)\) to \((-\phi_2)\) by accurate mechanical equipment. This leads to possible false asymmetries due to the variation of the neutron intensity over the scatterer, as well as an extra source of experimental error in angular determinations. These problems can be eliminated by a method suggested and applied by Hillman, et al.\((41)\). In this method the polarization vector of the neutrons is turned by using the Larmor precession vector of the neutron magnetic moment in a magnetic field.
CHAPTER IV

EXPERIMENTAL METHOD

The experimental work described in this thesis was performed with The Ohio State University 2 Mev. electrostatic accelerator. After leaving the accelerating tube, the beam enters an analyzing magnet for mass and energy analysis. The magnet deflects the beam through 90°. On leaving the magnet, the beam enters a strong-focusing lens and continues through a 1/8" diameter collimating system to a gas target located about 25 feet from the magnet.

The determination of polarization is accomplished by a measurement of the left-right symmetry in scattering from a liquid helium analyzer (Figure 4). Neutrons of approximately 6 Mev are generated by bombarding the nitrogen-filled gas target with deuterons. Neutrons emerging from the target in the horizontal plane and angle \( \Theta_1 \) are scattered by a liquid helium scintillation chamber (Figure 4). The neutrons scattered from this scintillation chamber in the horizontal plane at angle \( \Theta_2 \) enter a stilbene detector. The time of flight for the neutron over its
8-1/2 inch flight path from the helium to the stilbene is measured by a time to pulse height converter. Since the $^{14}\text{N}+\text{d}$ reaction produces many more gamma rays than neutrons a decay time discriminator circuit was used to supplement the time of flight discrimination.

Figure 5 shows the electronics.

**Calibration**

Before starting a series of measurements, it was necessary to check the calibration of the angular settings. The zeroes of both $\phi_1$ and $\phi_2$ were first established optically using a gun sight technique. A second check was then made of $\phi_1$ by filling the gas target with deuterium and measuring the angular distribution of the count rate in the liquid helium scintillator, the center of symmetry being zero degrees. In a similar manner, $\theta_2$ was checked by setting $\phi_1$ to $0^\circ$ and finding the $\theta_2$ angle about which the $L/R$ ratio was one for the neutrons scattered by the liquid helium. That is, $\theta_2$ was set so that the polarization was zero for $\phi_1 = 0^\circ$. As a further check on the calibration, the polarization of $D(d, n)\text{He}^3$ neutrons was measured several times for $\phi_1 = 45^\circ$ and $E_d = 1.32$ Mev. These measurements, which were taken at $\phi_1 = \pm 45^\circ$ to insure the elimination of false symmetries, gave a neutron polarization of $-0.13\pm0.03$ which is consistent with the results of other investigators (42).

In addition to the angular calibration, each of the scintillator channels were checked to establish constant gain. Also, the
pulse shape discriminator circuit was checked with neutrons from the D(d, n)He$^3$ reaction and with gamma rays from a cobalt-60 source to be certain that neutrons were being counted and that gamma rays were not.

**Gas Target**

The gas target provides collimation for the deuteron beam by use of four slits, giving an incident beam diameter of about 1/8". The target length is variable from 0 to 10 cm. However, a fixed length of 1.2 cm and a pressure of 15" Hg were used throughout these experiments, corresponding to a 220 kev gas target (43). The foil used to contain the gas is 1/20 mil nickel and the beam stop is a .010" tantalum disc. This is a 180 kev foil for the 1.61 Mev deuteron bombarding energy (44). The gas target is electrically insulated from ground in order to permit accurate integration of the current incident on the foil.

**Liquid Helium Analyzer**

When excited by the slowing down of a charged particle, helium emits ultraviolet radiation. Direct viewing of the ultraviolet scintillation is possible if quartz windows and photomultipliers with the proper spectral response photocathode are used. However, a somewhat simpler experimental procedure is to coat the scintillator cell with a wave-length shifter to convert the ultraviolet to visible light. The first experiments using a liquid helium scintillator were
done by Fleishman (45) and by Thorndike and Shlaer (46). In these experiments, a quaterphenyl coating on the cell walls was used as a wave-length shifter, and the resulting light pulse was viewed through a long lucite light pipe inserted into the dewar. Los Alamos (47) eliminated the lucite light pipe and viewed the scintillation through a quartz window at the bottom of the dewar.

The liquid helium analyzer used in the present experiment, shown in Figure 4, consists of a diphenyl stilbene coated cell inside of a liquid helium dewar. The cell is 1-1/8 inches in diameter by 2-3/4 inches long. The cylinder wall is 20 mil thick brass and the bottom is 20 mil aluminum. To provide a good reflecting base for the wave length shifter, the walls of the cell were coated with white tygon paint which was used in a similar application by Los Alamos. When the surfaces of the cell have been thoroughly cleaned with nitric acid and washed with acetone before application, this paint survives several cycles from room temperature to liquid helium temperature without cracking or blistering.

Diphenyl stilbene was used to shift the ultraviolet helium scintillations to the visible region required for efficient transmission through the lucite light pipe. The walls of the cell were coated with a heavy layer of diphenyl stilbene, about 150mg/cm$^2$. Several coating thicknesses were tried at the end of the light from 0 to 100mg/cm$^2$. It was found that an uncoated light pipe surface
yielded the largest pulses. The diphenyl stilbene was vacuum evaporated onto the surface at a pressure of about $10^{-6}$ mm of Hg. Quaterphenyl was also tried as a wave-length shifter, but the operation of the cell was much better with diphenyl stilbene.

The light pipe used to transmit the scintillations was lucite, one inch in diameter and 33 inches long. Pieces of lucite with a slight bluish tint were selected for best optical transmission. However, even with highly polished sides, the light pipe was only about 20 per cent efficient on bench tests. Its efficiency in the liquid helium dewar was probably slightly lower.

The resolution of the cell is about 34 per cent as measured with a U-233 alpha-source (Figure 6). Actually the resolution applicable to the experiment is somewhat poorer because light pulses originate from everywhere in the cell instead of a single position. The difference in the optical efficiency for pulses in the cell bottom compared to those at the top was measured with an alpha source on a cesium iodide crystal. Pulse heights with the source at the top of the cell were found to be about a factor of two higher than with the source at the bottom. The resolution of the cell to 1.5 Mev recoil pulse from 4.5 Mev neutrons from the D(d, n) reactions is shown in Figure 7. This curve was obtained by requiring a coincidence between the liquid helium scintillation and the final detector at an 80° scattering angle. The angle
subtended by the final detector represents an eight per cent range of energy for the helium recoil. The optics of the cell were improved since this data was taken so that a slightly better resolution is expected. Tests on the new cell are not complete.

The liquid helium cell responds to gammas as well as neutrons. A gamma ray undergoing a compton scatter in the reaction plane will produce a recoil electron with a maximum path of 1.12 inches through the active cell. With this range an electron can give up a maximum of 1 Mev in the cell, which is very close to the 1.5 Mev recoil of the \( \text{N}^{14}(\text{d}, \text{n}) \) neutron scattered at 65°. It is, therefore, not surprising that the He cell is sensitive to gammas.

The large length to diameter ratio of the neck of the dewar keeps liquid helium losses fairly low, about 0.1 liter per hour. One filling of the dewar was sufficient for 20 hours of operation.

**Final Detector**

The neutrons scattered by the liquid helium are detected in a 3 inch long by 2 inch diameter stilbene crystal. The detection efficiency for neutrons incident on this crystal is about 50 per cent. Stilbene was chosen for the final neutron detector because of its high efficiency for decay time discrimination. A plastic scintillator was tried first but the gammas contributed so many
coincidences between the liquid helium and final detector that an accurate separation of the effects by time of flight was not feasible over the flight distance used in the experiments.

Neutron and Gamma Shielding

In order to prevent the direct beam from the target from flooding the final detector it was necessary to provide a neutron and gamma shield. The shield is 2 feet in diameter by 8 inches thick, and is composed of an equal mixture of iron and boronated paraffin. The shield gives a minimum neutron attention factor of about 100 for 6 Mev neutrons and a minimum attenuation of about 20 for 6 Mev gammas.

In addition several concrete block baffles between the accelerator and target provide a large reduction in background from radiation other than that produced in the gas target.

Positioning and Support Mechanism

The position mechanism performs the function of maintaining the distance between gas target and liquid helium analyzer, as well as the distance between analyzer and final detector, constant. At the same time it permits easy setting of the angles $\theta_1$ and $\theta_2$ (Figure 3). The weight of the massive shield for the final detector is supported from the trolley of a simple rotatable boom in order
to relieve major load requirements from the positioning structures (Figure 8). This method of support permits very good positioning accuracy with angular measurements reproducible to about 0.1 degree and radial distances from center of rotation constant to about 10 mils.

Electronics

A block diagram of the electronics is shown in Figure 5. Pulses from the helium scintillator are picked up by an EMI type 9536-B phototube and amplified by a series of Hewlett Packard amplifiers. Since the count rate from the exposed helium cell is much higher than from the shielded stilbene crystal it is desirable to let the helium channel provide the stop pulse to the time to pulse height converter. The count rate limitation on the stop pulse is much less severe than on the start pulses. Because the helium channel pulse occurs first chronologically, it is necessary to delay this signal about 100 nanoseconds to achieve proper time sequencing. The fast pulse for the stilbene detector channel was taken directly from a dynode of the photomultiplier tube base, circuit and fed into the start of the time to pulse height converter, after proper amplification with Hewlett Packard amplifiers. The output of the time to pulse height circuit was put into a 400 channel analyzer in the delayed coincidence mode. The delayed
coincidence input was connected to the amplified output of the pulse shape discriminator. The resolution of the overall system at its best was approximately 4 nanoseconds.

As shown on the block diagram, the operation of each basic component is monitored by a scaler.

Since the irradiation of nitrogen by deuterium produces many more gammas than it does neutrons, it is expected that true coincidences between the liquid helium polarization analyzer and the final detector caused by gamma rays might be a problem. It can be seen in Figure 9, which represents a time of flight spectrum between the liquid helium and the final detector, that the gamma ray coincidences are indeed an order of magnitude greater than the neutron coincidences.

Pulse shape discrimination was applied to the stilbene crystal using the circuit of Daehnick and Sherr (47). The principal of separating electrons from heavier charged particles by pulse shape discrimination was first suggested by F. D. Brooks. Light pulses from a stilbene scintillator have a functional time dependence of

\[ I(t, E) = \alpha(E)e^{-t/6.2} + \beta_e^{-t/370} \]

where t is in nanoseconds. For protons \( (\beta/\gamma)_p = 0.021 \), and for electrons \( (\beta/\gamma)_e = 0.011 \). These ratios are slightly energy dependent. Basically the Daehnick and Sherr circuit separates
the current pulses I(t, E) into fast and slow components. After appropriate pulse shaping, the fast and slow components are combined in such manner as to give approximate pulse cancellation for \( (E/\alpha) = 0.011 \). A signal proportional to the fast component is obtained by differentiation of the anode current pulse of a 14 stage photomultiplier with a short time constant, and subsequently stretching by a peak detector diode. The slow component is taken from the 13th dynode with the signal grounded for the first 100 nanoseconds to eliminate the fast component.

The effectiveness of the gamma discrimination can be seen from Figure 10 which is the same spectrum as shown in Figure 9, but taken with the gamma discriminator supplying a coincidence signal to the multi-channel analyzer.
CHAPTER V

ESTIMATE OF ERRORS AND UNCERTAINTIES

The possible errors in this experiment are listed and, where possible, bounded in this section.

1. Statistical uncertainties: Because of the very low neutron intensities in this experiment, counting statistics were a major limitation to the experimental accuracy.

Since random background can show no time correlation, the background evaluation made use of the time-of-flight spectrum. Counts in those channels not near the neutron peak were averaged to give a background count per channel. This technique has the advantage of giving the random background simultaneously with the true neutron coincidences. Statistical uncertainties in the difference or ratio between two quantities were calculated in the usual way:

\[ \Delta (A-B) = \left[ \Delta A^2 + \Delta B^2 \right]^{1/2} \]

and

\[ \Delta \left( \frac{A}{B} \right) \left( \frac{A}{B} \right) = \left[ \left( \frac{\Delta A}{A} \right)^2 + \left( \frac{\Delta B}{B} \right)^2 \right]^{1/2} \] [47]
2. Uncertainty in the value of $\theta_1$: For the reaction considered, the polarization appears to vary slowly enough with $\theta_1$ that the maximum uncertainty of $1.5^\circ$ introduces an error of less than 1 per cent in the measured polarization.

3. Uncertainty in the value of $\theta_2$: Since the counting rate is extremely sensitive to the value of $\theta_2$, elaborate techniques were used to set this angle. The entire shield and detector were rotated about the geometrical center of the helium scatterer on quality bearings. The angle $\varepsilon_2$ was read from a vernier dial accurate to $0.1^\circ$. The zero position of $\varepsilon_2$ was determined by both optical sighting and by finding the center of symmetry in the angular distribution about $\varepsilon_2$ of neutrons scattered from the helium filled dewar, with $\theta_1$ set at 0. These two calibration methods agreed to within $\pm 0.2$ degrees. Good agreement between the left-right symmetries for $\pm \theta_1$ measured at several points indicate that there should be no large systematic error in $\varepsilon_2$.

4. Asymmetries in the helium container: It was found that asymmetries in the helium dewar could cause variation of about $\pm 0.4$ degrees if the dewar position was changed. However, this effect was essentially eliminated by keeping the dewar in a fixed position and performing the calibrations listed in the preceding paragraph with the dewar in this position.
5. Effects of strong magnetic fields on the photomultiplier: A magnetic shield around the photomultiplier essentially eliminated drifts in gain from this cause. The count rate from a gamma source, for several positions of the detector collimator varied by less than 1 per cent.

6. Neutron flux contamination: There was the possibility of extraneous neutron groups being present. However, neutrons from the next lower excited state are emitted with only about 1 Mev in energy and would have little likelihood of exceeding the bias set on the liquid helium cell. At any rate, no lower energy neutron group was observed in the time of flight spectrum.

The possibility of deuteron or carbon contamination of the foil or end cap of the gas target was also considered. Backgrounds, which were taken with helium replacing nitrogen in the target, show the presence only of a very small peak due to $\text{N}^{14}(d,n)$ neutrons representing only about 15 per cent of the $\text{N}^{14}(d,n)$ neutrons with the target filled (Figure 11). This type of background should not appreciably effect the measured polarization.

7. The finite geometry: The equation giving the polarization in terms of the measured $L/R$ asymmetry is derived on the assumption that the scatterer and detector are infinitesimally small. Thus, the scattering angle is perfectly defined, and the scattering plane is identical with the nuclear reaction plane. In
any real experiment these conditions can only be approximated.

In this experiment, the scatterer is a cylinder 2-1/2 inches long by 1-1/8 inches in diameter, and the detector is 3 inches long by 2 inches in diameter. The separation distance between source and scatterer was 8 inches, and the distance between scatterer and detector was 8.5 inches. The correction for scattering out of the reaction plane causes a constant decrease in $P_2$ of about 1 per cent. Since $P_2$ is not known to better than ±5 per cent, this correction is negligible. It does not affect the asymmetry ratio $L/R$. In addition, any shift in the center of detection of the scatterer in the reaction plane will lead to a false asymmetry (43). Variations of neutron current with angle produce a larger current on one side of the scatterer and detector than the other, causing the effective center to shift. Referring to Figure 3, only a shift of center along the "x" axis will be considered because such a shift can lead to false asymmetries while a shift along the 'y' axis cannot. The probability that a neutron scattered in the liquid helium volume, along the 'x' axis, enter the detector represented by its center detection, $D_0$, is

$$K_{12} \approx \frac{C_1 (1-C_2 \tan^{-1} \frac{C}{R_0})}{R_0^2 + \chi^2}$$

where $C_1 = a$ normalizing constant
\[ C_2 = \text{the fractional change in scattering cross-section per radian; measured at } 65^\circ \text{ to be 2.3} \]

\[ R_0 = \text{distance from center of scatterer to center of detection of detector} \]

It can be seen that \( \frac{\alpha}{R_0} \) is so small that \( \tan^{-1} \frac{\alpha}{R_0} \approx \frac{\alpha}{R_0} \).

Since \( \frac{\alpha}{R_0} \ll 1 \), \( K_{12} \) can be considerably simplified to

\[ K_{12} = \frac{C_1}{R_0^2} (1 - 2 \frac{\alpha}{R_0}) (1 - 2 \frac{\alpha^2}{R_0^2}) \approx \frac{C_1}{R_0^2} (1 - 2 \frac{\alpha^2}{R_0^2}) \]

The quantity \( \frac{\alpha^2}{R_0^2} \ll 2 \frac{\alpha}{R_0} \) and can now be neglected. The total count rate at the detector will be given by

\[ N = \int_{-a}^{a} \phi(\gamma) \frac{a^2 - \gamma^2}{R_0^2} (1 - 2 \frac{\alpha^2}{R_0^2}) d\gamma \]

The function \( \phi(\gamma) \) represents the distribution of neutron current along the x-axis and is approximated by a line with slope equal to

\[ \phi(\gamma) = C_3 (37 - \gamma) \]

where \( \gamma \) is in inches

\[ N_- = C_4 \int_{-a}^{a} (37 - \gamma)(1 - 2 \frac{\alpha^2}{R_0^2}) \frac{a^2 - \gamma^2}{R_0^2} d\gamma \]

When the scatterer is rotated to the diametral position \( (\phi_2 = -65^\circ) \) expression [52] becomes

\[ N_+ = C_4 \int_{-a=0.56}^{a=0.56} (37 - \gamma)(1 + 2 \frac{\alpha^2}{R_0^2}) \frac{a^2 - \gamma^2}{R_0^2} d\gamma \]

The false asymmetry introduced to an unpolarized beam is

\[ \frac{N_-}{N_+} = \frac{37 + 0.0227}{32 - 0.0227} = 1.0027 \]
Thus, the false asymmetry due to the shift in center of detection is negligible as might be expected since the angular distribution does not show extreme peaking, and the diameter of the helium chamber used in the present experiment is small compared to the separation distances. A slight deviation of center of detection is also expected in the final detector. However, this deviation introduces no false asymmetries. It does mean that the true value of $\theta_2$ and $-\theta_1$ are not exactly the $65^\circ$ which was read at the vernier. The shift in center of detection is approximately 0.07 inch, changing the effective values of $\theta_2$ and $-\theta_2$ to $64.5^\circ$. An exact correction for the asymmetry due to finite geometries could have been carried out by a numerical evaluation of the expression

$$L = \frac{L}{R} = \frac{\int \sigma_1 \sigma_2 \sigma^u(\varepsilon) \left[ 1 - P_1 P_2 (\varepsilon) \cos \phi \right] d\tau_1 d\tau_2}{\int \sigma_1 \sigma_2 \sigma^u(\varepsilon) \left[ 1 + P_1 P_2 (\varepsilon) \cos \phi \right] d\tau_1 d\tau_2} \quad [55]$$

where $\tau_1$ and $\tau_2$ are the volumes of the scatterer and detector, and $\phi$ is the angle between $P_1$ and the normal to the scattering plane. Evaluations of the type have been carried out by Monahan and Elwyn (48) for some simple geometries using a high speed computer.

8. Multiple scattering: Since the mean free path for a 6.0 Mev neutron in liquid helium is 29 cm, the effect of multiple scattering in the 1.43 cm radius helium cell is negligible.
However, effects are possible due to scattering events occurring in materials outside the cell. It is therefore necessary to determine how multiple scattering effects the experimental results. It can be readily seen that, to a good approximation, second scatter loss of neutrons which are headed for the detector will have no effect on the asymmetry ratio \( L/R \) because the fraction of neutrons "i" scattered out should be the same for the left and right experiment. Thus: \( \frac{f_L}{f_R} = \frac{L}{R} \). It is, therefore, the neutrons scattered into the detector which are of concern. However, those neutrons scattered into the detector which were not first scattered in the liquid helium scintillator cell are of no importance because they will be eliminated by the time of flight coincidence analyzer. Likewise those neutrons which make a strongly forward angle scatter in the helium cell cannot produce a large enough helium recoil pulse to overcome the helium channel bias, unless the second scatter is also in the cell (about a 0.5 Mev helium recoil is required). Since the helium cross-section strongly favors small angle scattering the latter requirement greatly limits the "in scattering" events. It is estimated that with the above limitation, the relative error due to multiple scattering is approximately \( \frac{\Delta P}{P} \approx 5 \) per cent. To correct for this error it would be necessary to slightly increase the absolute polarization values shown in Figure 12.
9. Collimator effects: The iron-paraffin collimator surrounding the detector was responsible for some neutron "in scattering." The use of paraffin in the collimator, of course, tended to minimize this effect because of the very low albedo of this material to fast neutrons. Actually the only effect of the collimator scattering is to increase the effective solid angle subtended by the detector. Since it has been shown that the finite geometry corrections are negligible for the detector, this is not considered to be an important factor.

10. Uncertainties in the (He$^4$+n) phases: The polarization in the scattering of neutrons by helium is calculated from the phase shifts given by Seagrave (28). The angular distribution of fast neutrons has been studied in the 0.4 to 2.73 Mev range by Adair (49), in the 2 to 3 Mev range by Demanins, et al. (50), under 4.15 Mev by Baldwin, et al. (51), in the 2 to 7 Mev range by Seagrave (28), between 6 and 7 Mev by Marin, et al. (52), and at very high energies by Schwartz (53) and Tannerwald (54). Dodder and Gammel (55) have analyzed existing data on p-He$^4$ scattering to 9.5 Mev and have applied their results to n-He$^4$ scattering. Although discrepancies still exist in phase shifts at very low energies, below 3 Mev, and at very high energies, the major investigators in the energy region applicable to the present experiment are in good agreement. Marin, et al. (52) actually
used the $^14_N(d,n)^15_O$ with deuteron bombarding energies covering the range of the present experiment. Their results were in good agreement with Dodder and Gammel and with Seagrave.

For the 6 Mev neutron energy of interest in the present experiment the following phase shifts were used

$$\delta_{1^-} = +48^\circ \quad \delta_{1^+} = +116^\circ \quad \delta_0 = -60^\circ$$

The polarization for a 65° lab angle was calculated from equation [36] to be -0.79. Baicker (56) has evaluated the change in polarization which might be expected from reasonable errors in the phase shifts. Uncertainty estimates by Dodder and Gammel of -5° in the $s$-phase shifts, and -2° in the $p$-phase shifts were used by Baicker. The net change in polarization due to these phase shift perturbations is $\Delta P_2 \approx 0.04$ to 0.06 in the angular range of interest to the present experiments.

11. Electronic drift: All components on the helium scintillator channel of this experiment were monitored by scalers continuously throughout the experiment. If any deviation over 1 per cent was noted in the count, the experiment was re-run. However, all of these components were very stable. Since the stilbene crystal and collimator were rotated to a position of radically different background during one half of each experiment, it was not possible to monitor the stability in the stilbene channel through the change. However, the gamma background count were
monitored during each half of the experiment and indicated no drifts greater than 1 per cent. Checks were also made several times with the gamma source to insure that the change in position did not effect the photomultiplier gain.

However, the pulse shape discriminator could not be effectively monitored and may have been subject at times to drift. The time of flight spectra for each of the runs were carefully examined to determine if the bias of this circuit had shifted, and allowed some gammas to pass. Two of the tests were discarded because evidence of this type of drift was found.
CHAPTER VI

EXPERIMENTAL RESULTS AND CORRELATIONS

The reaction studied in these experiments was $N^{14}(d, n)O^{15}$. The polarization for the ground state neutrons were measured at an average deuteron energy of 1.32 Mev over the forward angles as shown in Figure 12. The nitrogen target thickness was 220 Kev for this deuteron energy.

Goldfarb (57) has summarized some of the aims of polarization and angular correlation studies in nuclear reactions as (1) to obtain information regarding resonance levels, (2) to determine the spins and parities of the residual nucleus, (3) to evaluate the character of the nuclear coupling, (4) to investigate the nature of direct process interactions, and (5) to measure static moments of excited nuclei.

Compound Nucleus

Austin, et al. (58) analyzed the level structure of $Be^{8}$ using experimental data for polarization to supplement differential cross-section information on the $Li^{7}(p, n)Be^{7}$ reaction. With a spin 1/2 particle on a spin 1/2 nucleus the compound nucleus model was
still manageable enough to permit as many as four level parameters to be readily evaluated by Austin, using the single level approximation for each resonance. In the present experiment with a spin 1 particle on a spin 1 nucleus, the situation is considerably more difficult. In fact, the complexity of the formulae for three or more levels is serious enough not to warrant their practical use.

There have been several measurements pertaining to the excited levels of $^{16}$O. Photodisintegration experiments on $^{16}$O by a number of experimenters (33, 59 through 71) indicate that there are many excited states in $^{16}$O between 20 and 25 Mev. $^{14}$N+d yields an excitation energy of 20.75 Mev in the compound nucleus $^{16}$O. Penfold and Spicer (65) have found ten levels in this region with widths less than 40 Kev. Figure 13 summarizes information obtained from the reactions $^{16}$O($\gamma$,n)$^{15}$O (64, 65), $^{16}$O($\gamma$,p)$^{15}$N (59 through 63), $^{16}$O+$(\gamma,\alpha)$ (64), $^{14}$N(d,$\gamma$)$^{12}$C (67, 69), $^{14}$N(d,n)$^{15}$O (33, 70, 71), and $^{14}$N(d,p)$^{15}$N (33, 71). From the gamma excitation experiments, it is possible to find levels at essentially any energy in the 20 to 25 Mev region. However, the $^{14}$N(d,n)$^{15}$O and $^{14}$N(d,p)$^{15}$N experiments (70, 71) indicate, within the experimental accuracy, only two broad levels at 1.9 and 2.7 Mev. It appears to be plausible to explain this difference in level structure in three ways:
(1) Assuming that the $^{14}\text{N} + (d, n)^{15}\text{O}$ reaction proceeds by compound nucleus formation, isotopic spin selection rules might lead to different levels. Both $^{14}\text{N}$ and the deuteron are $T = 0$ nuclei, so that $^{14}\text{N} + d$ can only form $T = 0$ states. Gamma ray absorption in the 20 Mev excitation region is mainly electric dipole which has an isotopic spin selection rule $\Delta T = \pm 1$. If isotopic spin is a good quantum number in this region, only $T = 1$ states of $^{16}\text{O}$ will be excited. However, Wilkinson (72) states that isotopic spin is not a very good quantum number in this region, the impurity ranging from 10 to 50 per cent in intensity. On the other hand, Brown (73) predicts a pure isotopic spin $T = 1$, level state at an excitation energy of about 22.3 Mev.

(2) It is possible that the difference is that the $^{14}\text{N} + (d, n)^{15}\text{O}$ reaction proceeds primarily by means of a surface reaction, while the photonucleus reaction proceeds mainly by compound nucleus formation. Attempts to fit the angular distribution using the exchange stripping theory of Owen and Madansky (74) have not been very successful. Retz-Schmidt and Weil (75) concluded that a combination of compound nucleus and direct reaction is probably needed.

(3) The resolution for the $^{14}\text{N} + (d, n)^{15}\text{O}$ cross-section experiments was not nearly as good as for the Penfold and Spicer photoneutron experiments. It is, therefore, possible that the very
broad peaks in the $^{14}\text{N}(d,n)O^{15}$ total cross-section represent a composition of a number of closely spaced levels seen in the photonuclear experiments. In particular, the broad 22.6 Mev level in the $^{14}\text{N}(d,n)O^{15}$ reaction appears to coincide with a group of levels between 22.4 and 23 Mev measured by Penfold and Spicer.

The presence of a broad $1^-$ level in $O^{16}$ near the bombarding energies used in the present experiments was predicted by Brown (73) and measured in $(e,p'e')$ (76), $(d,p)$ (77), and $(\gamma,n)$ (78) experiments. Dodge and Barber (76) predicted a $1^-$ and $2^+$ level on the basis of differential cross-sections analyses of the $O^{16}(e,p'e')$ reaction. The measured total cross-section curve for the $^{14}\text{N}(d,n)O^{15}$ reaction shows evidence for resonances at about 1.9 and 2.7 Mev so that a two-level description appears possible. Therefore, an attempt was made to determine whether the observed polarization and the cross-section data could be correlated in terms of a reaction proceeding through the $O^{16}$ compound nucleus in which only 2 levels were important.

The expressions necessary for the calculation of the cross-sections and polarization were obtained from the general formulae given by Lustig (79) and Simon and Welton (29), respectively. Lustig's formulation is a natural extension of that of Blatt and
Biedenharn (30). Several assumptions were introduced to simplify these expressions while retaining a physically reasonable model. It was assumed that:

1. the Wigner-Eisenbud (80) formula, with the one level assumption is applicable. (A complete 2 level formalism considerably complicates the calculation.)

2. incident orbital angular moments greater than \( J = 1 \) can be neglected.

3. the level shift is neglected.

The single level approximation is based on the fact that close level spacings are not expected in light nuclei and that the experimental total cross-section indicates only a slight overlap of the levels. Neglect of orbital angular moments greater than one is justified from the penetrabilities for 1.32 Mev deuterons on \( \text{N}^{14} \).

It is seen in Table I that the penetrability for d-waves is more than an order of magnitude less than for S-waves. A similar assumption cannot be made for the outgoing neutrons. Because of the 5 Mev Q value of the reaction, the barrier penetrability for S wave is within an order of magnitude of the penetrability for f-wave neutrons.

| TABLE I |
|-----------------|-----------------|-----------------|-----------------|
| PENETRABILITIES FOR 3.2 MeV DEUTERONS AND FOR 6 MeV NEUTRONS |
| \( \ell = 0 \) | \( \ell = 1 \) | \( \ell = 2 \) | \( \ell = 3 \) |
| Deuterons | .272 | .084 | .0125 |
| Neutrons | 2.29 | 1.92 | 1.21 | .429 |
The values for the deuteron penetrabilities were taken from the graphs of Sharp, Gove, and Paul (81). Penetrabilities for neutrons were taken from the tables of Monaham, Biedenharn, and Schiffer (82).

In view of previous experimental evidence for a 1\(^-\) and 2\(^+\) level in \(^{16}\)O, the formulae for the differential cross-section and polarization with these two levels, were tried.

\[
\sigma(\theta) = a_0 P_0 + a_1 P_1(\cos\theta) + a_2 P_2(\cos\theta)
\]

\[
a_0 = \frac{\lambda^2}{9} \left[ \frac{[2.31 \delta_1^2(\xi'10) + 1.22 \delta_2^2(\xi'12)] (\delta_1^2(\xi21) + \gamma_1^2(\xi11) + \gamma_1^2(\xi01))}{4(E_\text{F} - E_1)^2 + \Gamma_1^2} 
+ 5.44 \delta_2^2(\xi20) \left[ \frac{1.92 \delta_2^2(\xi11) + 0.429 \delta'_2^2(\xi13)}{4(E_\text{F} - E_2)^2 + \Gamma_2^2} \right] \right]
\]

\[
a_1 = \frac{\lambda^2}{9} \times 2.08 \left[ 7.45 \delta_1(\xi'10), \delta_2(\xi'11) \cos a + 1.05 \delta_1(\xi'12), \delta_2(\xi'11) \cos b 
+ 0.39 \delta_1(\xi'12), \delta_2(\xi'13) \cos c \right] \times \delta_1(\xi21) \delta_2(\xi20) \left[ \frac{4(E_\text{D} - E_1)^2 + \Gamma_1^2}{4(E_\text{D} - E_2)^2 + \Gamma_2^2} \right]^{-1/2}
\]

\[
a_2 = \frac{\lambda^2}{9} \left[ \frac{366 \delta_1^2(\xi'12) + 473 \delta_1(\xi'10), \delta_1(\xi'12) \cos(\gamma(\xi'0') - \gamma(\xi'2))}{\delta_1(\xi21) - (61 \delta_1^2(\xi'12) + 2.37 \delta_1(\xi'10), \delta_1(\xi'12) \cos(\gamma(\xi'0') - \gamma(\xi'2)))} 
\times \delta_1^2(\xi11) - (2.22 \delta_1^2(\xi12) + 4.75 \delta_1(\xi10), \delta_1(\xi12) \cos(\gamma(\xi0') - \gamma(\xi2'))) \right] \times \delta_1^2(\xi01) \times \left[ \frac{4(E_\text{D} - E_1)^2 + \Gamma_1^2}{4(E_\text{D} - E_2)^2 + \Gamma_2^2} \right]^{-1}
\]

and

\[
P_n(\theta) = \left( \frac{i_1 + 1}{i_1} \right)^{1/2} \frac{dP_n(\theta)}{\sigma(\theta)} = (b_1 P_1'(\theta) + b_2 P_2'(\theta)) 1/\sigma(\theta)
\]
The partial widths are related to the reduced widths by the equation:

$$
\Gamma_{\alpha s}^{k} = 2 \pi P_{\alpha \ell} \chi_{k}^{2}(\alpha, s, \ell)
$$

where the penetrability $P_{\alpha \ell}$ is defined by

$$
P_{\alpha \ell} = \frac{k_{\alpha \ell}}{F_{\ell}^{2} + G_{\ell}^{2}}
$$

The primes refer to the exit channels and the unprimed $\alpha$'s refer to entrance channels. The symbols $\Gamma_{1}$ and $\Gamma_{2}$ refer to the total width for the $1^{-}$ and $2^{+}$ states respectively while $E_{1}$ and $E_{2}$ refer to the effective resonance energy of these states. The coulomb phase shifts were taken from the table in reference 81.
with $k_\omega$, the wave number of the relative motion in channel $\omega$ and "a" is the channel radius of the nucleus. The hard sphere phase shifts $\eta(\omega l)$ were calculated from the relationship

$$\tan \eta(\omega l) = \frac{j_l(ka)}{n_l(ka)}$$

where $j_l$ and $n_l$ are spherical bessel functions of the first and second kind.

Retz-Schmidt and Weil's (75) experimental differential cross-sections for the $N^{14}(d, n)O^{15}$ reaction in the energy range of interest could be expressed adequately in terms of the first three Legendre polynomials shown in Table II. The presence of the $P_1$ terms in the cross sections require that at least one interference term between levels of different parity be present. With the present assumption that penetrability limits the incident channels to $s$ and $p$-waves, the large $P_2$ contribution must come from the negative parity state. The positive parity state is restricted to $s$-wave and is restricted to $L=2L=0$.

**TABLE II**

**LEGENDRE EXPANSION OF CROSS SECTIONS**

<table>
<thead>
<tr>
<th>E Mev</th>
<th>$a_0$</th>
<th>$a_1$</th>
<th>$a_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>.911</td>
<td>0.50</td>
<td>.06</td>
<td>0.16</td>
</tr>
<tr>
<td>1.17</td>
<td>.84</td>
<td>.28</td>
<td>.54</td>
</tr>
<tr>
<td>(Interpolated)1.32</td>
<td>1.02</td>
<td>.46</td>
<td>.70</td>
</tr>
<tr>
<td>1.51</td>
<td>1.24</td>
<td>.68</td>
<td>.90</td>
</tr>
</tbody>
</table>
Since the effective deuteron energy was 1.32 Mev for this experiment, the prime interest is in obtaining parameters for this energy.

It is difficult to obtain enough $P_2$ contribution in $\sigma(\theta)$ with the present level choice. The maximum value for the ratio $\frac{a_2}{a_0}$ depends only on the ratio of $\chi_1(1^0)/\chi_1(1^{12})$. Since the $2^+$ level must give a positive $P_0$ contribution and can have no $P_2$ component, any $2^+$ level which must later be added decreases the $\frac{a_2}{a_0}$ ratio.

Table III gives the ratio $\frac{a_2}{a_0}$ for a range of $\chi_1(1^0)/\chi_1(1^{12})$ ratios with $\chi_2(2^0)$ assumed zero. Each channel spin, 2, 1, and 0 is considered separately. Obviously, from Table II, the ratio $\chi_1(1^0)/\chi_1(1^{12})$ must be in the range of 0 to +1, if a sufficient $P_2$ contribution is to be possible when the $2^+$ level is included.
### TABLE III

\[ \frac{a_2}{a_0} \]

VARIATION OF COMPOUND NUCLEUS PARAMETERS

<table>
<thead>
<tr>
<th>( \frac{J'(\alpha'10)}{J'(\alpha'12)} )</th>
<th>S = 0</th>
<th>S = 1</th>
<th>S = 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>+2</td>
<td>.479</td>
<td>- .241</td>
<td>.072</td>
</tr>
<tr>
<td>-2</td>
<td>- .246</td>
<td>.123</td>
<td>0</td>
</tr>
<tr>
<td>+1.5</td>
<td>.635</td>
<td>- .317</td>
<td>.102</td>
</tr>
<tr>
<td>-1.5</td>
<td>- .254</td>
<td>.126</td>
<td>.013</td>
</tr>
<tr>
<td>+1</td>
<td>.882</td>
<td>- .443</td>
<td>.16</td>
</tr>
<tr>
<td>-1</td>
<td>- .0905</td>
<td>.097</td>
<td>.051</td>
</tr>
<tr>
<td>+ .5</td>
<td>1.21</td>
<td>- .60</td>
<td>.264</td>
</tr>
<tr>
<td>- .5</td>
<td>.15</td>
<td>- .078</td>
<td>.153</td>
</tr>
<tr>
<td>+ .3</td>
<td>1.25</td>
<td>- .61</td>
<td>.293</td>
</tr>
<tr>
<td>- .3</td>
<td>.455</td>
<td>- .22</td>
<td>.21</td>
</tr>
<tr>
<td>+ .1</td>
<td>1.14</td>
<td>- .574</td>
<td>.317</td>
</tr>
<tr>
<td>- .1</td>
<td>.84</td>
<td>- .415</td>
<td>.285</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>- .505</td>
<td>.303</td>
</tr>
</tbody>
</table>
The $P_2^1$ component of the differential polarization is dependent only on the 1$^-$ level for the 2 level scheme being considered.

The experimental data is consistent with polarization resulting primarily from a $P_2^1$ component with $b_2^1$ of approximately 0.07. A small contribution from $P_1$ terms is also possible. Table IV shows a set of parameters which best fit the experimental cross-section and polarization data available.

**TABLE IV
BEST COMPOUND NUCLEUS PARAMETERS**

<table>
<thead>
<tr>
<th>$\gamma_1(\alpha'10)$</th>
<th>$\gamma_1(\alpha'01)$</th>
<th>$\gamma_2(\alpha'11)$</th>
<th>$\gamma_2(\alpha'12)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_1(\alpha'10)$</td>
<td>$\delta_1(\alpha'12)$</td>
<td>$\delta_1(\alpha'12)$</td>
<td>$\delta_1(\alpha'12)$</td>
</tr>
<tr>
<td>$\gamma_1(\alpha11)$</td>
<td>$\gamma_2(\alpha'13)$</td>
<td>$\gamma_2(\alpha'13)$</td>
<td>$\gamma_2(\alpha'20)$</td>
</tr>
<tr>
<td>$\gamma_1(\alpha11)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma_2(\alpha'13)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma_2(\alpha'20)$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\Gamma_1 = 1$ Mev  \hspace{1cm} $\Gamma_2 = 1$ Mev

$E_1 = 1.9$ Mev  \hspace{1cm} $E_2 = 2.7$ Mev

Deuteron channel $a_D = 4.3 \, f$  \hspace{1cm} Neutron channel radius $a_n = 4.8 \, f$

Normalizing the free reduced widths so that $a_o$ agrees with the 1.32 Mev data yields

1.32 Mev (calculated) $\sigma_{(\theta)} = 1.02 \, P_0^+ + 42 \, P_1^+ + 65 \, P_2$

(measured) $\sigma_{(\theta)} = 1.02 \, P_0^+ + 46 \, P_1^+ + 70 \, P_2$

Calculated $P(\theta) = -.07 \, P_1^1 + 1.4 \, P_2^1$
A comparison of the calculated polarization with the measured polarization is shown in figure 12.

At .91 Mev

Calculated $\sigma(\theta) = .22 P_0 + .07 P_1 + .11 P_2$

Measured $\sigma(\theta) = .50 P_0 + .06 P_1 + .16 P_2$

At 1.51 Mev

Calculated $\sigma(\theta) = 1.78 P_0 + .71 P_1 + .2 P_2$

Measured $\sigma(\theta) = 1.24 P_0 + .68 P_1 + .90 P_2$

The general comparison of calculated and experimental results (Figure 14) with varying energy indicate that the penetrability of the deuteron wave is too highly energy dependent for the chosen channel radius to permit a correlation for any level choice. However, this problem can be partially circumvented by allowing the channel radius to change with energy. Austin (58) partially justifies this procedure by noting that far-away levels can add to the apparent hard sphere phase shift through the R-matrix.

Changes in channel radius of a factor of 3 were needed to explain some of Austin's Li$^7$(p, n)Be$^7$ data. By treating the hard sphere phase shift as somewhat arbitrary constants, it would be possible to obtain a much better fit to the present data. Some correction for the energy spread due to the finite target thickness should be applied. The angular distribution experiments (75) used thicknesses which varied from 20 to 120 Kev so that no single correction
is applicable. However, even the 120 Kev target is thin enough that finite thickness corrections will change the results by no more than 10 per cent. It might also be mentioned that a series of low-lying resonances observed in the range of 21 Mev in the O^{16} compound nucleus by Penfold and Spicer could explain some of the discrepancy at 0.91 Mev.

Brown's (73) model for the excited O^{16} nucleus actually predicted a 1^- resonance at about 1.5 Mev bombarding energy with an isotopic spin of 1. Such a state could not be reached with a deuteron (T = 0) on N^{14}(T = 0). However, the present experimental evidence does indicate the presence either of 1^- level, or a 3 level scheme with 2 levels of odd parity. No single odd parity level, other than the 1^- level can lead to the P_2^1 term observed in the polarization measurements, assuming \ell = 1 and \ell^\prime = 3. If a three level scheme is considered, the 2^- level appears to be a likely contributor because it can lead to a sizeable addition to the P_2(0) term in \sigma(0). The level assignment of the positive parity state is not really established from the present calculation. The experimental data can be explained, with the same energy limitation, by assuming a 0^+ level instead of the 2^+ level used here. On this assumption channel spin 0 states give rise to the interference, and channel spin 2 states need not be used. This may be physically more reasonable than the present assumption which
includes channel spin 0 and 2 reduced widths but no channel spin 1. If the spin orbit coupling favors channel spin zero, it does not appear likely that it can also permit 2 but not 1.

Direct Interaction

The possibility that the $N^{14}(d,n_0)O^{15}$ reaction may proceed at least partially by a stripping process cannot be overlooked. For this reason distorted wave Born approximation calculations were run on the Sally code at Oak Ridge. The optical model parameters for the deuteron wave were obtained from recent results of Seiler, et al. (83) on elastic scattering of deuterons by $N^{14}$ in the energy range from 700 Kev to 2.3 Mev. The neutron optical model parameters were taken from the Los Alamos tabulations (84). The input data used for the calculations is listed in Table V.
TABLE V

SALLY INPUT FOR 1.32 Mev CASE

<table>
<thead>
<tr>
<th>Entrance Channel</th>
<th>Exit Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_D = 1.32$ Mev</td>
<td>$Q = 5.027$ Mev</td>
</tr>
<tr>
<td>$V = 21.3$ Mev</td>
<td>$V = 43$ Mev</td>
</tr>
<tr>
<td>$W = 4.83$ Mev</td>
<td>$W = 6.45$</td>
</tr>
<tr>
<td>$r_o = 1.9f$</td>
<td>$r_o = 1.4$</td>
</tr>
<tr>
<td>$r_c = 1.9f$</td>
<td>$r_c = 1.4$</td>
</tr>
<tr>
<td>$a = .827$</td>
<td>$a = .35$</td>
</tr>
</tbody>
</table>

Woods-Saxon potentials were used.

\[
\begin{align*}
\text{Re}U(r) &= -\frac{V}{e^{\chi}+1} \\
\chi &= \frac{r-R}{a} \\
R &= r_o(m_i)^{1/3} \\
\text{Im}U(r) &= -\frac{W}{e^{\chi}+1}
\end{align*}
\]
Calculations of neutron angular distributions and polarizations were made at three energies, 1.32 Mev, 1.7 Mev, and 2.1 Mev (figures 15 and 16). The total reaction cross-section predicted by these calculations was an order of magnitude too high at 1.32 Mev. The calculated polarization at the forward angles was very small, a maximum of 2 per cent, and positive in sign. The sign and general shape of the forward angle polarization were in approximate agreement with the experiment, but the magnitude was too small. It is interesting to note that the predominant sign of the polarization predicts greater distortion for the neutron wave than for the deuteron (if the process is assumed to be stripping). This is contrary to other evidence which indicates that almost invariably, the deuteron wave is more distorted in a stripping reaction (27), which tends to show that this reaction is not a stripping process.
CHAPTER VII

CONCLUSIONS

The reaction studied in this investigation has been found to yield partially polarized neutrons at a deuteron bombarding energy of 1.32 Mev. It appears that the reaction may be useful as a source of energetic polarized neutrons but that an investigation over a broader range of energies and angles is required. Both compound nucleus and direct interaction theory predict high polarizations at some angles and energies.

The complexity of the reaction with its large number of compound nucleus parameters makes a positive identification of level structure on the basis of the present experimental data difficult. However, it appears that the reaction can be explained by the compound nucleus model at the energies considered here. The direct interaction model does not appear to explain the experiments, although a systematic variation of input parameters might help the situation. It would be interesting to examine the reaction for comparisons at higher deuteron energies where the stripping process is more likely to be predominant.
Several comments can be made regarding the experimental technique used in this investigation. The use of the liquid helium scintillation appears to offer several advantages, in the reduction of both background and multiple scattering, over other time-of-flight techniques. Combined with the gamma discriminator circuit, the system is capable of very accurate polarization measurements over a wide range of reaction.
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FIGURE 1. SOURCES OF POLARIZED NEUTRONS

FIGURE 2. DEUTERON STRIPPING POLARIZATION
FIGURE 3. POLARIZATION EXPERIMENT
Stainless steel tubing (0.010-inch wall thickness Teflon gasket)

Liquid-nitrogen reservoir

Outer vacuum wall

Liquid-helium chamber

Thin-walled section

FIGURE 4. DEWAR WITH CELL
FIGURE 5. ELECTRONICS
FIGURE 6. U$^{233}$ SOURCE IN LIQUID-HELIUM CELL
FIGURE 7. 4.3 MEV D(d,n) NEUTRONS RECOILING 80 DEG IN HELIUM CELL
FIGURE 8. EXPERIMENTAL APPARATUS
FIGURE 9. TIME-OF-FLIGHT SPECTRUM WITHOUT DECAY TIME DISCRIMINATION OF THE NEUTRONS FROM THE REACTION N^{14}(d,n)
FIGURE 10. TIME-OF-FLIGHT SPECTRUM WITH DECAY TIME DISCRIMINATION OF THE NEUTRONS FROM THE REACTION $^14_N(d,n)$
FIGURE 11. BACKGROUND WITH HELIUM GAS IN TARGET
FIGURE 12. EXPERIMENTAL AND CALCULATED POLARIZATION OF THE NEUTRONS FROM THE REACTION $^{14}_{\text{N}}(d,n)^{15}_{\text{O}}$
FIGURE 13. EXCITATION LEVELS IN O\textsuperscript{16}
FIGURE 14. COMPARISON OF COMPOUND NUCLEUS CALCULATIONS WITH MEASURED CROSS SECTIONS
FIGURE 15. DIRECT INTERACTION CALCULATION OF CROSS SECTION
FIGURE 16. DIRECT INTERACTION CALCULATIONS OF POLARIZATION
AUTOBIOGRAPHY

I, Harold Morton Epstein, was born in Denver, Colorado, December 1, 1928. I received my secondary-school education in the public schools of Denver, Colorado, and my undergraduate training at the University of Colorado, which granted me the Bachelor of Science degree, with honors, in 1950. In 1954, I began my studies at The Ohio State University where I specialized in the Department of Physics and Astronomy.