A COMPARISON OF THE STOPPING POWERS OF HYDROGEN AND DEUTERIUM AND THE ANGULAR DISTRIBUTION AND CORRELATION PATTERNS IN PROTON BOMBARDMENT OF $^{19}$F AND $^{15}$N

by

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CHAPTER I - A COMPARISON OF THE STOPPING POWERS OF HYDROGEN AND DEUTERIUM

I. INTRODUCTION

The process of energy loss \(\frac{-dE}{dx}\) by alpha particles in passing through matter has been investigated by many authors and a theoretical relation as deduced by Bethe is given as

\[
\frac{-dE}{dx} = \frac{4\pi Z^2 e^4 N}{3m\nu^2} (\log \frac{2m\nu^2}{I})
\]

\(\frac{-dE}{dx}\) is the energy loss for collision processes for particles of charge \(eZ\) and speed \(\nu\) moving through an absorber of effective nuclear charge \(Z'\), effective ionization potential \(I\) and atomic density \(N\). \(m\) is the mass of an electron.

In the derivation of this formula it is assumed that all energy is lost in the ionization and excitation of the atoms of the stopping material. In the case of the two stable isotopes of hydrogen, the ionization potential of the electron will be only slightly altered by the presence of the extra neutron in the deuterium nucleus.

Most previous experimental work on the stopping powers of hydrogen and deuterium would seem to indicate that the stopping powers are very similar, which is in agreement with the theoretical predictions. In 1949, however, it was reported by Harrick and Eichholz that the stopping power of deuterium was approximately 6% greater than the stopping power of hydro-
The specific ionization for a single alpha-particle track, measured from the end of the track

Plate I
This result cast doubt on the validity of the theoretical assumption that the energy loss for alpha particles is due only to ionization and excitation of the atoms.

It was considered necessary, therefore, to make a new measurement of the stopping power of deuterium in order to resolve the apparent discrepancy between theory and experiment.

**THEORY**

The mean range for a single alpha particle can be computed from equation (1) by using the relation

\[
\bar{R} = \int_0^R dx = \int_0^E \left( -\frac{dE}{dx} \right)^{-1} dE 
\]

The stopping power \(-\frac{dE}{dx}\) of an absorber for an alpha particle of a given energy is related to the specific ionization by

\[
\frac{dE}{dx} = \mathcal{E} \rho 
\]

\(\mathcal{E}\) is the mean energy associated with the formation of an ion pair. Plate I shows the relative specific ionization for a single alpha particle, of mean range (3.8 cm), measured from the end of the range. The increase in specific ionization of the alpha particle near the end of its range is expected, since \(\frac{dE}{dx} \propto \frac{1}{\sqrt{\mathcal{E}}} \rho\).

As each alpha particle makes only a finite number of collisions and each collision has a discrete energy loss, it is to be expected that the ranges of individual alpha particles will have a distribution about some mean range. If \(\bar{R}\) is the mean range of an alpha particle and \(y dR\) gives the fraction of alpha particles in the beam which comes to rest between \(R\) and \(R + dR\) from the source, then the curve \(y\) can be approximated by the Gaussian relation
COMPARISON OF DIFFERENT METHODS OF MEASURING RANGES

PLATE II
\[ y = (\frac{1}{16\pi \alpha^2}) \exp \left( \frac{-R^2}{2\alpha^2} \right) \] ..........................(4)

\( \alpha \) is the half-width at \( \frac{1}{e} \) of the differential range curve (Plate II).

Plate II shows the following range relations for polonium alpha particles in air:

Curve a. a number-distance curve with a number-distance extrapolated number range \( R_n \) at 3.897 cm

Curve b. a differential range curve with mean range 3.842 cm

Curve c. a portion of a specific ionization curve for an alpha particle beam with an ionization extrapolated range at 3.870 cm

Curve d. a portion of a specific ionization curve for a single alpha particle of mean range 3.842 cm.

It can be seen that the extrapolated ionization range \( R_1 \) is not equal to the extrapolated number-distance range. The relation between \( R_n \) and \( \bar{R} \) is given by

\[ R_n - \bar{R} = \frac{1}{2\pi \alpha} \] ..........................(5)

The stopping power of a substance can be defined in a number of ways, but the most common definition is the ratio of the mean range in the substance to that in a standard material, usually air. The mean ranges are measured at 15°C and 760 mm mercury.
II. METHODS OF MEASURING THE RANGE OF ALPHA PARTICLES

A. THIN IONIZATION CHAMBER

In analyzing data from thin ionization chambers, the usual procedure is to plot a number-distance curve, obtain the extrapolated number range, and determine the mean range by direct substitution into equation (3). In analyzing data from specific ionization measurements, however, the mean range can be determined from the extrapolated ionization range only from the empirical relation:

\[ R_{\text{ex}} = (0.8\alpha - 0.06) \text{mm} \]  

Extrapolated number-distance range measurements suffer from chamber depth corrections, i.e. one must know the minimum depth that the particle has to traverse inside the chamber to produce a pulse that will be counted. To make this correction, it is necessary to know the variation of ionization with distance from the end of the range, as well as the signal-to-noise ratio, amplifier response and bias volts.

The observed distribution in range always has a greater value for \( \alpha \), the range straggling parameter, than the theoretical value of 0.062 for air. Livingston and Holloway have been able to account for this increase by including all sources of straggling:

1. Range Straggling - Defined as the \( \frac{1}{2} \) width of \( y \) (differential range curve, Plate II) at \( \frac{1}{6} \) of its maximum.

2. Noise Straggling - The pulse produced in the chamber either adds to or subtracts from the random noise pulses producing additional straggling.
3. Ionization Straggling - The energy required for ionization is not constant but varies about a mean value, approximately 32 volts per ion pair in air.

4. Angular Straggling - Due to angular deviations, the paths are not the same length for various alpha particles, thus a straggling effect is produced.

5. Foil Straggling - Slight non-uniformities in the foil which form the chamber window can lead to an increase in straggling.

6. Source Straggling - This and the angular straggling are the only effects mentioned so far that are not symmetrical about the mean range. Source straggling decreases the mean range and can be caused by source thickness, roughness or dirtiness.

B. OTHER METHODS OF MEASURING ALPHA PARTICLE RANGES

1. Differential Ionization Chamber

The ionization from two shallow ionization chambers with opposite potentials is collected on a common grid. Essentially, this method measures the position of maximum change of ionization along the path of an alpha particle and leads to a direct determination of the mean range.

2. Scintillation Method

Alpha particles may be counted on a ZnS screen placed between the source and the observer. Ranges determined by this method are usually short due to the difficulty of counting very small flashes visually. This method is much more effective if a photo-multiplier tube is used in place of visual counting.

3. Wilson Cloud Chamber

A pair of stereoscopic pictures enables one to measure the track.
lengths and leads directly to a determination of the mean range. The dis-
advantages of this method are (a) unknown composition of gases at time of
expansion, and (b) the rapid falling off of the ionization, making the last
part of the range hard to see.

4. Photographic Method

Any ionizing radiation or particle will produce activation on
absorption in the emulsion of a photographic plate. This method is not
too good for low energy alpha particles because of the coarseness of the
photographic grains, and, as a rule, is used only for a check on the ener-
gy of the alpha particles.

5. Magnetic Deflection$^{16,17,18}$

The velocity of a charged particle can be found from the amount
that it is bent when passed through a magnetic field. This magnetic
deflection method leads to very accurate values for the alpha particle
velocity, but, unfortunately, the range can be only approximated from the
measured velocities as there is no precise range energy relation.
SHALLOW IONIZATION CHAMBER

1. Collimated Source
2. MM Pitch Screw
3. Register
4. Micrometer
5. Chamber
6. H.T. Output
7. Aluminum Window
8. Collector
9. Rubber Gasket

PLATE III
III. DESCRIPTION OF THE APPARATUS

A. CHAMBER

Plate III shows a cross-sectional view of the four sections of the chamber.

Section I contains the movable platform upon which the collimated source is mounted. The source position is set by rotating a screw of one mm pitch. Complete revolutions are registered on a mechanical counter and partial turns are read to the nearest 1/100 mm from a calibrated drum.

Section II shows the thin chamber itself and the method of insulating the collector and the high tension face plate. The collimated alpha particles enter the thin chamber through an aluminum window which is pasted to the copper face of the chamber with aqua-dag. The aluminum window has an air-equivalent of approximately 1.2 cm. This thickness for the aluminum foil was chosen for a number of reasons: (a) the face must be rigid to reduce microphonics, (b) this thickness is more uniform than thinner foils, and (c) the chamber would not be deep enough for the full range of a polonium alpha particle in hydrogen or deuterium without increasing the pressure above atmospheric or interposing other absorbers.

It is to be noted that the collector must have the best insulation possible in order that none of the charge collected shall be lost through, or soaked up by, the insulator. The insulator for the high voltage electrode need not be of such high quality, but it is necessary that the high voltage input lead should have a large capacity to ground in order to by-
pass any electromagnetic pick up before it reaches the chamber. It is of the utmost importance that the capacity of the chamber be kept as low as possible so that the voltage will be a maximum for a given charge collected.

The chamber depth of 3 mm was chosen for this experiment as this is deep enough to give a good signal for hydrogen and is less than 1.5% of the total path length.

B. ELECTRONICS

1. Power Supplies

Two regulated power supplies were used to supply the power for the amplifiers. One was used as a 300 volt plate supply and the other as a variable negative rail from -100 to -150. In order to ensure complete isolation from earlier amplifier stages and from the fluctuations that are inherent in a.c. voltage supplies, a battery supply was used for the plate voltage of the pre-amplifier. All tubes were heated with a 6 volt d.c. storage battery and thus any a.c. coupling between filaments and cathodes was eliminated.

The high voltage supply was a conventional regulated supply and was capable of delivering 2000 volts with very little a.c. ripple. It was necessary to place a filter network in the high tension line just before it entered the chamber, in order to eliminate any spurious counts due to electromagnetic pick up.

2. Pulse Formation in Parallel Plate Ionization Chambers

As all gas-filled counters and chambers function by the separation and collection of the positive and negative ions formed in the gas, it is important to know how a pulse is formed. If the collecting electrode is positive and has a capacity C, it would appear that the change of potential
PULSE FORMATION IN A PARALLEL PLATE CHAMBER

PLATE IV
of the collector is due to a charge $-e$ being placed on a capacity $C$. This over-simplified picture is wrong because it neglects the induction effects which the two ions have been exerting since the creation of the ion pair. If at a time $t$ after the ion pair formation, the positive electrode has induced charges $-q_+(t)$ and $-q_-(t)$, the potential on that electrode will be

$$P(t) = \frac{q_+(t) + q_-(t)}{C}$$

.....(7)

where $P(o) = 0$ when $q_+(o) = -q_-(o)$.

It is interesting to note that the charges induced on the other electrode are complementary to those considered here, and, therefore, the pulses formed on the two electrodes are identical in form but opposite in sign. When the negative ion has been completely collected at time $t_1$, the potential of the collector will be

$$P(t_1) = \frac{-e + q_+(t_1)}{C}$$

.....(8)

The simplified picture in which the potential would be $-\frac{e}{C}$ when the charge $-e$ has been collected is thus incorrect, and corresponds to the case of complete collection of both negative and positive ions. Plate IV shows the actual pulse shape.

As the collection time $t_2$ (Plate IV) of the positive ions is more than 1000 times longer than that of free electrons, it is advisable to construct an amplifier with a short time constant so that electron collection alone is responsible for the pulse amplified. This is called a fast chamber as compared to a slow chamber in which the positive ions also are collected and give an addition to the pulse height (see Plate IV). Unfortunately, with a slow chamber, the clipping time (shortest RC time constant of amplifier) must be made longer than the pulse rise time $t_2$ (Plate IV). This method has the disadvantage of a slow maximum counting rate, and
greatly increased microphonics.

For a fast chamber with electron collection only \((t_2 \gg RC \gg t_1)\), the pulse profile is given by

\[
P(t) = \frac{q_c(t)}{c} + \frac{Q_r}{c} \quad \text{.................................(9)}
\]

where \(Q_r = q_r(0) = \text{constant} \).

3. Amplifiers

The output signal of an amplifier usually has superimposed on it a variety of extraneous signal components termed "noise". The various types of noise can be classified according to their origin as follows:

a. Hum introduced from power supply
b. microphonic noise
c. noise picked up from external sources
d. noise arising from defective components
e. inherent tube and resistor noise

Theoretically, the only type of noise that can not be completely eliminated is that due to tube and resistor noise. In practice, perfection is hard to obtain, but the various types of noise can be greatly reduced with care. In constructing the amplifiers (Plates V, VI), the following points were considered.

The high mutual conductance pentodes that were used are extremely microphonic as well as very susceptible to hum pick up from an a.c. operated heater. To reduce these factors a d.c. heater supply was used and the amplifier and chamber were mounted on soft sponge rubber as a protection against shock. Also, it was found necessary to reduce the low-frequency response to lessen microphonic pick up.

Electromagnetic pick up was greatly reduced by proper shielding of
the pre-amplifier which was completely contained in a copper tube. Also a common ground was used in an effort to eliminate any electromagnetic pick-up loops.

For a pulse amplifier having a single RC cut-off at low and high frequencies, the equivalent rms noise charge \( q_n \) on the capacity of the detector can be calculated as \(^{19}\)

\[
q_n^2 = \left( \frac{kT}{2\pi R} + \frac{kT'}{2\pi R_g} \right) \frac{f_2}{f_1(f_1+f_2)} + 2\pi kTBR_s(C+C_1)^2 \frac{f_2^2}{f_1+f_2} \ldots \ldots (10)
\]

Where \( R \) is the input resistance between grid and ground, \( R_g \) is the equivalent input noise resistance of the first tube due to grid current. \( R_s \) is the equivalent series grid noise resistance commonly used to express the magnitude of shot effect voltages in the plate circuit. \( C \) is the detector capacity, \( C_1 \) is the input capacitance of the amplifier, \( K \) is Boltzman's constant and \( T \) is the temperature. The frequencies \( f_1 \) and \( f_2 \) are the lower and upper \( \frac{1}{2} \) power frequencies. To reduce the first term the grid of the input 6AK5 was left floating \( (R \rightarrow \infty) \).

A plot of \( Q_n = 0.6745 \, q_n \) against \( C \) (chamber capacity) shows a linear relation exists between the two; thus the first two terms, which are due to thermal noise and grid current respectively, are negligible compared to the noise from the shot effect. In order to reduce the shot effect, the input 6AK5 was triode-connected as the mean-square shot noise of a pentode is generally three times greater than that of the same tube triode-connected\(^ {19}\), due to partition noise. The 6AK5 used was hand-picked for its low noise as all 6AK5's are not equally good.

Elmore and Sands\(^ {19}\) give an experimentally determined curve showing the signal-to-noise ratio as a function of clipping time. This curve was found useful as a guide in selecting the proper clipping time.
Some of the advantages of the push-pull main amplifier used are:

1. Changes in the main supply current are very small. The tubes are self-compensating as pairs, reaction through the supply line is thus reduced, and the amplifier is more nearly independent of the impedance of the power supply, removing the necessity for large decoupling condensers.

2. Either sign of input may be used and either sign of output is available.

3. The gain is large only for out-of-phase or differential inputs at the grids by virtue of the use of the cathode-coupling resistors of the long-tail pair. Hence, in-phase effects such as hum on the supply line cause the grids to rise and fall, but the cathodes do likewise and there is little amplification.

4. The gain is a function mainly of the tube current and is more or less independent of the combination of grid and screen voltages used. More particularly, it is independent of the cathode emission and gain is stabilized against changes in heater voltage.

5. Gain control is obtained by the variable low resistance joining the cathodes which gives smooth noise-free action.

6. The amplifier is linear over a larger range of output pulses than a single tube amplifier.

C. DEUTERIUM GENERATOR

The deuterium generator (Plate VII) consists of an electrolysis tube to generate the deuterium from heavy water, a pressure equalizer to keep the deuterium separate from the oxygen, a phosphorous pentoxide dryer, a liquid air trap, a gas holder, and a mercury pump to transfer the deuterium into the storage flask.
IV. EXPERIMENTAL PROCEDURE

A. FINAL AMPLIFIER ADJUSTMENTS

The final value selected for the clipping time was determined experimentally with hydrogen in the chamber as the range of this gas was to be measured. The maximum signal-to-noise ratio was realized with a clipping time of 10 microseconds, which is approximately the value predicted by the curves given in Elmore and Sands. It is to be noted that this is not the optimum value for the clipping time if the gas used forms negative ions, as, for example, air. It is advisable, therefore, to use a gas such as argon for a standard because both argon and hydrogen allow electron collection and will give pulses of the same order of rise time.

It will be noted that maximum signal-to-noise ratio does not imply maximum pulse height. A larger pulse will be produced if the clipping time is made long enough to include the rise due to the positive ion collection, but when this is done, microphonics increase the noise level so that there is a net loss in signal-to-noise ratio.

An optimum value for the chamber voltage was chosen in much the same manner as for the clipping time, but, as would be expected, the signal-to-noise ratio does not depend on the chamber voltage as long as the voltage is high enough for complete electron collection.

The chamber itself was thoroughly washed first with concentrated nitric acid then with alcohol in an effort to reduce the background due to alpha particles from the walls, and the inside was painted with pure
PLATE VIII

SIGNAL TO NOISE.

ARGON IN CHAMBER

\[ \frac{S/N}{555-495} = 8.25 \]

DISCRIMINATOR VOLTS 

COUNTS PER MINUTE

10 15 20 25 30 35 40 45 50 55
aqua-dag. The background finally obtained was approximately 30 counts/min.

B. SOURCE PREPARATION$^{20, 21, 22}$

Approximately a dozen old radon needles were available for the preparation of a polonium source. The procedure for preparing the polonium source was as follows.

The radon needles were smashed and dissolved in concentrated nitric acid, then evaporated to dryness. The residue was next dissolved in concentrated hydrochloric acid and again evaporated to dryness. This latter process was repeated at least three times. (All evaporation was done with a water bath, not with an open flame, to avoid spattering.) Finally, the residue was dissolved in 5N HCl.

The polonium was then separated from the RaDEF solution as follows. A silver button was mounted on a source holder and polished. One drop of the RaDEF solution was put onto the silver button, and after one minute, the button was immersed in a large volume of water. The film of polonium thus deposited was so thin that it was visible only as a slight colouring to the silver when placed under a strong light.

The thin source, prepared as outlined above, was compared to a much stronger source prepared by rotating the silver button in the RaDEF solution until all the polonium had been deposited by electrochemical action$^{22}$. Plate IX shows the number-distance curves for the two sources. The thin source is much weaker as would be expected, and, therefore, its maximum counting rate has been normalized to that of the stronger source to allow a direct comparison. Curves A and B are the curves for the thick source and the thin source, respectively, while curve C shows the range straggling expected for an infinitely thin source. It is to be noted that curves A
PLATE IX
STRAGGLING FOR DIFFERENT SOURCE THICKNESS

THEORETICAL CURVE FOR RANGE STRAGGLING ONLY

THIN SOURCE

THICK SOURCE

3.783
3.804
3.842
3.897
and B include other straggling factors besides the range straggling.

C. GENERATION OF DEUTERIUM

The operation of the deuterium generator can best be understood with reference to Plate VII. To commence operation the system must be completely evacuated. This evacuation is best accomplished by pumping through taps 8 and 10 simultaneously. Taps 5 and 7 are closed after the reservoir and mercury pump are full of mercury. Tap 9 is also closed while taps 1, 2, 3, 4 and 6 are open. When the system has been completely evacuated, taps 1, 2, 3, 4, 6, 8 and 10 are closed. Heavy water with potassium sulphate (1gm/25cc) as electrolyte can now be introduced into the electrolysis chamber through tap 10, being sure not to admit any air. The electrodes can now be connected and a current of approximately .5 amps passed through the electrolyte. The first stage in the operation is very critical and the generator must be watched constantly; otherwise, too large a pressure will be built up in the electrolysis tube.

Taps 1, 2, 3, 4 and 5 are opened as atmospheric pressure is gradually built up in each section of the apparatus. Stopcock 9 is left open after atmospheric pressure is obtained in the tubes themselves. Once tap 5 is opened the reservoir is connected and the generator can be left to operate by itself until the reservoir is filled. While the storage tank is below atmospheric pressure, the reservoir can be emptied by simply opening tap 6 cautiously and drawing the deuterium into the storage tank. After the storage tank reaches atmospheric pressure the mercury pump must be used as follows. The generator is shut off and tap 4 closed. Taps 5 and 7 are then opened and by lowering the mercury level in the pump the reservoir is emptied. Now tap 5 is closed and tap 6 is opened, and once more the mer-
cury level is raised, forcing the deuterium into the storage tank. The entire process is repeated until the storage tank contains the required amount of deuterium. The phosphorous pentoxide and the liquid air trap remove any water vapour that may come through the oil pressure equalizer. (Water vapour pressure at -190°C is less than $10^{-6}$ mm).

D. PURIFICATION AND HANDLING OF GASES

As the chamber was pumped down to approximately 10 microns with a mechanical fore-pump before admitting the gases, any residual gas would amount to only about part in 10,000, which is certainly insignificant.

The heavy water used in the deuterium generator was quoted as 99.5% pure heavy water. Upon filling the ionization chamber with deuterium, the first measurements indicated that the stopping power of the deuterium was about 6% greater than that of hydrogen. The electrolytic hydrogen and argon were obtained in lecture bottles at 1500 lbs/sq inch and were of high purity - better than 99.9%. Water vapour on the chamber was eliminated by means of a liquid air trap.

As the results for the stopping power of this deuterium were not consistent, it was decided that the generator must have originally contained some air in the reservoir due to faulty pumping, or to a small leak when the reservoir was below atmospheric pressure. In order to save the deuterium already generated, it was decided to pump the deuterium out of the ionization chamber and purify it by passing it through a palladium lead. When this was done, the original discrepancy between the stopping powers of deuterium and hydrogen was non-existent. For consistency, the hydrogen also was introduced into the chamber through a palladium leak. This process did not change the range, which was identical with that obtained when the hydrogen was admitted directly into the chamber.
As a further check gas samples were taken and sent for analysis. (see Possible Sources of Error in Results, Section V. -C).

E. CALIBRATION OF THE SOURCE MICROMETER

Even after all possible precautions for reducing spurious noise effects had been taken, it was found necessary to take all readings at night when acoustical and electrical noise were at a minimum.

The actual performance of the complete system can be judged by the signal-to-noise ratio obtained (see Plate VIII) for a chamber depth of 3 mm. With argon in the chamber a signal-to-noise ratio of 9 was obtained and with hydrogen (or deuterium) a ratio of approximately 3 was obtained. The reduced signal-to-noise ratio for hydrogen is to be expected due to the decreased stopping power of hydrogen.

The signal-to-noise ratio was dependent upon the state of discharge of the filament battery. Therefore, in order to obtain reproducible results, the battery was fully charged before each run and the amplifiers allowed to operate for about two hours in order to reach thermal equilibrium. Also, in order to check the amplifiers performance, a signal-to-noise test was taken immediately before each range measurement.

The actual calibration was obtained by plotting a number-distance curve for hydrogen and using the accepted value for the stopping power of hydrogen \( (224)^3 \) to calculate the stopping power of deuterium. Hydrogen was chosen as a standard for the comparison because hydrogen and deuterium have theoretically very similar stopping powers, and, therefore, any error inherent in one measurement should be the same in the other. Such an error might arise from the chamber penetration correction, which can be determined only approximately. As an additional check on the correctness of results
each run with hydrogen or deuterium in the chamber was followed by a similar run with argon in the chamber. In this way, the stopping power of hydrogen was measured in terms of the stopping power of argon, which was then compared to air by using the accepted stopping power of argon compared to air \((0.929)^3\). Two additional runs were made in which the range of argon was compared directly to that of air to check the accepted value for the stopping power of argon.

In order that each point on the number-distance curve should have the same statistical weight, the same number of counts were taken for each point on the curve. Since 2% standard deviation on each point requires approximately 2000 counts, the source strength was chosen to give approximately 2000 counts per minute.
V. RESULTS AND DISCUSSIONS

A. CORRECTIONS TO EXPERIMENTAL DATA

The mean range is defined as that range reached by just one-half of the particles that leave the source. The mean range will depend, of course, on the self-absorption of the source, but the stopping power will still be given by $S = \frac{R_m \text{ air}}{R_m \text{ gas}}$ provided $R_m \text{ air}$ and $R_m \text{ gas}$ are measured from the same source.

In finding the intercept for the extrapolated number-distance range, only the points on the linear portion of the number-distance plot (see Plate X) were considered. The background was subtracted from each count, and a straight line was drawn through these points to give the best intercept. The best line was determined by two separate methods, (a) using a thread to fit the line by eye on a large scale plot, and (b) using least squares. Both methods gave the same results.

Having obtained the intercept, the extrapolated number-distance range was found by considering:

1. The distance from the chamber face to the source. (From the calibration of the micrometer scale with range in a standard gas.)

2. The equivalent range of the aluminum foil. The stopping power of aluminum was taken as 1.57 mg/cm$^2$, which is the average of the values given by Rosenblum$^1$, and Marsden and Richardson$^1$.

3. The chamber depth penetration, which was found at least to a first order approximation by using the method described in Appendix I.
UNCORRECTED EXPERIMENTAL NUMBER DISTANCE CURVES ~ PLATE X

AIR
JULY 25 1951

ARGON
JULY 25 1951

HYDROGEN
SEPT 25 1951

COUNTS PER MINUTE

MICROMETER READING CM

300
0 3.4 3.5 3.6 3.625 3.7 3.7181 3.9 3.903 4.0

1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0

MICROMETER READING CM

0 12.0 12.5 13.0 13.008 13.99
1. The correction for temperature and pressure. The ranges were reduced to standard conditions.

\[ R_0 = \frac{RPT_0}{P_0 T_0} \]

\( T_0, P_0, R_0 \) refer to standard temperature, pressure & ranges. \( T_0 = 288^\circ \text{K} \), \( P_0 = 760 \text{ mm mercury} \).

B. RESULTS

<table>
<thead>
<tr>
<th>Stopping Power Relative to Hydrogen</th>
<th>Stopping Power Relative to Air</th>
<th>Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>.929</td>
<td>Argon</td>
</tr>
<tr>
<td>l</td>
<td>.220</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>1.012</td>
<td>.222</td>
<td>Deuterium</td>
</tr>
</tbody>
</table>

Table I shows the results obtained in this experiment. The values quoted for argon and deuterium are the mean of two sets of readings, and those for hydrogen are the mean of four sets of readings. The stopping power is defined from the mean range characteristic of the source.

Plate X shows a typical plot for air, argon and hydrogen.

C. POSSIBLE SOURCES OF ERROR IN RESULTS

1. Statistical

The best intercepts obtained from approximately 20 points on the linear section of the extrapolated number-distance curve were found in the least squares analysis to have uncertainties of .006, .005 and .015 cm for air, argon and hydrogen, respectively.

2. Foil

Any error caused by the foil would be due to choosing the wrong air
equivalent for aluminum. The stopping power of aluminum used was 1.57 mg/cm$^2$ equivalent to 1 cm of air, which is the average of the two values, 1.62 and 1.51. The uncertainty, therefore, is plus or minus .05 mg/cm$^2$. Because of the thickness of the window used (1.890 mg/cm$^2$), there is a possible error of .04 cm in the range in argon, or an error of 1.6% in the stopping power of hydrogen or deuterium.

3. Chamber Depth

The chamber depth penetrations were 1.25, .90 and 2.40 mm for air, argon and hydrogen (deuterium), respectively. (See Appendix I for method of calculating). These calculated values are probably a good first approximation.

4. Temperature and Pressure

The temperature was read to the closest $\frac{1}{2}$ degree which corresponds to uncertainties of .005, .005, .020 cm for air, argon and hydrogen, respectively. The barometer was read to 1/10 mm, giving an uncertainty too small to be considered.

5. Gas Purity

Argon and hydrogen were obtained in lecture bottles and were quoted as 99.9% pure, thus any error introduced from this cause was certainly small.

As a further check on the purity of the hydrogen and the deuterium used, a mass spectrometric analysis was obtained from Drs. Thode and Fleming, McMaster University. Unfortunately, the hydrogen gas sample was contaminated during transit, but the deuterium analysis is as follows.
In explaining the analysis, Dr. Fleming stated that the values given probably represent a lower limit on the deuterium content, since the most probable sources of error would result in an apparent increase in hydrogen content.

The appearance of 1.29% water vapour in the sample can be explained only by assuming contamination of the sample after it left the chamber, since all water vapour in the chamber should have been removed by the liquid air trap. If the water content if ignored, therefore, the lower limit for the deuterium content can be set as 98.33%. The hydrogen impurity, .83%, would not introduce any appreciable error in the stopping power, but the .38% of other impurities, mostly nitrogen, could lead to an error of 1.6% in the stopping power of deuterium. It is quite possible that some of the impurities were introduced in taking the sample.

Considering the above possible sources of error, the stopping powers
can be quoted with the following estimated errors.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Stopping Power</th>
<th>Estimated Probable Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argon</td>
<td>.929</td>
<td>± .007</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>.220</td>
<td>± .005</td>
</tr>
<tr>
<td>Deuterium</td>
<td>.222</td>
<td>± .005</td>
</tr>
</tbody>
</table>

D. COMPARISON OF RESULTS WITH PREVIOUS DATA

The following table lists the values of stopping powers found in this experiment and shows the accepted values for hydrogen and argon as found by other workers.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Stopping Power</th>
<th>Previous Work</th>
<th>This Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argon</td>
<td>.929</td>
<td>.929 ±0.007</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.929</td>
<td>.929 ±0.007</td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>.220</td>
<td>.220 ±0.005</td>
<td></td>
</tr>
<tr>
<td>Deuterium</td>
<td>.222</td>
<td>.222 ±0.005</td>
<td></td>
</tr>
</tbody>
</table>

The extrapolated range of polonium alpha particles in air used as a standard was taken from Holloway and Livingston and is quoted as being 3.897 cm at 15°C and 760 mm mercury.

The stopping powers of hydrogen and argon are in agreement with the well-established values as given by Gray.

The stopping power obtained for deuterium is in accord with the work of Schultz, but is in disagreement with the work of Eichholz and Harrick.
PLATE XI

EXPERIMENTAL RANGE NUMBER CURVE WITH A PHOTO-MULTIPLIER AND AN ANTHRACENE CRYSTAL

COUNTS PER MINUTE

MICROMETER READING

0 9.2 9.3 9.4 9.5 9.6 9.7
V. CONCLUSIONS

In agreement with theoretical predictions, the stopping powers of hydrogen and deuterium appear to be the same within the accuracy of this experiment. In the theoretical derivation of \( \frac{dE}{dx} \) the assumption is made that energy loss is due entirely to ionization and excitation of the absorbing atoms. The results of this experiment indicate that this assumption is a valid one.

To detect a difference in the stopping powers of hydrogen and deuterium due to the difference in ionization potentials would require an increase in the accuracy of this experiment by a factor of 100 or more. With present experimental techniques, this accuracy would be difficult if not impossible to accomplish.

Although the object of the experiment has been met to a reasonable extent, it is quite likely that the thin ionization chamber will be replaced by either a differential chamber where chamber penetration difficulties are non-existent, or by a scintillation counter using modern photo-multiplier tubes as pulse amplifiers. With a photo-multiplier scintillation counter, it should be possible to detect 10 KEV pulses as compared to the 150 KEV required for the thin ionization chamber.

Plate XI shows a preliminary number-range curve which was obtained from an EMI photo-multiplier scintillation counter with anthracene crystal without taking any special effort to increase the signal-to-noise ratio.
This curve compares very favourably with the ones obtained from the thin ionization chamber after taking all possible steps to increase the signal-to-noise ratio.
CHAPTER II - ANGULAR DISTRIBUTION AND CORRELATION PATTERNS IN PROTON BOMBARDMENT OF F\textsuperscript{19} AND N\textsuperscript{15}

PART A - RADIATION PATTERNS FROM EXCITED STATES OF O\textsuperscript{16}

I. INTRODUCTION

When F\textsuperscript{19} is bombarded by protons there are three competing reactions\textsuperscript{23,24}

1. F\textsuperscript{19}(pα)O\textsuperscript{16} short range α
2. F\textsuperscript{19}(pα)O\textsuperscript{16} long range α
3. F\textsuperscript{19}(pαπ)O\textsuperscript{16} short range α

(π refers to nuclear pair production).

The first reaction is the one of interest in this experiment. The yield of alpha particles changes rapidly with bombarding energy, and resonance levels have been measured and found to occur at the following proton energies (KEV) 340, 480, 590, 660, 820, 870, 890, 935, 1092. It is known also that the gamma radiation has three distinct energies, approximately 6.13, 6.9, 7.1 MEV, the relative intensities depending on the bombarding energy of the protons. At the lowest resonance (340 KEV proton energy) almost all of the disintegrations seem to lead to the same excited state of O\textsuperscript{16}. Gamma rays 6.13 MEV are then emitted in the transition to the O\textsuperscript{16} ground-state. No long-range alpha particles corresponding to the direct
ANGULAR CORRELATION BETWEEN $\alpha$-PARTICLES AND $\gamma$-RAYS IN THE REACTION $F^{19}(p,\alpha\gamma)O^{18}$

PLATE XII
transition from the Ne$^{20}$ level to the ground-state of O$^{16}$ are observed, though they are much favoured energetically.

Experimental work on alpha gamma angular correlation for $F^{19}(\alpha\gamma)O^{16}$ reaction has been carried on at Cavendish laboratory for the 340 KEV resonance. Both alpha particles and gamma rays were observed in a plane perpendicular to the proton beam. The alpha particles were detected with a proportional counter and with a window thick enough to exclude scattered protons from the thick CaF$_2$ target. The 6.1 MEV gamma rays were detected with a lead-walled geiger counter. Coincidences between the alpha particle and the gamma rays were measured as a function of the angle between the counters.

The angular distribution of alpha particles with respect to the proton beam is isotropic, and one can take as the simplest assumption that the Ne$^{20}$ is formed by s-protons. This means that it has no preferred orientation and it is not until the alpha particle is emitted that a fixed direction in space is defined. The gamma ray then has an angular distribution with respect to this axis, as has been found by Barnes et al, and the observed correlation function has a term in $\cos \Theta$. (The results are shown in Plate XII)

It was concluded from the experimental results that (a) the resonance level of neon 20 is formed by $l=0$ ($l=$ orbital momentum) protons and has $J=1$ ($J =$ total angular momentum) and is probably of even parity because alpha particle emission to the ground state of O$^{16}$ is not observed, (b) since neon 20 has even parity and is formed by $l=0$ protons, $F^{19}$ also has even parity, and (c) the neon 20 emits alpha particles with $l=3$ leaving an excited oxygen 16 nucleus with $j=3$ and odd parity.

In view of the wealth of information which was obtained from the study
of only one resonance, it would be very interesting to extend the study of
the \((\alpha \gamma)\) angular correlation to the higher resonances in an effort to
assign quantum numbers to each of the known levels of \(^{16}\text{O}\) and \(^{20}\text{Ne}\). A very
serious difficulty arises, however, as the proton energy is increased. The
340 keV resonance is the only one at which the alpha range exceeds the
scattered proton range. For this reason, the protons can be easily exclu-
scated from the counter by interposing absorbing screens while still admitting
the alpha particles. Extension of the measurement of the alpha gamma angu-
lar correlation to the higher resonances, therefore, reduces to the rather
difficult feat of designing a counter which will count only alpha particles
in the presence of a vastly larger number of more penetrating protons.
Appendix II shows calculated curves on the number of scattered protons as
a function of angle and energy.

Possible Methods of Counting Alpha Particles in the Presence of a
Strong Flux of Protons of Longer Range

1. **Magnetic Separation**

A magnetic analyzer could be used to separate the two particles,
then a conventional proportional counter could be used for counting the
alpha particles. The disadvantages of this method are (a) construction of
a magnet capable of resolving the particles, and (b) vastly reduced count-
ing rates due to a decrease in the effective solid angle of the counter.

2. **Very Fast Coincidence Circuit**

A very fast coincidence circuit could give a real to random coin-
cidence ratio of 1 if the resolving time was less than \(5 \times 10^{-10}\). Appen-
dix III contains the calculations on real to random ratios.

3. **Coincidence Circuit with Anthracene Film**

A fast coincidence circuit could be used in conjunction with an
anthracene film. The anthracene film would give pulses which would depend on the rate of energy loss \( \left( \frac{dE}{dx} \right) \) in the film, and as \( \left( \frac{dE}{dx} \right) \) is greater for alpha particles than for protons, the pulses from the alpha particles would be much greater than the pulses from protons. If this were true, the resolving time of the coincidence circuit would not have to be so short. Recent publications,\textsuperscript{25,26} however, show that the specific scintillation \( \left( \frac{dL}{dx} \right) \) does not increase linearly with \( \left( \frac{dE}{dx} \right) \), but instead a saturation effect is observed. In spite of this effect, the pulse from a 2 MEV alpha particle may be made nearly twice that from a 2 MEV proton by proper choice of the film thickness. (See Appendix IV)
II. DESCRIPTION OF APPARATUS

A. ELECTRONIC EQUIPMENT NECESSARY

Plate XIV is a block diagram of the electronic equipment that is required to perform an alpha gamma angular correlation experiment using a fast coincidence circuit. An E.M.I. type photomultiplier tube is used with a thin anthracene film as the alpha detector. A 5819 RCA photo-multiplier with a large anthracene crystal is used as the gamma detector. The high speed discriminator following the Chalk River design employs an EFP 60 secondary emission tube and is capable of producing a standard pulse which rises in a few millimicroseconds. This discriminator is being constructed by Dr. D. B. James and will be available for the experiment.

The coincidence circuit is that of Garwin and has a measured resolving time of $3 \times 10^{-8}$ seconds. To function properly the input pulses to the mixer must be greater than 3 volts. Atomic instrument amplifiers and scalers are available to complete the necessary electronics.

B. REACTION CHAMBER

The scattering chamber (Plate XIII) was designed and constructed with two purposes in mind: to study the response of thin sections of anthracene to protons and to determine the angular distribution of the alpha particles from the $^{19}_p\alpha^8_0^{16}$ reaction. (This angular distribution is required for the interpreting of the angular correlation experiment.)

The chamber has 12 ports ($30^\circ$ intervals) into which the magnetically
PLATE XIV

BLOCK DIAGRAM OF THE ELECTRONICS REQUIRED FOR A HIGH SPEED COINCIDENCE ANGULAR CORRELATION EXPERIMENT.
shielded scintillation counter can be fitted. The vacuum seals for all ports are made with rubber gaskets.
III. FILMS FROM ORGANIC PHOSPHORS

Although there are many references in literature to organic scintillators, both liquid and crystalline, there has been little work done on their response to heavy particles, and the work that has been done is of very recent origin. In fact, it was only after most of the work reported here had been completed that anything was published on the relative pulse heights produced by protons and alpha particles, and nowhere in literature has anyone published a method of producing a thin film from organic scintillators.

Anthracene and terphenyl of high purity were chosen as the organic scintillators. It is unfortunate that the pulse rise time in inorganic scintillators is so long, because they show a good response to alpha particles.

Since anthracene and terphenyl have a crystalline structure, it is not as simple as would be supposed to produce the uniform clear layer of the pure scintillator that is desired.

Many different methods of film formation were tried and the better films produced were tested for alpha particle response on an 18 channel kick sorter.

Techniques Employed in the Production of Thin Films

1. Evaporation of an anthracene solution on a water surface.

The anthracene was dissolved in a suitable organic solvent which would float on a water surface and evaporate, leaving the anthracene as a film on the water surface.
The following table lists the various solvents tried and the results.

**TABLE IV**

<table>
<thead>
<tr>
<th>Solvent (Saturated with Anthracene)</th>
<th>Remarks on Film Produced on Water Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>Too violent a surface effect</td>
</tr>
<tr>
<td></td>
<td>Film uneven and crystalline</td>
</tr>
<tr>
<td></td>
<td>Film very thin</td>
</tr>
<tr>
<td>Chloroform</td>
<td>Density of chloroform too great, does not form a suitable film</td>
</tr>
<tr>
<td>Ether</td>
<td>Surface tension breaks film as it is formed</td>
</tr>
<tr>
<td>Carbon Disulphide</td>
<td>Forms granular islands</td>
</tr>
</tbody>
</table>

Other solvents such as acetone, amyl alcohol and ethyl alcohol were tried also, but the solubility of anthracene in these was too small to make film formation a possibility. Zapon (commercial laquer) was added to the benzene solution in an effort to reduce surface activity, but it was found that the films thus produced did not scintillate.

2. **Evaporation of Anthracene Solutions on Glass Plates**

The same solutions as tried above on water were painted onto glass slides and allowed to evaporate to dryness. In all cases, the surface formed was very uneven due to crystal formation. The best film produced in this manner came from a chloroform solution.

3. **Crystals Grown from Solution**

Saturated solutions of anthracene in benzene, chloroform and carbon disulphide were allowed to evaporate slowly at room temperature, producing crystals of pure anthracene.

The crystals formed from a chloroform solution were needle-shaped, and, therefore, of little use, but the crystals formed from benzene and
carbon disulphide solutions were in a useable leaf form. The leaf crystals, however, were either very small or if given time to grow to a sufficient size, too thick. This is a good method of making flat crystals of anthracene approximately 1/10 mm thick.

4. Evaporation of Anthracene onto a Glass Plate in a Vacuum

The anthracene was heated in vacuo and allowed to condense on a glass plate. The thickness could be controlled by the amount of anthracene evaporated. The required thickness, .5 to 1, mg/cm², could be obtained easily but, unfortunately, the surface formed was not as uniform as would be desired, because the anthracene tends to form crystalline grains as it condenses on the glass.

5. Film Produced from an Anthracene Melt

Finely powdered anthracene was placed between two glass slides which were separated by an aluminum foil of the film thickness required (approximately .001 cm). The anthracene was thus confined to the area not covered by the aluminum foil and was of the proper thickness. The slides were heated (on a hot plate) until the anthracene flowed, and then allowed to cool. The top plate and the aluminum foil were removed when the anthracene had solidified, leaving the required anthracene film. This procedure resulted in a satisfactory film.

6. Film Produced from a Plastic Phosphor

The plastic phosphor consists of a small percentage of terphenyl in a polymerized monomer of styrene. Uniform thin sections were made by dissolving the plastic in benzene and painting the solution on a glass slide, but the plastic film did not give the large pulses that were produced by anthracene of the same thickness. (see next section)

7. Film Produced from Pure Terphenyl

The above techniques were tried with terphenyl as with anthracene and the results were very similar. (see next section)
PLATE XV
RESPONSE OF A THICK SECTION OF ANTHRACENE TO ALPHA PARTICLES OF DIFFERENT ENERGY

PULSE HEIGHT $\propto$ ALPHA PARTICLE ENERGY
ARBITRARY UNITS
IV. RESPONSE OF THIN ORGANIC FILMS TO ALPHA PARTICLES

In order to test the pulses from the films of anthracene and terphenyl, a light-tight chamber was constructed within which was mounted a movable alpha source. It was thus possible to have any desired fraction of the alpha range fall within the film.

Plate XV shows the pulses formed by a crystal of anthracene grown from a carbon disulphide solution. The crystal was much thicker than the equivalent range of polonium alpha particles in anthracene. Therefore, the pulses diminished in size as the source was moved farther from the crystal.

Plate XVI shows similar curves for a thin film produced by method 5. The thickness of this film as determined by weighing was 1.1 mg/cm$^2$. Assuming that 1.4 mg/cm$^2$ of anthracene is equivalent to 1 air cm, this corresponds to an equivalent range in air of approximately 0.8 cm. The pulse height does not decrease as the source is moved away from the film, showing that the film is much thinner than the range of the alpha particles (3.84 cm).

Very similar results were obtained using pure terphenyl in place of anthracene, but the plastic phosphor gave a much smaller pulse. The pulses produced in the plastic phosphor are roughly one-half the size of those produced in anthracene or terphenyl for the same energy of alpha particles.

From the pulse heights observed for a thick section of anthracene, Plate XV, it is possible to plot the response of anthracene to alpha particles in the energy range 0.5 to 5.0 MEV. Taylor et al have published a response curve for alpha particles of energies from 2 MEV to 20 MEV. The
PLATE XVI

RESPONSE OF A THIN SECTION OF ANTHRACENE TO ALPHA PARTICLES OF DIFFERENT ENERGIES

PULSE HEIGHT \(\rightarrow\) CONSTANT FOR DIFFERENT ALPHA PARTICLE ENERGIES
insert in Plate XVII shows this curve. The results obtained in this experiment are plotted and fitted to this curve at 4 MEV (Plate XVII), and are seen to be a smooth continuation of the results obtained by Taylor et al.²⁶
RESPONSE OF ANTHRACENE TO ALPHA PARTICLES

PLATE XVII
V. CONCLUSIONS

From the preceding section, it is concluded that a satisfactory and relatively simple method of producing thin scintillation films of anthracene has been developed. The response of these films to alpha particles of varying energy agrees well with the exciton theory of Birks (see Appendix IV). Assuming that this theory correctly predicts the response of these films to protons, it would appear difficult to discriminate between protons and alpha particles in organic phosphors on the basis of pulse size alone. As soon as a resolved beam of protons is available from the Van de Graaff generator, the response of these films to protons will be checked.

If it proves impossible to discriminate between protons and alpha particles on pulse size alone, it will be necessary to decrease the resolving time of the coincidence mixer to about $5 \times 10^{-10}$ seconds. The Garwin circuit is probably not capable of such a short resolving time, but a suitable coincidence circuit for this work is being developed by Dr. D. B. James.
PART B - ANGULAR DISTRIBUTIONS FOR GROUND-STATE ALPHA PARTICLES FROM $N^{15}(p\alpha)c^{12}$ REACTION

I. INTRODUCTION

In view of the power of the angular distribution and correlation method, it is natural to look at the analogous set of reactions for the proton bombardment of $N^{15}$. These reactions are

- $N^{15}(p\alpha)c^{12}$ short range alpha particles
- $N^{15}(p\alpha)c^{12}$ long range alpha particles

The yield for the reactions $N^{15}(p\alpha)c^{12}$ and $N^{15}(p\alpha)c^{12}$ has been measured up to a proton energy of 1.2 MEV, resonance states of the $C^{16}$ compound nucleus occurring at proton energies of 0.9, 1.0, 1.2 MEV\(^{10}\). For the resonance at 1.2 MEV, both states of $C^{12}$ can result, the cross-section being 0.6 and 0.2 barn for the reaction leading to ground and excited states of $C^{12}$ respectively. The gamma ray transition energy is 4.465 MEV. Wilkinson reports an energy of 4.465 ± .04 MEV and a high order of anisotropy of order 1 + 0.3 cos\(^2\theta\) near the 900 KEV level.

In order to assign the angular momentum and parity of the 4.465 MEV state of $C^{12}$, the angular distribution of the gamma rays with respect to the proton beam is insufficient by itself. A knowledge of the parity and angular momentum of the $C^{16}$ excited state could be determined by the $N^{15}(p\alpha)c^{12}$ reaction, and would probably enable an unambiguous assignment of quantum numbers to all states involved. If necessary further knowledge could be obtained by examining the alpha gamma angular correlation.
II. THEORY

A. GENERAL PRINCIPLES OF TWO-STAGE PROCESSES

Reduced to its simplest terms, the two-stage process is essentially a fluorescence problem. In fluorescence, light of one wave-length is absorbed by a system and the capture cross section of atoms for radiation is largest when the total energy corresponds to a stationary state of the system. Subsequently, some other light is emitted. The dispersion of light is described in roughly the same terms. The essential form of the differential cross section in the analogous case where a heavy particle (proton) is absorbed and a heavy particle (ex. alpha particle) is emitted is given as

\[ \mathcal{G}(\theta, \phi) = \frac{1}{\pi} \sum_{J_z} \sum_{J_z'} \left[ \sum_{P, P'} C_{P, P'}(J, J_z, J_z') \right] \left( \frac{E - E_r}{E - E_r + \frac{1}{2} l} \right) \left( \frac{J_r, J_z, l, j, j'}{J'} \right) \left( \frac{Y_{l, j}^{\ell}}{Y_{l, j'}^{\ell'}} \theta, \phi \right) \]

In this formula \( g_\ell(E) \) and \( g_{\ell'}(E') \) represent slowly varying functions of energy and serve as parameters when one compares theory with experiment. They represent something like intrinsic probabilities of reaction once one has brought the nuclei together. \( P \) and \( P' \) are barrier penetrabilities for the incident and emitted particles, respectively. The subscript \( r \) refers to the various resonances and the \( Y_{l, j}^{\ell} \) refers to the associated Legendre polynomials.

- \( \ell \): orbital angular momentum of incident particle
- \( \ell_z \): Z-component of \( \ell \), and is zero because of the choice of Z-axis
- \( j \): total spin angular momentum of incident particle and target nucleus
- \( J_z \): Z-component of \( J \)
- \( J \): total angular momentum of compound nucleus
\[ J_z \]  
Z-component of \( \mathbf{J} \)

\( \ell' \) and \( \ell'_z \)  
are the orbital angular momentum and its z-component for the emitted particle

\( j' \) and \( j'_z \)  
are the spin angular momentum and its z-component of the resultant particles

The transformation coefficients \( \langle \ell\ell'_z j j'_z | J_{\ell} \rangle \) are listed in Condon and Shortley, pages 73-78. Since conservation of angular momentum holds in these problems

\[ |\ell - j| \leq J \leq (\ell + j) \]

\[ J_z = j'_z \text{ since } \ell'_z = 0 \]

All possible angular distributions up to \( J \) equals \( h \) for the compound nucleus have been worked out and are listed in the section below.

**B. CALCULATED ANGULAR DISTRIBUTION FOR THE GROUND-STATE ALPHA PARTICLE IN THE \( N^{15}(p \alpha)C^{12} \) REACTION**

The distribution has been calculated assuming five overlapping excited states in \( 0^{16} \) with spins of \( 0^+, 1^-, 2^+, 3^-, 4^+ \) where the signs indicate the parity of the state (\(-\), odd parity, \(+\) even parity).

The following assumptions following earlier experimental results were made

(a) \( N^{15} \) has a spin of \( \frac{1}{2} \) and odd parity, and

(b) \( C^{12} \) has a spin of \( 0^\prime \) and even parity.

Therefore, \( C^{12} + \infty \) has a spin of \( 0 \) and even parity.

All possible proton and alpha particle angular momenta which are consistent with the above assignment to the \( 0^{16} \) compound nuclear states have been included. In order that unknown nuclear factors, ex. penetrability, resonance denominators, can be allowed for, each alpha particle has associated with it a separate amplitude and phase factor of the form \( A e^{ia} \), where "A" is the amplitude and "a" is the phase angle.
Including total angular momentum of the compound nucleus up to \( \hbar \), there are nine ways in which the reaction can take place. These are listed below.

<table>
<thead>
<tr>
<th>No</th>
<th>Total Spin of ( \text{N}^{15} + p )</th>
<th>( L_p )</th>
<th>( \text{C}^{16} )</th>
<th>( \text{C}^{12} + \alpha )</th>
<th>Amplitude and Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( 1 )</td>
<td>( 1 )</td>
<td>( 0^+ )</td>
<td>( 0 )</td>
<td>( 0 )</td>
</tr>
<tr>
<td>2</td>
<td>( 1 )</td>
<td>( 0 )</td>
<td>( 1^- )</td>
<td>( 1 )</td>
<td>( 0 )</td>
</tr>
<tr>
<td>3</td>
<td>( 1 )</td>
<td>( 2 )</td>
<td>( 1^- )</td>
<td>( 1 )</td>
<td>( 0 )</td>
</tr>
<tr>
<td>4</td>
<td>( 1 )</td>
<td>( 1 )</td>
<td>( 2^+ )</td>
<td>( 2 )</td>
<td>( 0 )</td>
</tr>
<tr>
<td>5</td>
<td>( 1 )</td>
<td>( 3 )</td>
<td>( 2^+ )</td>
<td>( 2 )</td>
<td>( 0 )</td>
</tr>
<tr>
<td>6</td>
<td>( 1 )</td>
<td>( 2 )</td>
<td>( 3^- )</td>
<td>( 3 )</td>
<td>( 0 )</td>
</tr>
<tr>
<td>7</td>
<td>( 1 )</td>
<td>( 4 )</td>
<td>( 3^- )</td>
<td>( 3 )</td>
<td>( 0 )</td>
</tr>
<tr>
<td>8</td>
<td>( 1 )</td>
<td>( 3 )</td>
<td>( 4^+ )</td>
<td>( 4 )</td>
<td>( 0 )</td>
</tr>
<tr>
<td>9</td>
<td>( 1 )</td>
<td>( 5 )</td>
<td>( 4^+ )</td>
<td>( 4 )</td>
<td>( 0 )</td>
</tr>
</tbody>
</table>

Any combination of the five states of the \( \text{O}^{16} \) compound nucleus can be taken by collecting those terms which contain the amplitude and phase factors corresponding to them. Ex: Assuming \( \text{C}^{16} \) to have two overlapping levels of \( (0^+) \) and \( (3^-) \), the following terms must be collected:

\[
A^2 + F^2 + G^2 + A\cos(a-f) + A\cos(a-g) + F\cos(f-g)
\]

Essentially, this is a procedure whereby the amplitudes of the unwanted states are put equal to zero.

The angular distributions of ground-state alpha particles from the \( \text{N}^{15}(p\alpha)\text{C}^{12} \) reaction are thus as follows. The abbreviation \( c^n = \cos^n \) is used throughout.

\( \text{O}^{16} \) Spin States

\begin{tabular}{c|c|c}
Involved & Angular Distribution & \\
(0+) & \( 1/6 A^2 \) & \\
\end{tabular}
<table>
<thead>
<tr>
<th>Spin States Involved</th>
<th>Angular Distribution (Cont'd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1-)(1-)</td>
<td></td>
</tr>
<tr>
<td>3/2B^2</td>
<td></td>
</tr>
<tr>
<td>3/20Y^2(1+3c^2)</td>
<td></td>
</tr>
<tr>
<td>3/4 \sqrt{2/5} BY\cos(b-y)(1-3c^2)</td>
<td></td>
</tr>
<tr>
<td>(2+)(2+)</td>
<td></td>
</tr>
<tr>
<td>5/12 D^2(1+3c^2)</td>
<td></td>
</tr>
<tr>
<td>15/56 E^2(1-2c^2+5c^4)</td>
<td></td>
</tr>
<tr>
<td>5/8 \sqrt{2/7} DE \cos(d-e)(-1+12c^2-15c^4)</td>
<td></td>
</tr>
<tr>
<td>(3-)(3-)</td>
<td></td>
</tr>
<tr>
<td>21/40 F^2(1-2c^2+5c^4)</td>
<td></td>
</tr>
<tr>
<td>7/288 G^2(9+45c^2-165c^4+175c^6)</td>
<td></td>
</tr>
<tr>
<td>7/16 1/\sqrt{15} FG\cos(f-g)(3-69c^2+225c^4-175c^6)</td>
<td></td>
</tr>
<tr>
<td>(4+)(4+)</td>
<td></td>
</tr>
<tr>
<td>9/224 H^2(9+45c^2-165c^4+175c^6)</td>
<td></td>
</tr>
<tr>
<td>145/110 K^2(9+36c^2+294c^4-64c^6+144c^8)</td>
<td></td>
</tr>
<tr>
<td>9/64 \sqrt{3/77} HK\cos(h-k)(-9+360c^2-2130c^4+3920c^6-2205c^8)</td>
<td></td>
</tr>
<tr>
<td>(0+)(1-)</td>
<td></td>
</tr>
<tr>
<td>3/2 A\cos(a-b)(-c)</td>
<td></td>
</tr>
<tr>
<td>1/10 AY\cos(a-y)(+c)</td>
<td></td>
</tr>
<tr>
<td>(0+)(2+)</td>
<td></td>
</tr>
<tr>
<td>1/6 \sqrt{5/2} AD\cos(a-d)(1-3c^2)</td>
<td></td>
</tr>
<tr>
<td>1/4 \sqrt{5/7} AE\cos(a-e)(-1+3c^2)</td>
<td></td>
</tr>
<tr>
<td>(0+)(3-)</td>
<td></td>
</tr>
<tr>
<td>1/4 \sqrt{7/5} AF\cos(a-f)(3c-5c^3)</td>
<td></td>
</tr>
<tr>
<td>3/8 \sqrt{7/27} AG\cos(a-g)(-3+5c^3)</td>
<td></td>
</tr>
<tr>
<td>(0+)(4+)</td>
<td></td>
</tr>
<tr>
<td>3/16 \sqrt{1/21} AH\cos(a-h)(-3+30c^2-35c^4)</td>
<td></td>
</tr>
<tr>
<td>(1-)(2+)</td>
<td></td>
</tr>
<tr>
<td>3/16 \sqrt{7/33} AK\cos(a-k)(3-30c^2+35c^4)</td>
<td></td>
</tr>
<tr>
<td>1/2 \sqrt{10} BD\cos(b-d)(c)</td>
<td></td>
</tr>
<tr>
<td>1/4 \sqrt{15/7} BE\cos(b-e)(3c-5c^3)</td>
<td></td>
</tr>
<tr>
<td>1/4 YD\cos(y-d)(5c-9c^3)</td>
<td></td>
</tr>
<tr>
<td>3/\sqrt{11} YE\cos(y-e)(c^3)</td>
<td></td>
</tr>
</tbody>
</table>
Spin States Involved

Angular Distribution (Cont'd)

(1-)(3-)

\( \frac{1}{4} \sqrt{63/8} \sin(b-f) (-1 + 3c^2) \)
\( 1/2 \sqrt{3/5} \sin(b-g) (-3 + 30c^2 - 35c^4) \)
\( 3/40 \sqrt{1/4} \sin(y-f) (-1 + 12c^2 - 15c^4) \)
\( 1/16 \sqrt{1/4} \sin(y-g) (-3 - 6c^2 + 25c^4) \)

(1-)(4+)

\( 3/2 \sqrt{3/7} \sin(b-h) (-3c + 5c^3) \)
\( 3/16 \sqrt{15/11} \sin(b-k) (-15c + 70c^3 - 63c^5) \)
\( 3/16 \sqrt{6/35} \sin(y-h) (-21c + 110c^3 - 105c^5) \)
\( 3/16 \sqrt{6/11} \sin(y-k) (-3c - 10c^3 + 21c^5) \)

(2+)(3-)

\( \frac{1}{2} \sqrt{11/4} \sin(d-f) (c^3) \)
\( 1/48 \sqrt{70/3} \sin(d-g) (-21c + 110c^3 - 105c^5) \)
\( 3/8 \sin(e-f) (-5c + 26c^3 - 25c^5) \)
\( 1/8 \sqrt{5/3} \sin(e-g) (3c - 10c^3 + 15c^5) \)

(2+)(4+)

\( 1/16 \sqrt{30/7} \sin(d-h) (-3 - 6c^2 + 25c^4) \)
\( 5/32 \sqrt{6/11} \sin(d-k) (3 - 75c^2 + 215c^4 - 189c^6) \)
\( 3/112 \sqrt{15} \sin(e-h) (-69c^2 + 225c^4 - 175c^6) \)
\( 15/32 \sqrt{3/77} \sin(e-k) (-3 + 15c^2 - 45c^4 + 9c^6) \)

(3-)(4+)

\( 3/16 \sqrt{3/5} \sin(f-h) (3c - 10c^3 + 30c^5) \)
\( 3/32 \sqrt{21/11} \sin(f-k) (21c - 205c^3 + 453c^5 - 315c^7) \)
\( 1/32 \sin(g-h) (81c - 795c^3 + 1775c^5 - 1225c^7) \)
\( 1/16 \sqrt{5/11} \sin(g-k) (30c^3 - 85c^5 + 70c^7) \)
BALL BEARING STOP

ROTATING ARM

- COUNTER ADJUSTMENT

THIN WINDOW, SCATTERING CHAMBER

PLATE XVIII
III. DESCRIPTION OF APPARATUS

A. REACTION CHAMBER

Calculations (see Appendix V) show that the range of the alpha particles at $180^\circ$ to the beam direction in the laboratory system of coordinates would have a range of only 2.3 cm in air. The chamber shown in Plate XVIII was constructed with 21 windows all of which have an equivalent air range of less than 1.56 cm. The windows on one side of the chamber are $10^\circ$ apart, while the three on the other for monitoring purposes are placed at $40^\circ$, $90^\circ$ and $130^\circ$, respectively. The proportional counter can be accurately moved from window to window by a calibrated arm with a ball-bearing stop every $10^\circ$. The counter can be moved towards or away from the target by means of a screw.

B. COUNTER AND AUXILIARY APPARATUS

A proportional counter is used to distinguish between alpha pulses and any other pulses from other sources.

The counter is shown in Plate XVIII. A very thin window is the main feature of the proportional counter (0.5 cm air equivalent). At $180^\circ$ the alpha particle will thus expend $0.4 \cdot \text{MEV} (2.30 - 2.06 = 0.24 \text{ cm})$ in the counter, which is sufficient to give a good-sized pulse.

The necessary electronic circuits have been constructed and tested and have been found to be satisfactory. An auxiliary reaction chamber has been constructed for the measurement of the gamma ray angular distribution.
All tests of equipment indicate that the experiment is feasible and completion of the experiment awaits a stable resolved beam from the Van de Graaff generator.
APPENDIX I

SAMPLE CALCULATION

The experimental extrapolated range for air corresponded to a reading of 3.712 cm on the micrometer. To find the actual distance from the origin, the known value of the extrapolated range for air at 15°C and 760 mm, i.e. 3.897 cm, was used. Now, not all of the 3.897 cm is in air. The aluminum window has an air equivalent of .968 cm, therefore, the actual range in air is 3.897 - .968 = 2.929 cm from the origin, if the experimental range was at 15°C and 760 mm mercury. But since the experimental temperature and pressure differed from these values, a correction is necessary to make the two identical.

\[ R' = \frac{R_o P_o T}{P T_0} \]

\[ R' = 2.929 \times \frac{760 \times 297}{758.2 \times 288} = 3.026 \text{ cm} \]

Therefore, a reading of 3.712 cm on the micrometer corresponds to an actual distance of 3.026. The micrometer correction is then

\[ 3.712 - 3.026 = .686 \text{ cm} \]

For argon, which was found to have an uncorrected extrapolated range corresponding to a distance of 4.003 cm on the micrometer, the following corrections are applied.

1. Micrometer Correction

\[ R' = 4.003 - .686 = 3.317 \text{ cm} \]
2. Temperature and Pressure Correction

\[ R_0 = \frac{R^{P,T}_0}{P_0} = 3.317 \times 0.968 = 3.210 \]

3. Chamber Depth Correction

Since the signal-to-noise ratio is greater for argon than for air, the alpha particle will not have to penetrate the chamber as far to produce the same size pulse in argon as in air. This means that the origin from which we measured the air range will have shifted toward the front of the chamber for argon. In order to have the origin the same, we must subtract the difference in chamber penetration from the observed argon range.

Experimentally, the signal-to-noise ratio for air at the maximum of the Bragg curve was 6 (see Plate VIII). Since the maximum specific ionization is approximately 6000 ion pairs per mm, a chamber depth of 3 mm would correspond to a total of 18,000 ion pairs formed. If the signal-to-noise ratio is 6, then \( \frac{1}{6} \times 18,000 \) or 3000 ion pairs are required before a pulse is recorded. By numerical integration of the specific ionization curve for a single alpha particle, the penetration required to produce 3000 ion pairs was found to be 1.25 mm.

For argon, the signal-to-noise ratio was found to be approximately \( 8 \frac{1}{3} \). Therefore, \( \frac{25}{18} \) times as many ions were formed by argon in the 3 mm as were formed from air. If the relative ionization is constant over all energies for air to argon, one would assume that the penetration would be given by \( \frac{18}{25} \) of the value found for air.

\[ \frac{18}{25} \times 1.25 = 0.90 \text{ mm} \]

The correction is, therefore, 1.25 - 0.90 = 0.35 mm, which is subtracted from 3.210 to give a corrected extrapolated range of 3.175.

The mean ranges are now easily found from the graph by subtracting
the observed straggling parameter, \( S = R_{\text{ex}} - R_m \), from the corrected extrapolated range.

\[
\begin{align*}
\text{Mean Range in Air} & = 2.929 - .087 = 2.842 \\
\text{Mean Range in Argon} & = 3.175 - .108 = 3.067
\end{align*}
\]

Therefore, the stopping power of argon is given by

\[
\frac{R_m \text{ air}}{R_m \text{ argon}} = \frac{2.842}{3.067} = .927
\]
RUTHERFORD SCATTERING OF PROTONS — PLATE.

LOG (N₀) — FOR ONE PERCENT OF A UNIT SOLID ANGLE 1 µAMP OF PROTONS INCIDENT ON TARGET.

LOG (N₀) — FOR A PROTON BEAM OF \( \frac{1}{100} \) µAMP.

RUTHERFORD SCATTERING OF PROTONS — PLATE XIX.
APPENDIX II

Number of Scattered Protons as a Function of Energy and Angle

Plate XIX shows the family of curves obtained when the number of protons scattered at various angles is plotted against the energy of the incident protons.

The curves were calculated from the Rutherford scattering formula.

\[ N(\theta) = \frac{1}{4}N_0N_t\left(\frac{e^2ZZ'}{mv^2}\right)^2 \frac{1}{\sin^2\theta/2} \]

- \( N_0 \) = number of incident particles per second
- \( N \) = number of atoms/cc in target
- \( t \) = target thickness cm
- \( e \) = electronic charge
- \( Z \) = charge on incident particle
- \( Z' \) = atomic number of target
- \( \frac{1}{2}mv^2 \) = energy of the incident particle

The curves were calculated for an aluminum target of 2 mm air equivalent thickness. Clearly the number of scattered protons could be further reduced by using a thinner target of low atomic number. Thin films of collodion or formar would reduce the number of scattered protons.
APPENDIX III

Ratio of True to Chance Coincidences for the $^{19}(p\alpha \chi)_{0}^{16}$ Angular Correlation Experiment

The number of true coincidences is given by

$$N_T = k N_0 \xi_1 \xi_2 \eta_1 \eta_2$$

where $k =$ probability that the incident particle shall produce the required reaction, and

- $N_0 =$ number of incident particles per second
- $\xi_1, \xi_2 =$ the efficiencies of two counters
- $\eta_1, \eta_2 =$ the solid angle subtended by the counters

The number of chance counts is given by

$$N_c = 2 N_1 N_2 \tau$$

$\tau$ is the resolving time in seconds, $N_1$ and $N_2$ are the single channel counting rates. If $N_1$ refers to the alpha counter, then the scattered protons will determine the counting rate in that channel because their number far exceeds the number of alpha particles in the reaction.

- $N_1 = N_0 X$, where $X$ is the Rutherford scattering probability
- $N_2 = k N_0 \xi_2 \eta_2$

then the ratio of true coincidences to chance coincidences is

$$R = \frac{k N_0 \xi_1 \xi_2 \eta_1 \eta_2}{2 N_1 N_2 \tau} = \frac{1}{2 N_0 X \tau}$$

For the experiment to be feasible, $R$ should not be less than unity.

If we substitute the following numerical values
\[ k = 10^{-7}, \quad N_0 = 6 \times 10^{12}/\text{sec} = 1 \text{ microamp of beam} \quad \xi_1 = 1, \]

\[ \xi_2 = 0.25, \quad \gamma_1 = \gamma_2 = 10^{-2}, \quad \text{and} \quad N_1 = 10^7/\text{sec}, \]

we obtain \[ \tau = 5 \times 10^{-10} \text{ sec}. \]

The value of \( N_1 \) above was calculated for 2 mm air equivalent thickness of aluminum. By substituting a thinner hydrocarbon film, \( N_1 \) can be reduced by a factor of 100 without too much difficulty. Then the required resolving time is \[ \tau = 5 \times 10^{-8} \] which is easily obtainable.
PLATE XX RELATIVE RESPONSE OF ANTHRACENE TO ALPHA PARTICLES AND PROTONS FOR DIFFERENT FILM THICKNESSES
APPENDIX IV

Exciton Theory

The variation of $\frac{dL}{dx}$ (specific fluorescence) with $(-\frac{dE}{dx})$ (specific energy loss) may be explained using the exciton theory\textsuperscript{25}. On this theory, the electronic energy excited by the ionizing particle (the exciton) is transferred from molecule to molecule within the crystal, until it is either emitted as radiation or quenched by a damaged molecule.

If the number of excitons produced per unit path length is $A\frac{dE}{dr}$ and the local concentration of damaged molecules is $B\frac{dE}{dx}$ molecules per undamaged molecule and the exciton capture probability of a damage molecule relative to an undamaged molecule is $k$, then the specific fluorescence is

$$\frac{dL}{dx} = \frac{A\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}$$

The values for anthracene are $A = 82.5$ and $kB = 7.15$, as calculated from the experimental data on alpha particles.

In Plate XX, the ratio of the specific fluorescence of alpha particles to the specific fluorescence of protons is plotted against proton energy for films of different thickness. The incident alpha particle energy is assumed to be 2 MEV.
PLATE XXI

RANGE OF GROUND-STATE ALPHA PARTICLES FROM $N^{15}(p \alpha)C^{12}$ IN LAB. COORDINATES AS A FUNCTION OF $\Theta$ AND PROTON ENERGY

---

$N^{15}$ ALPHA PARTICLE RANGE

SCATTERED PROTON RANGE
APPENDIX V

Alpha particle ranges from the $^\text{15}_\text{N}(p \alpha)^\text{12}_\text{C}$ reaction as a function of $\phi$ (lab coordinates) and proton energy have been calculated from the general formula

$$M_{E/2} = \left(\frac{M_1 M_2}{M}\right)^{1/2} E_1^{1/2} \cos \phi + (M_2 Q + M_0 M_3 E_3 - M_1 M_2 E_1 \sin^2 \phi)^{1/2}$$

The subscript 0 refers to the target nucleus, 1 to the incident particle, 2 to the emitted particle, and 3 to the residual nucleus. $M_0, \ldots, M_3$ are the masses of the four nuclei, and $M$ the mass of the compound nucleus. $E_0, \ldots, E_3$ are the kinetic energies of the particles.

Plate XXI shows the scattered proton range at $\phi = 0$ as a function of energy.
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<th>Journal</th>
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ABSTRACT

The stopping powers of hydrogen and deuterium have been compared, using a thin ionization chamber. The results were found to be consistent with the present-day theory on the method of energy loss.

A method for the preparation of thin films of organic phosphors has been devised and the response of these films to alpha particles has been tested.

All necessary apparatus for the study of angular correlation and distribution patterns for $^1H(p, \gamma) ^{16}O$ and $N^{15}(p, \alpha) C^{12}$ reactions has been constructed. The theoretical angular distribution patterns for the $N^{15}(p, \alpha) C^{12}$ reaction have been calculated.