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DETECTION OF THE AZIMUTHAL POLARIZATION OF THE NEUTRON-PROTON INTERACTION IN THE 150 MEV ENERGY REGION

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DETECTION OF THE AZIMUTHAL POLARIZATION OF THE NEUTRON-PROTON INTERACTION IN THE 150 MEV ENERGY REGION

Louis Wouters
(Thesis)
September 18, 1951
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DETECTION OF THE AZIMUTHAL POLARIZATION OF THE NEUTRON-PROTON INTERACTION IN THE 150 MEV ENERGY REGION

Louis Wouters

I. INTRODUCTION

I.1 Among the many experiments carried out at low energies to measure the interaction between the fundamental particles, neutrons and protons, have been those which measure the spin dependence. In the low energy range, this spin dependence manifests itself as the variation in relative singlet and triplet cross-sections as a function of the interaction energy, in the range 10 ev (Singlet >> Triplet) to 10 Mev (Triplet >> Singlet). ¹

The detailed nature of the interaction is reflected in the differential scattering cross-section only at much higher relative energies, such that the de Broglie wavelength becomes small compared to the range of nuclear forces, (100 to 300 Mev).² If the interaction is interpreted in the usual way, as a potential energy function in the Schroedinger equation, there should be included, in addition to the ordinary "central force" potential term, certain terms descriptive of non-central potentials.³

Of more consequence, is the principal experimental information which is interpreted using a complicated potential: the quadrupole moment of the deuteron and the shape of the differential n-p scattering cross-section at high energies (for which the inclusion of a tensor interaction yields a better fit). In addition, the high energy scattering data has indicated the charge exchange nature of the representative potential, which is now usually chosen symmetric, i.e: "half ordinary, half exchange". Christian
and Hart\textsuperscript{4} have used the numbers descriptive of these phenomena to evaluate the relative magnitude of the central, tensor and spin-spin components:

\[ V = \left[ a + (1-a)P_{12} \right] \left\{ \alpha \frac{e^{-kr}}{r} + \beta f(r) \left[ \frac{(\sigma_1 \cdot r)(\sigma_2 \cdot r)}{r^2} - \frac{T_1 \cdot T_2}{3} \right] + \gamma g(r) \sigma_1 \cdot \sigma_2 \right\} \]

That the solution of the corresponding Schrödinger equation must be spin dependent is evident from the form of this potential; if an experiment were performed in which the scattering target consisted of completely aligned protons, and the incident neutron flux consisted of correspondingly aligned neutrons, an azimuthal variation in the shape of the angular distribution of scattered flux would be observed.\textsuperscript{5} These spin-dependent effects become similarly observable in a double scattering experiment using an initially unpolarized particle beam and unpolarized targets. A small part of the flux scattered and partly polarized by the first n-p interaction is used as the incident flux in the second n-p interaction; the azimuthal dependence of the second-scattered flux is measured at various given scattering angles, by means of an azimuthal array of particle detectors.

1.2 It is useful to point out the experimental analogy of the latter arrangement with the demonstration of polarization of visible light by double reflection. The first scatterer acts as polarizer, and the second, as analyzer. The experiment is thus conveniently described as an "n-p polarization" experiment.

1.3 An approximate prediction of the results of such an experiment can be conveniently developed from an equivalent interpretation of the high-
energy differential scattering data. Christian and Hart have also calculated the proper coefficients in a partial wave expansion in the various orders of angular momentum. Swanson has used these (together with a properly modified Born approximation solution of the potential problem for the higher order terms) to calculate the "polarization amplitude" $P(\theta)$, presented in Fig. 1.

This is a statistical measure of the fraction of nucleons having a preferred spin orientation; see also next section. It may be shown by statistical arguments that the azimuthal asymmetry appearing in the second-scattered flux can be expressed by:

$$\frac{I(\theta_1, \theta_2, \phi)}{I(\theta_1, \theta_2, \phi + \pi)} = \frac{1 + P(\theta_1) P(\theta_2) \cos \phi}{1 - P(\theta_1) P(\theta_2) \cos \phi}$$

which is the ratio of the flux intensities measured by two detectors separated azimuthally by $180^\circ$, but adjusted to the same subtended second-scattering angle ($\theta_2$). In particular, the maximum "right-to-left" ratio is

$$\frac{I(\theta_1, \theta_2, 0)}{I(\theta_1, \theta_2, \pi)} = \frac{1 + P(\theta_1) P(\theta_2)}{1 - P(\theta_1) P(\theta_2)}$$

where:

- $\theta_1$ = first scattering angle
- $\theta_2$ = second scattering angle
- $\phi$ = azimuthal angle at second scattering with respect to plane of first scattering. The significance of these angles becomes more apparent in Fig. 2, which schematically illustrates the double scattering experiment.

It is seen from Fig. 1 that there is an optimum scattering angle for which the polarization effect is expected to be most pronounced; in the indicated region of interest, this is not critically dependent on energy.
OPERATING POINTS AT MAXIMUM POLARIZATION (SEE TABLE II)

P(θ) predicted theoretically (Swanson) from Christian-Hart Tensor Force Model.
Figure 2
Angular orientations and equivalent experiments

$\theta_1$ = first scattering angle
$\theta_2$ = second scattering angle
$\phi$ = azimuthal angle (between scattering planes)
$\phi = 0$ on right hand side facing oncoming particles
The curve shown, is calculated for an exchange symmetric potential, in which case, it is axiomatic that there be zero polarization at 90° in the center of mass system.

This experiment should thus yield direct confirmation of the existence of short-range, non-central nuclear forces; its performance and the results are here described.

I.4. Suppose we have N unpolarized particles scattered such that

\[ \frac{1}{2^N} \left( \frac{\Omega_1}{\Omega_2} \right) \]  

enter into each element of solid angle \( \Omega_1 \), located at opposite azimuths ("Right" and "Left") but equal scattering angles. Since there are just two possible spin orientations, \( \frac{1}{2}N \) will initially occupy each orientation. Suppose now that a spin dependent effect measured by the polarization amplitude \( P_1 \) operates so that on the right side of the scattering \( \frac{N}{4} \left( \frac{\Omega_1}{\Omega_2} \right) \) scatter with spin up. Then by symmetry arguments we can summarize:

\[
\begin{align*}
\frac{N}{4} \left( \frac{\Omega_1}{\Omega_2} \right) & \begin{cases} 
(1+P_1) & \text{spin up, to right} \\
(1-P_1) & \text{spin up, to left} \\
(1+P_1) & \text{spin down, to left} \\
(1-P_1) & \text{spin down, to right} 
\end{cases}
\end{align*}
\]

All are accounted for.

Now suppose this process is repeated once more with just the ones scattered to the right; then on the right hand side of this second scattering:

\[
\begin{align*}
\frac{N}{4} \left( \frac{\Omega_1}{\Omega_2} \right) & \left( \frac{\Omega_1}{\Omega_2} \right) (1+P_1)(1+P_2) \quad \text{appear with spin up} \\
\frac{N}{4} \left( \frac{\Omega_1}{\Omega_2} \right) & \left( \frac{\Omega_1}{\Omega_2} \right) (1-P_1)(1-P_2) \quad \text{appear with spin down}
\end{align*}
\]
On the left hand side:

\[ \frac{N(\delta \Omega_1)}{N_1(\delta \Omega_1)} \frac{(\delta \Omega_2)}{\Omega_2} (1+P_1)(1-P_2) \]  
appear with spin up

\[ \frac{N(\delta \Omega_1)}{N_1(\delta \Omega_1)} \frac{(\delta \Omega_2)}{\Omega_2} (1-P_1)(1+P_2) \]  
appear with spin down

Then the right/left ratio is:

\[ \frac{R}{L} = \frac{(1+P_1)(1+P_2)+(1-P_1)(1-P_2)}{(1+P_1)(1-P_2)+(1-P_1)(1+P_2)} = \frac{1+P_1P_2}{1-P_1P_2} \]

More extensive statistical considerations show that for an intermediate relative azimuthal angle (\( \phi \)) between the scattering planes, the intensity ratio is given (almost self-evidently) by:

\[ \frac{R}{L} = \frac{1 + P(\theta_1) P(\theta_2) \cos \phi}{1 - P(\theta_1) P(\theta_2) \cos \phi} \]
II. PRINCIPLES OF THE EXPERIMENT

II.1 The double scattering experiment has been described above as occurring ideally between the fundamental particles; it should be pointed out that both events may be either "n-p" or "p-n" interactions. The four ways in which the ideal experiment can then be carried out in the laboratory system, are illustrated in Fig. 2a-d. By considering the respective interactions in the center of mass system, it can be seen that the polarization amplitude dependence for p-n is obtained simply by inversion of the curve for n-p (Fig. 1). Thus the meaning of the "right-to-left ratio" is merely reversed in certain cases depending on the number of permutations from the n-n-n experiment (Fig. 2c) for which the predictions are calculated. This multiplicity of equivalent experiments makes for leeway in arranging the practical test.

Experimentally, such idealized situations must be approximated; in particular, it is not possible to realize a dense, fixed "neutron target". Either, one must use neutrons bound in nuclei, or else one must employ the method of Fig. 2d. In practice, proton targets usually consist of hydrogenous slabs or spheres. (At high energies, the background arising from the non-hydrogeneous component must be removed by a "subtraction" experiment.) A deuterium compound is useful as a "neutron target" provided that the experiment is arranged to measure only the consequences of an elastic collision of the impinging proton with the weakly-bound neutron (such as, again, by a subtraction experiment). Watson and Swanson\textsuperscript{7} have calculated that the interaction between, say a proton and a deuteron is indeed grossly describable by a combination of the n-p interaction and the p-p interaction at energies very high compared to the binding energy.
II.2: By a simple calculation, it is readily seen that the particle flux attenuation in a double scattering experiment is quite large ($10^6$ or more). It is thus imperative to use the highest possible beam fluxes, as well as the largest permissible detector apertures. Because it is theoretically predicted that the azimuthal effects should vary only slowly with the various angles, particle detectors of relatively large aperture are used, as compared to those employed in the more orthodox scattering experiments.

Initially, the experiment was arranged such that the second scatterer subtended a large solid angle with respect to the first. However, preliminary measurements showed that the overwhelming background of once-scattered particles entering the detectors directly could not be conveniently eliminated, at flux densities yielding a reasonable twice-scattered intensity. An order of magnitude argument shows that this is a consequence of the pulsed nature of the accelerator flux:

Individual rf pulses per second at 60 f.m. p.p.s.  
80 microseconds, 16 mc.: ........................................ 7000

This thus measures the available counting intervals in the counters, which have a resolving time of the order of the individual rf beam pulse length.

Attenuation per scattering (at $30^\circ$): ........................................ $\sim 10^4$

Minimum acceptable true (second-scattered)

counting rate: ........................................ 0.1 count/sec.

First scattered flux into second scatterer and into the individual
counters of each telescope (Section III): ........................................ 1000 c.p.s.

Accidental coincidence rate: ........................................ 300 c.p.s.

This is computed using the usual "open-window" formula applied to the number of discrete available intervals, i.e. 7000.
Thus we see that an appreciable number of the available counting intervals are occupied by pulses from the first scatterer (calculated on the basis of the elastic scattering alone). Consequently the accidental coincidence rate is prohibitively high.

It should be pointed out that, because of the transition effect, nothing is gained by inserting small shields between the scatterer and counters, unless these are well separated so that really thick shields can be used.

In that initial experiment, the 280 Mev neutron beam generated by proton bombardment of a beryllium target in the 184-inch cyclotron was employed as the primary flux in the arrangement of the form of Fig. 2d.

II.3 The scheme finally adopted, which insures completely adequate protection for the detectors from the once-scattered flux, is one in which the entire primary particle flux generated by the accelerator is intercepted by a deuteride target inside the accelerator shielding. A properly directed aperture in that shielding then permits a well-collimated, once-scattered beam to emerge and impinge on the second target located externally. In such an arrangement, the drastic reduction in solid angle subtended by the second scatterer, is more than compensated by the enormous increase in flux impinging on the first scatterer, so that this arrangement leads to a more satisfactory data collection rate.

Thus, using the internal circulating proton beam of the 184-inch cyclotron as the primary flux, the neutrons scattered from a lithium deuteride target become the secondary flux, inasmuch as the cyclotron field magnetically separates the scattered protons. The scheme thus corresponds to that of Fig. 2b; it also resembles the usual n-p scattering experiment, except for the azimuthal detector array, and excepting the important difference that the
first scattering (neutron generation) is performed at an angle theoretically predicted as optimum for exhibiting the polarization. Of course, a difference experiment using lithium hydride is desirable to remove the unwanted bound neutron contribution. The effect of the second (external) scattering is measured using the orthodox paraffin-carbon scatterer difference method. The scattered protons are detected in this experiment (rather than the neutrons), because of the simplicity and high efficiency for detecting those particles using scintillation counter telescopes in which energy discrimination is easily obtained by range selection. While this general scheme may be adaptable to any accelerator, it has clearly evolved to fit the geometrical and electrical properties peculiar to the 184-inch cyclotron.

II.4 By what practical, experimentally measured numbers can the polarization effect be recognized? If a determination is made of the distribution of doubly-scattered flux at the optimum angles, the effect should reveal itself at once as an azimuthal asymmetry. Such a measurement constitutes an essentially static measurement, dependent on the accurate control of many factors, geometrical and physical; there are many possible causes of apparent asymmetries in the measured flux. (see also Section VI, Appendix A) It is much more satisfactory to measure such an effect by a dynamic method, so that the polarization manifests itself as a change in the apparent relative intensities detected by the azimuthal counter array. This can be accomplished very simply by measuring the effect of changing either scattering angle ($\theta_1$ or $\theta_2$). It will be seen that, for a number of geometrical reasons, it is desirable to vary the first scattering angle $\theta_1$, rather than the second, $\theta_2$. This has also the outstanding advantage of permitting a normalization of the system by means of a zero scattering angle measurement at which clearly no polarization is to be expected.
III. DETAILS OF THE APPARATUS

The relative orientation and general arrangement are illustrated in Fig. 3.

III.1 First Scatterer: The first scatterer is mounted inside the cyclotron vacuum tank at the end of an adjustable probe which slides in and out (through a vacuum seal), along a line parallel to, and underneath the axis of the so-called "half-energy" port in the concrete cyclotron shield. It is seen from Fig. 3 that a target so mounted in the median plane of the cyclotron intercepts the circulating beam such that the neutrons scattered towards the "half-energy" port are scattered at angles ranging from about 0° when the target is pushed in against the "dummy" dee, to 45° when pulled out to the outermost beam trajectory.

Table I shows that the energy of the elastically scattered neutrons emerging through that hole, is almost constant over the whole angular range, because of the almost exact compensation of the change in beam energy as a function of radius, by the opposing change in energy dependence with scattering angle. This arrangement greatly simplifies the performance of the experiment, as well as the interpretation of the measurements of the second (external) scattering.

It will be noticed from geometrical considerations that the beam radius intercepted at each angle is inversely related as \( \cos \theta_1 \), so that the corresponding energy is related inversely as \( \cos^2 \theta_1 \). This exactly cancels the \( \cos^2 \theta_1 \) dependence of the energy of the scattered particle, so that the emergent beam energy is independent of scattering angle except for small order effects introduced by radial variation of the magnetic field and by relativistic terms.
61 FT.
INCLUDING 23 FT. PASSAGE
THRU CONCRETE SHIELDING

OPERATIONAL POSITIONS OF
FIRST SCATTERER PROBE (A)
(Li,D,U,H)

HALF-ENERGY PORT
AND PROBE
ALSO ONE-SCATTERED
BEAM

5" 60° 60° RADIUS
CIRCLING HOPP-R

OUTER WALL OF
CONCRETE SHIELDING

MONITOR SCATTERER AND
TELESCOPE

SECOND SCATTERER
(B) (PARAFFIN,
CARBON)

3 FT. COPPER
BEAM COLLIMATOR

AZIMUTHAL TELESCOPES
AND MOUNTING FRAME

DC. BEAM MONITOR

FIGURE 3 - SCHEMATIC LAYOUT OF n-p
POLARIZATION EXPERIMENT
(SCALE NOT UNIFORM)

MU2564
<table>
<thead>
<tr>
<th>Scatter Angle $\theta_1$</th>
<th>Radius</th>
<th>Proton Energy (MeV)</th>
<th>Elastic Scatter Energy (MeV)</th>
<th>Average Scatter Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>45°</td>
<td>78-1/2&quot;</td>
<td>340</td>
<td>162</td>
<td>145</td>
</tr>
<tr>
<td>30°</td>
<td>64&quot;</td>
<td>340</td>
<td>171</td>
<td>152</td>
</tr>
<tr>
<td>20°</td>
<td>59</td>
<td>205</td>
<td>177</td>
<td>157</td>
</tr>
<tr>
<td>0° (1-1/2° actual)</td>
<td>55-1/2&quot;</td>
<td>180</td>
<td>180</td>
<td>160</td>
</tr>
</tbody>
</table>
The LiH and LiD targets used in the experiment were procured from the Chemistry Department of the University of California; Mr. Raleigh McKisson was responsible for carrying through the hydrogenation and the difficult vacuum casting processes, which resulted in fairly solid rectangular blocks of these compounds of dimensions 3 in. x 1 in x 1/2 in. In the experiment, these are clamped by one end at a skew angle, to ensure that only the target material is bombarded, that the bombarding protons make approximately the same number of multiple traversals, and that the material in the scattering path is approximately of constant thickness over the entire range of probe positions.

The choice of the lithium compounds is indicated by the need for a compound having as small a number of "extraneous" neutrons as possible, and by the requirement of a high melting point. The target power dissipation at maximum beam current is of the order of hundreds of watts; while the targets did not melt, there has been marked sputtering as the experiments progressed, so that the LiD target has gradually reduced in size to about one-third its original length. No correlated changes in experimental results could be observed.

III.2 Collimating system: The emergent scattered neutron beam passes through a round glass window of uniform thickness and is thence collimated by a passage through the cyclotron's concrete shielding. A smaller (2" x 2") rectangular copper collimator, three feet long, further defines this beam at the outer end of this hole. This protects the azimuthal counter telescope array from direct bombardment.

Because the target position is also movable in a plane normal to the emergent path, its alignment has been thoroughly checked during each data
collection "run", by means of photographic film fitted with fluorescent neutron intensifiers. In all cases it is found that visual alignment of the internal target by observation through the collimation system and through the round glass port is completely adequate. Accurate visual alignment is simplified by "shadowing" the target against the main cyclotron target, previously adjusted to its well-established position when in line with the collimating system.

III.3 Second Scatterer: The second scatterer is mounted integrally with the frame holding the azimuthal counter array. This frame consists of two semi-circular crossed tracks, oriented so as to permit mounting four counter telescopes at any scattering angle in the planes defined by the azimuthal angles: $0^\circ$, $90^\circ$, $180^\circ$, $270^\circ$, respectively. The outer extremeties of the tracks are fastened to a rigid steel pipe ring which is in turn supported by means of heavy-duty laboratory mounting devices onto a heavy steel frame. These mounting devices provide a simple but rigid means of making small adjustments for final alignment. This "rig" is illustrated in Fig. 4.

As can be seen from the statistical expression for azimuthal asymmetry presented above, the most informative azimuthal angles at which to observe the distribution are those for which no effect is expected ($90^\circ$, $270^\circ$) and those for which maximum effect is expected ($0^\circ$, $180^\circ$); this then justifies the described arrangement.

The $0^\circ$-$180^\circ$ plane (horizontal) is aligned coincident with the first (internal) scattering plane, and the $90^\circ$-$270^\circ$ plane (vertical) is aligned such that their line of intersection coincides with the axis of the collimating system. It is seen that the second scatterer (paraffin/carbon spheres) is mounted on that axis, by means of a grid of tightly stretched steel wires.
forming a small square frame, in which the scattering spheres are secured by small indentations cut into them. By considering the slope of the differential scattering cross-section, it may be noted that the relative intensities scattered into the various azimuthal counter telescopes are very critically a function of scattering angles (Fig. 11), so that errors in mounting the scatterers could easily obscure the investigation.* The illustrated scheme was developed as a compromise achieving adequate rigidity, together with a low background due to scattering of neutrons intercepted by the mounting mechanism.

Spherical scatterers are chosen principally because the scattering from such a shape shows the least sensitivity to misorientations, i.e. it is a gross approximation to a point scatterer. The beam and scatterer dimensions are chosen such that it is easy to align the system so that the scatterer is completely "covered" by beam flux, yet the counter telescope array is well outside the beam.

The scatterer details are shown in Fig. 5. The paraffin scatterer is simply a wax sphere; the carbon scatterer is a slightly smaller hollow sphere. Its inner and outer radii are chosen so that the amount of carbon is closely the same as that estimated to be in the wax sphere, and also so that the energy loss along the longest scattered path at the expected scattering angle is not much greater than the energy loss along a corresponding path in the wax. It can be shown that such a geometry can be made to approximate the ideal conditions on the pair of scatterers for a small range of angles, of:

(a) Same effective geometrical dimensions

(b) Same amount of non-hydrogeneous matter

* At $30^\circ$ Lab. angle and 150 Mev energy, a $1^\circ$ error appears equivalent to a 20 percent polarization effect, in the absolute sense. See also Fig. 10
PARAFFIN (CH<sub>2</sub>OH)
1.69 gms H, 9.76 gms C

CARBON HOLLOW (ASSEMBLED IN TWO HALVES)
9.86 gms C

**LOSS OF ENERGY ALONG INDICATED PATH**

<table>
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<tr>
<th></th>
<th>INITIAL ENERGY</th>
<th>135 MEV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PARAFFIN</strong></td>
<td>ALONG RAD.:</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>ALONG DIAM.:</td>
<td>25</td>
</tr>
<tr>
<td><strong>CARBON</strong></td>
<td>ALONG RAD.:</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>ALONG LONGEST PATH:</td>
<td>25</td>
</tr>
</tbody>
</table>

**FIGURE 5**

SCATTERER PAIR DESIGNED FOR:

1. EQUAL AMOUNTS OF CARBON
2. ALMOST IDENTICAL GEOMETRIES
3. ALMOST EQUAL ENERGY LOSSES
(c) Same energy loss along corresponding paths.

The intersection of the counter support tracks must also lie in line with the collimated beam in order to define experimentally the 0° axis of the second scattering; a small center hole drilled through the tracks permits rough visual alignment of the frame and the scatterer support wires. Final alignment is done more accurately by using a telescope several yards behind the apparatus, which has been previously aligned along the beam axis. Again the accuracy of alignment is checked photographically by noting the position of the shadow cast by the crossed tracks across the collimated beam.

III.4 Azimuthal Counter Telescopes: The telescopes, illustrated in Fig. 6, consist of two single scintillation counters mounted on a small metal box-frame, which fastens onto the locating tracks in such a way that the two counters are in line with the second scatterer. The individual counter consists of a parallel-plane faced cylindrical glass container filled with liquid phosphor (saturated terphenyl in m-xylene) which is observed by an ultra-violet sensitive photomultiplier tube (type 1P28). An intricately shaped, tight-fitting, polished aluminum reflector surrounds the bottle and mounts it on the tube. A black paper cover completes the assembly.

Table II summarizes the expected conditions at strategic points in the apparatus; it will be noted in particular that few elastically scattered protons are expected to have energies below about 60 Mev (at the optimum scattering angle). Hence the counter thickness is chosen such that only protons above that energy penetrate well into the second counter; thus a 60 Mev proton loses about 40 Mev in the first counter and the remaining 20 Mev in the second, a good portion of which is lost in the glass wall. The counter area is such that the telescopes count protons tracing any direct path from the scatterer into the rear counters; these then have an effective angular aperture of about 7° when mounted in the second-scattering frame.
<table>
<thead>
<tr>
<th>TABLE II</th>
<th>EXPECTED EXPERIMENTAL CONDITIONS AT STRATEGIC POINTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclotron beam current (Internal):</td>
<td>$10^{-7}$ Amp. $= 6 \times 10^2$ protons/sec.</td>
</tr>
<tr>
<td>Neutron flux scattered elastically* into 2nd scatterer ($7.6 \times 10^{-6}$ sterad.) from 0.45 eff. moles/cm$^2$ D neutrons</td>
<td>125000 $^0$</td>
</tr>
<tr>
<td>Proton flux scattered elastically into counters (0.013 sterad. eff.) From: 0.125 eff. moles/cm$^2$ H</td>
<td>10</td>
</tr>
<tr>
<td>Cyclotron beam energy:</td>
<td>180</td>
</tr>
<tr>
<td>First scattered energy:</td>
<td>Max: 180</td>
</tr>
<tr>
<td>Takes into acct:</td>
<td>Est. Mean: 155</td>
</tr>
<tr>
<td>Multiple traversals</td>
<td>Est. Min: 130</td>
</tr>
<tr>
<td>Scatterer absorption</td>
<td></td>
</tr>
<tr>
<td>Second scattered energy:</td>
<td>Maxa 135</td>
</tr>
<tr>
<td>Takes into acct:</td>
<td>Est. Mean: 107</td>
</tr>
<tr>
<td>Aperture effect</td>
<td>Est. Min: 75</td>
</tr>
<tr>
<td>Scatterer absorption</td>
<td></td>
</tr>
</tbody>
</table>

* Takes into account multiple traversals
The fluorescence emitted by the phosphor lies near the blue edge of the visible spectrum, and has a very short decay time ($< 2 \times 10^{-9}$ sec.). The correspondingly short electrical pulses generated by the photomultipliers whenever a particle traverses and excites the phosphors, are communicated through short coaxial cables of equal length to a local coincidence unit; the overall system has a measured pulse resolution time of about $5 \times 10^{-9}$ sec.

The coincidence circuit is a current-biased diode type, schematically illustrated in Fig. 7; this also shows the simple circuitry immediately associated with the photomultipliers.

It will be noted that the coincidence output is apparently attenuated in the ratio of about 15:1; this is necessary to avoid the added capacity of a cathode follower grid which would materially reduce the time resolution capabilities of the circuit, and yet at the same time it permits coupling the output signal into low impedance cable for further transmission, without unduly loading the circuit and spoiling the non-coincidence discrimination ratio. It is of course permissible to recover the coincidence signal by comparatively slow amplification, and the circuit capitalizes on that property. This coincidence circuit nevertheless requires fairly large signal pulses (5-10 volts) for unambiguous discrimination between coincident and non-coincident pulses.

In order to obtain such signal pulses without elaborate amplifying equipment, the photomultipliers are operated from a pulsed high voltage source, using a sensitive time of 100 microseconds synchronized to cover the 80 microsecond accelerator beam pulse which has a repetition rate of about 60 pulses per second. It is found that by pulsing the commercially available photomultipliers, materially higher voltage may be placed on their electrodes than under d.c. conditions, the duty cycle here being about 1:200.
These resistances necessary for softening H.V. pulse edges

(R = 2M ohms) identical thruout to properly divide H.V. pulse

C = .001 uF\n
(I = 0 to 100 ma, up to 100 ohms)

RG 65/u, RG 65/u, RG 63/u, equal lengths (10 ft. long)

TO AUX. D.C. SUPPLY, ADJUST R' TO PROPER BIAS CURRENT

NOTE: RESISTANCES IN OHMS
CAPACITANCES IN MFD
Since the overall gain and the space-charge limited output current are fairly steeply a function of voltage, it becomes possible by this means to obtain directly from the tube, sufficiently large proton pulses for reliable coincidence operation.

The limiting d.c. voltage is determined by breakdown due to a regenerative positive ion feedback effect between multiplier electrodes, in the residual cesium vapor. This has an onset time dependent on voltage, but for moderate over-volting, it is longer than the operational pulse duration used here, for perhaps half of the photomultipliers tested.

An incidental advantage of this form of pulse operation is the elimination of ambiguous counts due to neutrons which are created during other portions of the acceleration cycle, from the dees and other appurtenances within the cyclotron.

III.5 Auxiliary circuits: Briefly, the equipment used to supply the pulsed high voltage consists of a set of individual high voltage keying units (simple electronic switches), keyed by an adjustable width pulse generator (high power "one-shot" multivibrator) which is in turn triggered by a tunable rf discriminator unit coupled to the cyclotron oscillator. The electronic switches are so designed that the high voltage output pulse is essentially rectangular with a flat-top of height closely equal to the applied regulated d.c. voltage. These are purposely individual to permit simple adjustment of each photomultiplier to the proper operating point on the proton plateau by variation of the regulated d.c. voltage. In all operational aspects, the behavior of the system is the same as if the tubes were operated under d.c. conditions, once the discriminator is tuned to trigger at the beginning of the cyclotron beam pulse.

The keyed high voltage pulses do couple capacitively into the signal
circuits. In order to diminish the interference from this source as much as possible, the following steps are taken:

(a) The electrodes at the output end of the photomultiplier are operated using d.c. potentials.

(b) High voltage and signal circuits are separated

(c) The output impedance is made low, not only for proper operation of the coincidence circuit, but also to reduce the output circuit time constant — this is of the order of $2 \times 10^{-9}$ sec.

(d) The high voltage pulse edges are shaped to rise and to decay in at least 2 to 3 microseconds.

The combination of these steps reduces the differentiated pulse appearing on the signal circuits at the start and end of the high voltage pulse to a few percent of the normal proton signal pulse height.

The vicinity in which these experiments are conducted is traversed by a weak residual magnetic field from the cyclotron magnet, which interferes somewhat with photomultiplier operation. Fortunately, a moderate additional increase in operating voltage restores the normal gain, without recourse to magnetic shielding, for which there is little spare space.

The detection apparatus whose main features have been described, thus presents at the output of the coincidence units, a small, short electrical signal pulse whenever a particle traverses a counter telescope. These small pulses are lengthened and amplified through slower "pulse-generating amplifier" circuits (see Appendix B); the need for high speed resolution has now disappeared due to the much slower coincidence counting rate. The azimuthal distribution of "second-scattered" protons then finally appears as the relative counting rates of four scaler-register units. Circuit diagrams of the
strategic units will be found in appendix B.

III.6 Proton Plateaus: In order to insure that all protons, but only protons, are counted, the individual counter sensitivities must be adjusted so that they operate in the upper portion of the proton plateaus. This is the fairly flat region of the counting rate versus voltage curve obtained from a scintillation counter in a high-energy proton flux, and is due to the much greater total excitation energy loss from penetrating protons relative to other particles. Normally this is found by plotting out that curve for each tube as exemplified by Fig. 8; a short cut method was devised, in which additional gain is introduced following the coincidence circuit, sufficient to be able to observe on an oscilloscope, the small, residual non-coincidence pulses coming from the individual tubes. The high-voltage is raised (on each tube separately) until appreciable extra "grass" appears between obviously legitimate pulses, and the voltage is reduced by 50 to 100 volts. This operating point is always found to be sufficiently closely that obtained by the more tedious, orthodox method.

III.7 Beam Monitors: In order to normalize properly the beam intensity for paraffin and carbon difference "runs", a beam intensity monitor is necessary; such a monitor should preferably resemble the other counters and operate similarly. A fifth pulsed-photomultiplier scintillation-counter telescope is thus used to observe at a small angle a hydrogenous target placed well ahead of the second scatterer. This target is in the form of a flat plate which always covers all of the collimated beam so that all parts are equally attenuated. The counting rate of this telescope is adjusted (geometrically) to be several times that of the azimuthal telescopes,
THESE PLATEAUS FIRST LOCATED ROUGHLY BY EAR; ALSO EXAMINED OSCILLOSCOPICALLY.

FIGURE 8
SOME TYPICAL SCINTILLATION COUNTER PLATEAUS

MU 2558
so that monitor statistics will not materially influence the results.

It has often been noticed that the collimated neutron beam intensity does not correlate very well with the radiation intensity monitored for operational purposes inside the cyclotron shielding. Accordingly, a d.c. operated scintillation counter is set up as a rough external beam monitor behind all of the apparatus thus far described. The small average current flowing from the photomultiplier output anode is operationally used to maximize the beam intensity. A high-frequency bypass is incorporated to permit presentation of the beam pulse on a monitor oscilloscope; the photomultiplier high voltage keying pulse is presented on the same trace to permit proper synchronization. This needs to be readjusted whenever a change is made in internal probe position, of course.
IV. EXPERIMENTAL PROCEDURES

IV.1 In order to better appreciate the problems involved in deciding on the proper path of procedure in carrying out the measurement, it is appropriate to refer to Fig. 9 which displays the predicted variation of the "right/left" ratio for conditions of the experiment as listed in Table II. This applies to the contribution of the elastic neutrons only. Because of the masking due to Li neutrons, the effect is reduced by an uncertain factor which is to be determined from the LiD-LiH neutron yield measurements. It is customary to express the effect in terms of a percentage approximately equal to the decimal figure;* thus we speak of 10 percent polarization as equivalent to a right/left ratio of 1.10. In the practical experiment this is indeed the order of magnitude of the expected effect.

It has been indicated that it is much more preferable to observe the azimuthal effect by a dynamic method; the measurement consists in comparing the azimuthal distribution between two or more different scattering conditions. The azimuthal effect may be exhibited as a change in the relative counting rates of the counter telescopes when:

(a) the counter telescopes are rotated azimuthally,
(b) the second (external) scattering angle into the counter telescopes is varied simultaneously for all,
(c) the first (internal) scattering angle is varied,
(d) the scatterer materials are changed, comparing polarizing nuclei against presumably non-polarizing ones.

*See page 43
Fig. 9

NOTE:

(1) MEASURED 30° POINT PLOTTED RELATIVE TO 0° AS UNITY

(2) MEASURED 45° POINT PLOTTED RELATIVE TO 30° CENTER POINT.

FUNCTIONAL DEPENDENCE OF RATIOS FOR N-P POLARIZATION Curves predicted under conditions of Table II with θ = 30° EXPERIMENTAL POINTS SHOWN ARE NOT ADJUSTED FOR YIELD

MU2546
Methods (a) and (b) suffer from the drawbacks of requiring exceptionally accurate mechanical devices and counter geometries. Methods (c) and (d) involve the least extensive changes in the apparatus during the experiment, and require much less critical tolerances. The general trend of description so far has indicated the desirability of choosing as the adjustable element, one which affects the least number of the variables of the system, and whose influence can be easily monitored.

Variation of the internal scattering angle (c) has a number of advantages, some of which are not at once obvious. In particular, perhaps the most crucial point of the experiment is the difference between: the low sensitivity of the relative right/left ratios to the accuracy of the setting of constant second scattering angles, on the one hand, compared to: the high sensitivity of the absolute right/left ratio to the readjustment of the individual second scattering angles, on the other hand; i.e. the polarization is not critically a function of scattering angle, whereas the actual scattered intensity is. It is principally this factor which favors variation of $\Theta_1$ rather than $\Theta_2$. Method (c) thus presents the following major aspects:

No changes are made in the critical external scattering angles; even though their settings may not be all exactly equal, this has little influence on the relative right/left ratio, as pointed out.

The zero (internal) scattering angle measurement becomes possible, and it is the comparison of the distribution so obtained, with the distribution measured at other internal angles, which determines the contribution to the right/left ratio made by the polarization.

*See footnote on page 20
The emerging neutron beam passing from the first to the second scatterer is an almost constant energy beam at any internal angle $\theta_1$, as explained before. This means that there should be almost no change in relative overall sensitivities of the counter telescopes (despite moderate discrepancies in mechanical and electrical adjustments) when $\theta_1$ is changed.

Misalignment of the first scatterer might result in a false polarization observation; continuous monitoring of the alignment of the system by neutron-intensified film plates is done.

Change of scatterer materials (method d) is carried out to a certain extent as an integral part of the experiment; thus the degree of polarization due to the nuclei Li and C are roughly established in the course of the experiment. No other nuclei have been measured to date.

IV.2 It is helpful to recapitulate the pertinent steps required to complete the proper "setting-up" of the apparatus.

**Geometrical checks:**

1. Alignment of first scatterer (internal) by visual observation along axis of collimating system.

2. Alignment of external telescope along that axis.

3. Alignment of second scatterer and azimuthal frame by telescopic observation.

4. Exposure of photographic film behind apparatus during initial counter checks, to verify proper relative alignment of components. This procedure
is continued throughout the experiment, and for all data presented below, this film monitoring showed that the emergent flux always completely covered the second scatterer.

Counter checks: These checks are performed on the monitor and azimuthal telescopes, to a greater or lesser degree prior to each data-collecting period, whenever the equipment has been disturbed. In all of the operations for which data is presented below, these tests have been satisfactory:

(1) Individual counting rates, connecting single counters into the coincidence output line; this checks for abnormally high background due to stray beam and defective counter operation. This is never greater than perhaps five times the coincidence rate, the latter being always less than 10 counts per second.

(2) Resolution tests, inserting short lengths of coaxial line in one leg of the coincidence circuit; this checks for abnormal accidental rates as well as for faulty counters. Accidental counts are rarely observed in periods comparable with operational runs.

(3) Plateau determinations, already described, including verifying that breakdown occurs above the plateau, as a further check on the counters.

(4) Counting linearity tests, in which the proportionality of counting rate to beam intensity is checked; this will reveal abnormal blocking or accidental coincidences. Extremely good linearity is observed;
during the LiH-LiD neutron yield runs, linearity over a 20:1 range of counting rates was incidentally recorded. Only in the monitor has there been any indication of non-linearity at high intensities, and this is minimized by recording both carbon and paraffin data at the same intensity.

(5) Counter interchange tests to detect gross discrepancies in geometry or sensitivity; these show that the systematic asymmetries in counting rates are mostly due to geometrical effects.

(6) Background tests, measuring the effect of nearby sources of scattered protons, such as the monitor scatterer (which showed no effect). The background rates are generally less than 10 percent of the paraffin rates; since the scatterers are designed for direct paraffin-carbon subtraction, only occasional background data has been taken, to confirm that it remained low.

IV.3 The actual collection of the desired data is now almost self-explanatory; in all measurements, the following data is recorded:

Elapsed time, monitor reading, four telescope counter readings. Each set of runs consists of a paraffin run and a carbon run; a blank run is occasionally interspersed. A series of such sets of runs is made at certain strategic internal scattering angles ($\theta_1$) for both LiD and LiH. In order to facilitate detection of apparatus breakdown and drift, each set is kept reasonably short, and the complete series of necessary sets of runs can then be repeated several times during an operational period.
From Fig. 9 it will be seen that the most interesting internal angles ($\theta_1$) are $0^\circ$, $30^\circ$ and $45^\circ$; the external scattering angle is permanently set at $30^\circ$ for the array in all experiments.

The number of counts which it is necessary to collect, is determined by purely statistical considerations; it is desired to reduce those uncertainties to certainly less than the expected magnitude of the effect. It turns out that the rate of data collection at the wider scattering angles is actually limited by cyclotron output, so that consideration must be given to economy of time. The policy has been adopted of performing the series of runs belonging to two angles to be compared, at the same scattered beam intensity; in fact, the corresponding sets of runs are carried out under overall conditions as nearly identical as possible, as far as the azimuthal counter array is concerned.

The numbers collected by following this general scheme contain basically all the data necessary to verify and measure the polarization effect. To a rough approximation, those numbers as written down will already exhibit the effect, if present, but some fairly simple normalization computations are usually necessary to determine the truest results.

IV.4 In order to adjust the final results for the effect of the contribution of neutrons from Li, the LiD-LiH relative neutron yields should also be measured. The problem arises of monitoring the beam intensity for the two targets at two or more radii; the simplest solution, which is followed here, is to use the usual 2-inch Be cyclotron target as a comparison target. In this technique the intensity for LiD, and LiH at each angle is individually measured, and immediately following each measurement, the Be target is inserted automatically to intercept the
internal beam without in any way disturbing the other cyclotron controls. The sum of the four telescope counter readings is used as the measure of the beam intensity under each condition; the paraffin-carbon difference counting rates obtained for LiD and LiH are normalized to equal Be counting rates, for each substance. This procedure insures that the measured yields belong to the same neutron component for which the polarization effect is measured. While this is not by any means an absolute method, it yields numbers which, from the variations in observed rates, may be trusted to perhaps one part in four. If the LiD-LiH difference thus measured, is small, then the method does not yield very satisfactory numbers, because of the large net error.
V. RESULTS AND ANALYSIS

V.1 A summary of the data taken during several independent series of runs is presented in Table III; small monitoring normalization corrections have already been introduced. It is seen that the four counter telescopes did not collect exactly equal numbers of counts; there is also some variation from one series to the next. Each series actually consists of several sets of runs, but statistically significant effects appear only when a sufficient number of counts are grouped together, of course. An example of the scattering of the data is presented in Fig. 10 for the smaller sets of numbers, which show a scattering consistent with the expected statistical deviations. Each series is analyzed independently, the monitor data being used only to normalize the carbon-paraffin data within each group, inasmuch as there were appreciable geometrical changes in its position from one series to the next.

An examination of the ratios \( \frac{1}{3} \equiv \text{right/left} \) and \( \frac{2}{4} \equiv \text{up/down} \) shows a certain pattern which is helpful in choosing a reasonable mode of analysis. The up/down ratio remains essentially constant between most corresponding groups of runs, whereas the right/left ratio changes in a consistent way, in those cases for which a theoretical prediction is made.

V.2 Since our primary concern is with the latter, a normalization procedure is followed in which the data for counters 1 and 3 is adjusted to the same average value for corresponding groups. It is preferable to perform the normalization in this way rather than by monitor comparisons because, firstly, the monitor geometry is not constant between series of runs; secondly, the beam energy distribution seen by the monitor during
\( \theta_1 = 0^\circ, \text{PARAFFIN} \)

\[ \begin{array}{c}
R & L \\
R & L \\
R & L \\
\end{array} \]

\( \theta_1 = 0^\circ, \text{CARBON} \)

\[ \begin{array}{c}
R & L \\
L & R \\
L & R \\
\end{array} \]

\( \theta_1 = 30^\circ, \text{PARAFFIN} \)

\[ \begin{array}{c}
L & R \\
R & L \\
R & L \\
\end{array} \]

\( \theta_1 = 30^\circ, \text{CARBON} \)

\[ \begin{array}{c}
R & L \\
L & R \\
L & R \\
\end{array} \]

Identical runs grouped here for convenience; actually alternated during operation.

**Figure 10** - Typical case of statistical scattering of individual run data (Group B).

---

R Point and statistical deviation of right hand counter.

L Do. of left hand counter.
### TABLE III

**SUMMARY OF POLARIZATION MEASUREMENTS**

<table>
<thead>
<tr>
<th>DATA GROUP</th>
<th>MON 1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>MON 1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>APPROX. CORR</th>
<th>θ₁</th>
<th>θ₂</th>
<th>θ₂-θ₁</th>
<th>DIFF.</th>
<th>%Δ</th>
<th>%Δ DIFF.</th>
<th>DIF.</th>
<th>%SAVE</th>
<th>NET</th>
<th>%DIFF</th>
<th>PROB. ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>9000 3471</td>
<td>3475</td>
<td>2805</td>
<td>9000 3335</td>
<td>3580</td>
<td>3770</td>
<td>2677</td>
<td>2.40</td>
<td>1.327</td>
<td>1.338</td>
<td>0° 30&quot;</td>
<td>0° 30&quot;</td>
<td>964.91</td>
<td>1.018</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>9000 3471</td>
<td>3475</td>
<td>2805</td>
<td>9000 3335</td>
<td>3580</td>
<td>3770</td>
<td>2677</td>
<td>2.40</td>
<td>1.327</td>
<td>1.338</td>
<td>0° 30&quot;</td>
<td>0° 30&quot;</td>
<td>964.91</td>
<td>1.018</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>9000 3471</td>
<td>3475</td>
<td>2805</td>
<td>9000 3335</td>
<td>3580</td>
<td>3770</td>
<td>2677</td>
<td>2.40</td>
<td>1.327</td>
<td>1.338</td>
<td>0° 30&quot;</td>
<td>0° 30&quot;</td>
<td>964.91</td>
<td>1.018</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>D</td>
<td>9000 3471</td>
<td>3475</td>
<td>2805</td>
<td>9000 3335</td>
<td>3580</td>
<td>3770</td>
<td>2677</td>
<td>2.40</td>
<td>1.327</td>
<td>1.338</td>
<td>0° 30&quot;</td>
<td>0° 30&quot;</td>
<td>964.91</td>
<td>1.018</td>
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<tr>
<td>E</td>
<td>9000 3471</td>
<td>3475</td>
<td>2805</td>
<td>9000 3335</td>
<td>3580</td>
<td>3770</td>
<td>2677</td>
<td>2.40</td>
<td>1.327</td>
<td>1.338</td>
<td>0° 30&quot;</td>
<td>0° 30&quot;</td>
<td>964.91</td>
<td>1.018</td>
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<td></td>
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<tr>
<td>F</td>
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<td>3475</td>
<td>2805</td>
<td>9000 3335</td>
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<td>1.327</td>
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<td>0° 30&quot;</td>
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<td>1.018</td>
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<tr>
<td>G</td>
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<td>3475</td>
<td>2805</td>
<td>9000 3335</td>
<td>3580</td>
<td>3770</td>
<td>2677</td>
<td>2.40</td>
<td>1.327</td>
<td>1.338</td>
<td>0° 30&quot;</td>
<td>0° 30&quot;</td>
<td>964.91</td>
<td>1.018</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- **DIFF.** indicates the difference between measurements.
- **%Δ** represents the percentage difference.
- **%Δ DIFF.** shows the percentage difference from the mean.
- **DIF.** indicates the difference from the mean.
- **%SAVE** represents the percentage savings.
- **NET** indicates the net difference.
- **%DIFF** represents the percentage difference.
- **PROB. ERROR** indicates the probability error.

**Legend:**
- COUNTER TROUBLES
- COUNTER = LEFT
- COUNTER = RIGHT
- COUNTER = UP
- COUNTER = DOWN

**Counts:**
- **9000**
- **3471**
- **3475**
- **2805**
- **3335**
- **3580**
- **3770**
- **2677**
corresponding groups of runs presumably changes due to "internal" experimental variations, and since no paraffin-carbon difference is taken in its data, the counting ratio between monitor and azimuthal array is not a constant from group to group. Because the normalizing factor is not much different from unity, it has but a small effect on the azimuthal ratios and on the net right-left differences.

The polarization is most directly computed from the net change in normalized right-left intensity from one condition to the next; the ratio of this difference to the average number of counts is the quantity $f = 2 \times P_1 P_2$, conveniently expressed as the percentage polarization:

We measure the normalized flux intensities ($I_1$) and differences ($d$):

in condition (1): \[ \begin{align*}
    I_{1R} &= \bar{I} + \frac{d_1}{2} \\
    I_{1L} &= \bar{I} - \frac{d_1}{2}
\end{align*} \]

in condition (2): \[ \begin{align*}
    I_{2R} &= \bar{I} - \frac{d_2}{2} \\
    I_{2L} &= \bar{I} + \frac{d_2}{2}
\end{align*} \]

The average is \[ \bar{I} = \frac{I_{1R} + I_{1L}}{2} = \frac{I_{2R} + I_{2L}}{2} \]

and the net difference is: \[ d = d_1 + d_2 \]

The Right/Left ratio can be written:

\[ \frac{R/L}{I_{1L}/I_{2L}} = \frac{(I + \frac{d_1}{2}) (I + \frac{d_2}{2})}{(I - \frac{d_2}{2}) (I - \frac{d_1}{2})} = \frac{1 + \frac{d_1 + d_2}{2I}}{1 - \frac{d_1 + d_2}{2I}} \]
We define: \[ f = \frac{d_1 + d_2}{1} = \frac{d}{1} \]
and: 100 \( f \) percent is the percentage polarization.

Then:
\[ (R/L)_{\exp.} = \frac{1 + \frac{f}{2}}{1 - \frac{f}{2}} \approx 1 + f \]

As presented on page 9:
\[ (R/L)_{th.} = \frac{1 + P_1 P_2}{1 - P_1 P_2} \approx 1 + 2P_1 P_2 \]

so that:
\[ f = 2P_1 P_2 \]

The errors due to this method of computation or to the inaccuracy of the various averages and factors, are trivial compared to the statistical probable errors. It should be noted that the number thus calculated for each series is not correlated with the corresponding absolute ratios; this is an indication that it is indeed appropriate to measure and calculate the polarization by a relative change, without being concerned with the behavior of the absolute numbers.

V.3 In considering the up/down ratios, it is noted that there is one serious deviation (group B) from the rule that the up/down ratios remain constant within the probable error; this same data also contributes abnormally to the right/left ratio. A check of that group's numbers shows that this is reasonably interpretable as a random "piling up" of statistical fluctuations. Together with the statistically regular behavior of the
individual sets of data (Fig. 10), the constancy of the up/down ratio forms good criteria of the relative effect of instrumental errors, and it appears that this is at least as small as the statistical probable error. The indicated probable errors are indeed calculated just from the statistical deviations, in the usual way.

V.4 Data groups A through D show a consistent positive change in right/left ratio due to the change in internal scattering angle from 0° to 30°. In order to tie together this data, the net differences are added, and the corresponding average counts are added; the weighted percentage polarization is the ratio of these sums, and this is about 6.5 percent, uncorrected for the LiH difference.

Data group E shows a negative change in right/left ratio due to the change from 30° to 45°, and this amounts to about 7.5 percent (reverse) polarization.

Data group F shows that LiH exhibits no comparable change in right/left ratio, and thus probably would show at best a very small polarization effect.

Data group G attempts to extract some information from the carbon data; unfortunately the "blank" data is statistically much too poor to obtain a meaningful result from the C-B difference. The uncorrected data shows no right-left difference statistically to the order of 1 percent; even if the blank showed a polarization effect of as much as 5 percent, this would only influence the carbon result to the order of 2 percent.

Finally, the relative LiD-LiH neutron yield data is presented in Table IV. It is seen that at 0° scattering angle, the "free" neutron in LiD contributed perhaps 50 percent of the flux, whereas at 30°, it contributes
only 20 percent. The manner of computation is obvious. This implies that only one-fifth of the average counts at 30° may be attributed to that extra neutron, so that if the observed polarization is attributed entirely to it, the percentage expressing the phenomenological result should be multiplied by a factor of five.
TABLE IV
SUMMARY OF RELATIVE YIELD DATA
(Data Taken with Group F)

<table>
<thead>
<tr>
<th>TARGET</th>
<th>ANGLE</th>
<th>TIME</th>
<th>PARAFFIN</th>
<th>NORMAL CARBON</th>
<th>DIFF.</th>
<th>RATE</th>
<th>NORMAL RATE</th>
<th>LiD-LiH DIFF.</th>
<th>CONTRIBUT. TO &quot;ELASTIC&quot; ENERGY</th>
<th>PROTON ENERGY (MEV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiH</td>
<td>0°</td>
<td>738</td>
<td>4735</td>
<td>2165</td>
<td>2570</td>
<td>3.48</td>
<td>4.60</td>
<td>53%</td>
<td></td>
<td>180</td>
</tr>
<tr>
<td>Be</td>
<td>0°</td>
<td>333</td>
<td>4705</td>
<td>2180</td>
<td>2525</td>
<td>7.58</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LiD</td>
<td>0°</td>
<td>518</td>
<td>4602</td>
<td>1980</td>
<td>2622</td>
<td>5.05</td>
<td>8.74</td>
<td>4.14</td>
<td>47%</td>
<td>180</td>
</tr>
<tr>
<td>Be</td>
<td>0°</td>
<td>235</td>
<td>2409</td>
<td>1051</td>
<td>1358</td>
<td>5.78</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LiH</td>
<td>30°</td>
<td>1194</td>
<td>5125</td>
<td>2065</td>
<td>3060</td>
<td>2.56</td>
<td>1.20</td>
<td>80%</td>
<td></td>
<td>240</td>
</tr>
<tr>
<td>Be</td>
<td>153</td>
<td>5126</td>
<td>1900</td>
<td>3226</td>
<td>21.1</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LiD</td>
<td>30°</td>
<td>60</td>
<td>3570</td>
<td>1608</td>
<td>1962</td>
<td>4.88</td>
<td>1.51</td>
<td>47%</td>
<td></td>
<td>240</td>
</tr>
<tr>
<td>Be</td>
<td>60</td>
<td>3439</td>
<td>1490</td>
<td>1949</td>
<td>32.5</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Elastic Yield \(0°, 180\,\text{Mev}) = 13 \pm 100\%

The error is entirely experimental in origin because of the necessarily inadequate monitoring scheme. It is estimated from the variations in data taken during equal intervals.
VI. DISCUSSION

This experiment must necessarily be considered as an exploratory one; the geometrical arrangement is by no means the most satisfactory one for exploiting the advantages of the method finally used. A material improvement in statistics would require very considerable extension of operations, which is not warranted by the nature of the present equipment nor by particular procedural uncertainties. An elaborate analysis of the data would likewise be superfluous; however, it is desirable to show that the results are sufficiently selective to require a remarkable degree of coincidence or complexity on the part of any arbitrary "false polarization" mechanism, and preferably, these results should also have a consistent theoretical interpretation.

VI.1 Several sources of false polarization have been indicated in previous sections. Most of the simpler mechanisms can be eliminated as a consequence of one or another applicable operational check. The most serious possibility appeared to be that an error in setting the second (external) scattering angle together with a shift in scattered beam energy distribution due to an experimental "internal" change, might produce an effective polarization, because of the steep slope of the scattering curve (Fig. 11). Experimentally, this effect does not appear, inasmuch as small intentional variations (~1°) were introduced in the counter telescope positions, between the first four listed series of runs. While this altered the absolute right-left ratios as predicted, it did not essentially affect the individual polarization results. Theoretically, it turns out that in the critical region of scattering angles (vicinity of 60° c.m.),
\[
\left( \frac{d\sigma}{d\Omega} \right)_{\text{C.M.}} \approx 4 \cos \theta_{\text{LAB}} \left( \frac{d\sigma}{d\Omega} \right)_{\text{LAB}}
\]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{\textit{n-p Differential Cross-Sections}}
\end{figure}

FROM: HADLEY ET AL. PHYS. REV. 75, 351, 1949
KELLY ET AL. PHYS. REV. 75, 98, 1950

(180 MEV CURVE INTERPOLATED)
the scattering curve slopes are relatively insensitive to energy
(< 0.3 \times 10^{-27} \text{ cm}^2/\text{sterad.}/\text{rad.}/100 \text{ Mev}), so that a very considerable
alteration in energy distribution of the component measured by the paraffin-
carbon difference would be required. Among other rejected mechanisms:

Non-uniformity of fluxes striking either scatterer.

Changes in beam pulse width with radius, together with
differences in counter sensitive periods.

Changes in beam energy distribution with angle, together
with differences in counter energy cut-off.

In a more general sense, the carbon data in particular shows that under
identical conditions, there does exist an experimental situation in which
no polarization is observed by the adopted rules of procedure and analysis.
Finally an artificial mechanism would have to be selective to the LiD
scatterer, to the right/left counters, and would have to exhibit a reversal
in operation when passing through the range of scattering angles.

See also Appendix A

VI.2 The yield measurements lead to the surprising result that the
measured polarization percentage must be multiplied by five if the (30°)
polarization effect is attributed to the deuteron neutron. A simple and
informative check can be made on the yield results by comparing the 0° and
30° elastic neutron yield components; see Table IV. Keeping in mind that
the 0° and 30° yield results belong to two different initial energies, the
ratio of the expected "elastic" yields calculated from the n-p differential
cross-section data (Fig. 11), is:

\[
\frac{Y(0^\circ, 180 \text{ Mev})}{Y(30^\circ, 240 \text{ Mev})} \sim 5
\]
which is to be compared with the experimental value of 13. This would indicate that the "elastic" neutron contribution deduced from the LiD-LiH difference may be too small (and the multiplier too big) by a factor of about two. As stated before, the yield data is uncertain to one part in four; consequently, the percent contribution by the D neutron could as well have been 40 percent as the measured 20 percent, because of the sensitivity of the LiD-LiH difference.

VI.3 While the final results are not spectacularly outside probable error, there appears a reasonably unique pattern of behavior, whose pertinent features bear reiteration: (Fig 9)

(1) The azimuthal array is consistently sensitive to changes in the first scattering angle and scatterer materials.

(2) No consistent changes appear in the up/down ratios outside probable error.

(3) From the LiD data:
   (a) An increase in right/left ratio occurs from 0° to 30°, corresponding to a yield-adjusted polarization of the order of 30 percent.
   (b) A decrease in right/left ratio occurs from 30° to 45°, corresponding to a yield-adjusted polarization of the same order.

(4) From the LiH data, there is nearly no change in left/right ratio, with a sufficient statistical significance to indicate that at least the major part of the observed effect (with LiD) must be attributed to the extra neutron.

(5) From the (uncorrected) carbon data, it appears that this material exhibits no polarization.
The LiD result is directionally consistent with the tensor force model calculations, which predict a magnitude of 12 percent; the uncertain interpretation of the yield results makes comparison only qualitative. If, as it appears likely, the multiplier should be a factor of only about three, then the observed polarization would agree reasonably well with those predictions.

The original theoretical considerations took into account just the polarization contribution due to the tensor force interaction; other spin-dependent mechanisms, such as spin-orbit coupling, might also play a role, and these would be detectable not only by a discrepancy in the polarization magnitude at the angle considered optimum for exhibiting the tensor force effect, but also by a distortion in the angular dependence of the polarization. There are theoretical arguments (associated with the effect of spin-dependent terms on the cross sections) which indicate that the polarization should always appear at least in the same direction for any spin-dependent mechanisms (i.e. \( P \geq 0 \) always); such contributions are therefore additive. In addition, in an interaction governed by an almost symmetric exchange type of force, it is necessary that the polarization vanish not only at 0° but at 45° Lab (90° c.m.) as well.\(^2\) Thus in the directional sense at least, the measurements are also consistent with more general theoretical expectations.

The essentially zero result for LiH and for carbon can be (speculatively) interpreted as being a consequence of the "filled" nature of their nuclear structures; most of the lithium neutrons, and all of the carbon protons, are (instantaneously) paired off with nucleons of opposite spin. The introduction of a tensor-like potential in the Schrödinger wave equation for the scattering problem is often interpreted in terms of a momentary mesonic exchange, while the nucleons are within the nuclear force range. But also
in the bound system, in complex nuclei, the internucleonic forces may be represented in terms of saturated mesonic exchange currents between the nucleon pairs. Hence, in tightly-bound structures, in which the nucleons spend most of their time within a saturated nuclear force field, the tensor force might not be expected to manifest itself in interactions with those nucleons, to the extent that it does in the case of loosely-bound structures, such as deuterium.

VI.4 The results of this experiment are thus interpretable as a direct confirmation of the existence of non-central nucleon-nucleon interactions in the 150 Mev energy region.

VI.5 For the eventual purpose of improving statistical accuracy, extensive mechanical modifications are indicated, the major aspects of which follow:

The first scatterer probe should be automatically exchangeable and adjustable on a firm mechanical guide.

The azimuthal counters should be supported on an axially rotatable frame of cylindrical form, having an integral telescopic sight. The second scatterers should be mounted by means of locally fastened fine steel wires.

The counters should subtend a much broader azimuthal angle, as another step towards more rapid data collection.

The monitoring system should be an integral part of the structure and should operate at a "non-polarizing" angle.

The associated problem of determining relative neutron yields to a greater reliability, would also be simplified by such a program.

Procedurally, the measurements should be extended to explore the azimuthal and scattering angle ranges in greater detail. It would be of interest to investigate at least one other nucleus, - beryllium - which also has a "loose" nuclear structure.
VII. ACKNOWLEDGMENTS

The candidate wishes to express his sincere appreciation to Professor E. O. Lawrence for his encouragement and continued interest, to Professor R. L. Thornton for his continuous and imaginative guidance, to Professor Owen Chamberlain for pertinent experimental advice and information, and to Professor Robert Serber, Mr. Don Swanson and Mr. C. Leith for a number of revealing discussions on theoretical and interpretational aspects. He also wishes to thank Mr. A. Kirschbaum for assistance during construction and operation of the apparatus, and Mr. R. McKisson for conducting the LiD-LiH target manufacture. Finally, Mr. James Vale and the members of the 184-inch cyclotron crew are to be remembered for their continued success in accelerating a satisfactory number of protons under somewhat peculiar and occasionally trying circumstances.

This research was conducted under the auspices of the Atomic Energy Commission.
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APPENDIX A

Counter Interchange Tests:

An obvious check on the proper operation of the apparatus and on the experimental procedure is to collect significant data with the counter telescopes positionally interchanged. When this test was first performed, radical changes in sensitivity were immediately noticed which were associated with large corresponding shifts of the plateau for each tube of each telescope. In fact, those counters most affected were the right/left pair, those least affected being the up/down pair; by checking the direction of the plateau shift at each interchange, the trouble was eventually traced to the change in orientation of the photomultipliers in the stray cyclotron magnetic field. Most of the data taken with opposite telescopes interchanged is thus seriously influenced by this effect.

Since much of the time allotted to this check was consumed by that investigation, the data is also clouded by inadequate statistics, and should not be considered as pertinent. The net paraffin-carbon difference change (0° to 30°) is completely submerged in the statistical deviation, but the paraffin data by itself shows (statistically marginal) agreement with the behavior of extensive paraffin data previously collected in the normal positions.

More tests of this nature are clearly indicated and the equipment should be designed to mount in particular the right/left photomultipliers in the magnetically least sensitive position; magnetic shielding should be added, space permitting.
Figure 12 shows the rf synchronizing pulser circuit while Fig. 13 gives the circuit for the adjustable width keying pulse generator. The photomultiplier high voltage keyer and the pulse generating amplifier circuit diagrams are shown in Figs. 14 and 15 respectively.
TRIGGER INPUT FROM R.F. SYNC

PULSE WIDTH ADJUSTMENTS

THIS VALUE IS CRITICAL

NOTE: RESISTANCES IN OHMS
CAPACITANCES IN MFD.

FIGURE 13 - ADJUSTABLE WIDTH KEYING PULSE GENERATOR SHOWING ONE OUTPUT CHANNEL, TO DRIVE UP TO 8 H.V. KEYING CHANNELS.

MU2561
FIGURE 14
PHOTOMULTIPLEXER H.V. KEYER
SHOWING TWO OUTPUT CHANNELS (PER 3E29)

NOTE: RESISTANCES IN OHMS,
CAPACITANCES IN MFD.

MU2567
NOTE: RESISTANCES IN OHMS, CAPACITANCES IN MFD

CONNECT 6AC7, 6AG7 SHIELDS TO CATHODES

FEEDBACK SW. IN PULSE GENERATING AMP, TRIGGERS AT ~ .05 VOLT

OUTPUT PULSE 30V, .2 µSEC.; .2 µSEC. DEAD TIME