THE CONSTRUCTION OF A LOW VOLTAGE ION ACCELERATOR
FOR THE GENERATION OF NEUTRONS AND THE STUDY OF THE
DEUTERON ON DEUTERON REACTIONS AT LOW BOMBARDING ENERGIES

by

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A thesis submitted in partial fulfilment of
the requirements for the degree of
MASTER OF APPLIED SCIENCE
in the Department
of
PHYSICS

We accept this thesis as conforming to the standard
required from candidates for the degree of Master of Arts.

Members of the Department of Physics

The University of British Columbia

April, 1951
ABSTRACT

An ion accelerator has been constructed which is capable of accelerating very intense monoenergetic beams of protons or deuterons up to 50 KEV energy. Total ion currents of 500μ amps containing 30 to 40% atomic ions have been obtained. The intensity and high definition of the beam makes it possible to collimate after magnetic analysis, 50μ amps of protons or deuterons at 30 KEV energy into a 1/16 inch diameter spot on a target. This deuteron beam incident on a heavy ice target is capable of producing a neutron flux of $3 \times 10^8$ neutrons/sec from the "D on D" reaction at 50 KEV bombarding energy or the equivalent of the neutrons from 20 curies of radium used in a Ra-Be source.

The intrinsic interest of the D-D reactions to nuclear physics had prompted the construction of a scattering chamber to be used in conjunction with the accelerator. An experimental arrangement has been designed and constructed for the measurement of the energy dependent characteristics of the companion reactions, $D(d,n)He^3$ and $D(d,p)H^3$, which has a potential accuracy considerably greater than previously reported. As well, the extension of studies to much lower energies has been made possible by the large ion currents available.
ACKNOWLEDGEMENTS

This work was carried out under Consolidated grants from the National Research Council of Canada.

The author is pleased to express his gratitude to Dr. J.B. Warren under whose supervision the major part of this work was carried out and to Dr. K.R. More for assistance in the original planning of the project. An expression of thanks is also due other members of the staff, particularly Dr. C.A. Barnes, Mr. S.B. Woods and Mr. S.A. Heiberg for many helpful suggestions.

Also, the author wishes to acknowledge the work of Mr. A.J. Fraser of the machine shop staff, Mr. A. Salonen and Mr. J.L. Lees for their assistance in the construction of the apparatus.
# INDEX

I. INTRODUCTION

A. Object.............................................................. 1
B. Laboratory Sources of Neutrons................................. 1

II. CONSTRUCTION, DESCRIPTION AND PERFORMANCE OF THE LOW VOLTAGE ION ACCELERATOR

A. The Vacuum System.................................................. 5
B. The Ion Sources..................................................... 5
C. The Discharge Tube.................................................. 7
D. Extraction of Ions................................................... 10
E. The Discharge Gas Supply.......................................... 13
F. The Beam Focussing System........................................ 14
G. The Magnetic Analyzer............................................. 18
H. Overall Performance of Ion Accelerator and Magnetic Analyzer........................................ 21

III. THE STUDY OF THE DEUTERON ON DEUTERON REACTIONS AT LOW BOMBARDING ENERGIES

A. Theoretical Discussion of the "D on D" Reaction.................. 25
B. Discussion of Previous Work....................................... 31
C. Proposed Experiment
   1. Experimental Method........................................... 35
   2. The Scattering Chamber......................................... 37
   3. The Counters and Target...................................... 38
   4. Counter and Current Measuring Equipment..................... 40

IV. CONCLUSIONS.......................................................... 42

BIBLIOGRAPHY.................................................................. 44

APPENDIX

I. Calculation of Particle Energies as a Function of the Angle of Emission........... 46
II. Hε, mass dispersion and energy resolution calculations.................................. 49
III. Magnet Design.......................................................... 52
IV. Table of Neutron Energies from Photo-Neutron Sources.................................. 53
V. Calibration of the High Voltage Resistance Stack......................................... 53
<table>
<thead>
<tr>
<th>Plate</th>
<th>Description</th>
<th>Facing page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Energy Distribution of Neutrons from a typical photo-neutron source.</td>
<td>2</td>
</tr>
<tr>
<td>II</td>
<td>Proton Yield per μ-Coulomb of Incident Deuterons</td>
<td>3</td>
</tr>
<tr>
<td>III</td>
<td>D-D Neutron Spectrum at Different Angles and Energies</td>
<td>3</td>
</tr>
<tr>
<td>IV</td>
<td>Ion Source and Palladium Leak</td>
<td>7</td>
</tr>
<tr>
<td>V</td>
<td>Circuit Diagram of High Frequency Oscillator</td>
<td>8</td>
</tr>
<tr>
<td>VI</td>
<td>Potential Distribution in Discharge Tube</td>
<td>10</td>
</tr>
<tr>
<td>VII</td>
<td>Circuit Diagram of Power Supplies</td>
<td>14</td>
</tr>
<tr>
<td>VIII</td>
<td>Space Charge Spreading of Ion Beam</td>
<td>18</td>
</tr>
<tr>
<td>IX</td>
<td>Assembly of Magnet</td>
<td>20</td>
</tr>
<tr>
<td>X</td>
<td>Hysteresis Loop of Magnet</td>
<td>21</td>
</tr>
<tr>
<td>XI</td>
<td>Assembly of Magnet Chamber and Slit</td>
<td>22</td>
</tr>
<tr>
<td>XII</td>
<td>Analysis of the Ion Beam</td>
<td>23</td>
</tr>
<tr>
<td>XIII</td>
<td>Angular Distribution of Protons at 50 KEV in the centre of mass system</td>
<td>25</td>
</tr>
<tr>
<td>XIV</td>
<td>The Asymmetry Coefficient as a Function of Energy</td>
<td>25</td>
</tr>
<tr>
<td>XV</td>
<td>D-D Cross-Section for Proton Emission</td>
<td>26</td>
</tr>
<tr>
<td>XVI</td>
<td>Diagrammatic Top View of Scattering Chamber</td>
<td>31</td>
</tr>
<tr>
<td>XVII</td>
<td>Target Scheme used by T.P. Pepper</td>
<td>32</td>
</tr>
<tr>
<td>XVIII</td>
<td>Triton and He³ pulse distribution</td>
<td>32</td>
</tr>
<tr>
<td>XIX</td>
<td>Ratios of the Cross-sections of the D(d,n)He³ and D(d,p)H³ Reactions as a Function of Energy.</td>
<td>33</td>
</tr>
<tr>
<td>XX</td>
<td>Pulse Counting Rate as a Function of Energy</td>
<td>36</td>
</tr>
<tr>
<td>XXI</td>
<td>Pulse Amplitude Distribution from CdS Phosphor irradiated with Polonium alpha particles.</td>
<td>36</td>
</tr>
<tr>
<td>XXII</td>
<td>Schematic Counting Arrangement</td>
<td>37</td>
</tr>
<tr>
<td>Plate</td>
<td>Description</td>
<td>Facing Page</td>
</tr>
<tr>
<td>-------</td>
<td>--------------------------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>XXIII.</td>
<td>Assembly of Scattering Chamber</td>
<td>38</td>
</tr>
<tr>
<td>XXIV.</td>
<td>Detail of Target Mount</td>
<td>39</td>
</tr>
<tr>
<td>XXV.</td>
<td>Front View of Assembled Apparatus</td>
<td>42</td>
</tr>
<tr>
<td>XXVI.</td>
<td>Side View of Assembled Apparatus</td>
<td>43</td>
</tr>
</tbody>
</table>
THE CONSTRUCTION OF A LOW VOLTAGE ION ACCELERATOR FOR THE GENERATION OF NEUTRONS AND THE STUDY OF THE DEUTERON ON DEUTERON REACTIONS AT LOW BOMBARDING ENERGIES

I. INTRODUCTION

A. OBJECT

The experimental aim of this work has been to construct a low energy ion accelerator capable of accelerating an intense beam of ions up to about 50 KEV energy. The function of the accelerator is to provide a laboratory source of neutrons, variable in energy and intensity, using the $H^2$ on $H^2$ reaction. In addition to experiments involving neutrons, the characteristics of both this reaction and others at very low energies ($10-50$ KEV) is of considerable intrinsic interest so that a scattering chamber has been constructed for such measurements.

B. LABORATORY SOURCES OF NEUTRONS

A convenient but costly source of neutrons consists of an active alpha emitter, usually radium, mixed internally with beryllium. For many purposes its yield is inadequate as well as being uncontrollable. This type of source has been very useful as a standard of neutron flux ($1/2$ gram of Ra-Be
ENERGY DISTRIBUTION OF NEUTRONS FROM Mn-Be PHOTO-NEUTRON SOURCE

Plate I
giving about $6 \times 10^6$ neutrons/sec) but the exact value depends greatly on the fineness of the mixture. The neutron energy spectrum is broad since the alphas have a wide energy spread due to slowing down in the beryllium and as well, the emitted neutrons are moderated in the low mass beryllium matrix. The large penetrating background of $\gamma$-rays from the radium is also often objectionable, but can be avoided by use of a polonium alpha source. The latter has, however, a rather short half-life, (147 days).

With the advent of nuclear piles, it has been possible to make gamma emitting isotopes of very large activities. By making use of the photo-neutron ($\gamma, n$) reactions in $\text{H}_2$ (Threshold - 2.12 MEV) and $\text{Be}$ (Threshold - 1.63 MEV), "photo-neutron" sources have found application in the laboratory. $^{1,2}$ \text{Na}^{24} (E$_\gamma$ = 2.76 MEV), $\text{Sb}^{123}$ (E$_\gamma$ = 1.67 MEV), $\text{Mn}$ (E$_\gamma$ = 1.81 & 2.13 MEV) and $\text{In}$ (E$_\gamma$ = 1.8 & 2.08 MEV) gamma ray sources have been used. With a single energetic $\gamma$ above the photo-disintegration threshold and small amounts of $\text{H}_2$ or $\text{Be}$, the neutrons evolved are monoenergetic. The average yield for sources of this type is approximately $5 \times 10^4$ neutrons/sec/curie for 1 gm. of target material at 1 cm. The rather large amount of $\text{D}_2\text{O}$ or $\text{Be}$ necessary for efficient absorption of the $\gamma$-radiation also acts as a neutron moderator. Consequently, the resulting spectrum is usually broad (25% of the peak energy) as indicated by Plate I for a Mn-Be source. $^2$ The range of energies available is from 30 KEV to 1 MEV. (See also table of neutron energies from various reactions in
Plate II

Plate III

D-D NEUTRON SPECTRUM AT DIFFERENT ANGLES AND ENERGIES
Appendix IV).

The reaction $H^2(H^2,n)He^3$ (Don D) has been used extensively as a source of monoenergetic fast neutrons. Even with low energy incident deuterons, a large yield can be obtained so that a cheap, compact accelerator delivering only 50-100 KEV deuterons may be employed. With 50 KEV deuterons incident on a thick target of heavy ice, some $5 \times 10^4$ neutrons/sec. are emitted per micro-ampere of deuteron beam. (See Plate II. This excitation curve gives the yield of protons from the companion reaction $D(d,p)H^3$ which has approximately the same yield as the $D(d,n)H^3$. Thus the curve is applicable to neutron emission as well.) Thus this source will provide the equivalent of 5 curies of radium at 100 $\mu$a. of 50 KEV incident deuterons. The cost of the equivalent Ra-Be source would be approximately $100,000.

The energy of the neutrons varies with the incident energy and the angle of emission so that a narrow range of neutron energies is available. Table I below shows the angular variation of the neutron energies. A complete nomograph for the energy and angular dependance of neutron energies is given in reference 4. For a thick target, for any given angle of emission, there is a finite spread in neutron energies since the reactions arise from different deuteron energies due to slowing down of the beam in the target. Plate III shows the neutron spectrum for different angles of emission and incident energy. (See also appendix 1).
TABLE I

The reaction product energy in MEV as a function of the incident deuteron energy and the angle of emission.

<table>
<thead>
<tr>
<th>E_D KEV</th>
<th>E(180°)</th>
<th>E(0°)</th>
<th>E(180°)</th>
<th>E(0°)</th>
<th>E(180°)</th>
<th>E(0°)</th>
<th>E(180°)</th>
<th>E(0°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>2.20</td>
<td>2.81</td>
<td>.57</td>
<td>1.18</td>
<td>2.66</td>
<td>3.33</td>
<td>.741</td>
<td>1.40</td>
</tr>
<tr>
<td>50</td>
<td>2.25</td>
<td>2.76</td>
<td>.60</td>
<td>1.10</td>
<td>2.72</td>
<td>3.27</td>
<td>.781</td>
<td>1.33</td>
</tr>
<tr>
<td>20</td>
<td>2.34</td>
<td>2.66</td>
<td>.67</td>
<td>.99</td>
<td>2.82</td>
<td>3.16</td>
<td>.856</td>
<td>1.20</td>
</tr>
<tr>
<td>10</td>
<td>2.39</td>
<td>2.61</td>
<td>.71</td>
<td>.93</td>
<td>2.87</td>
<td>3.11</td>
<td>.898</td>
<td>1.14</td>
</tr>
</tbody>
</table>

Thus the "Don D" neutron source has many advantages over the aforementioned sources: an intense and completely variable source strength even at very low deuteron energies, "good" geometry (the well defined incident beam produces a point source at the target), very monoenergetic neutrons viewed at 90° to the low energy incident beam, and comparative inexpensiveness. Further, the companion reaction $H^2(d,p)H^3$ which has approximately the same reaction probability provides a very convenient method of monitoring the neutrons by means of counting the protons from this reaction.

A future alternative to the "Don D" reaction is the $H^3(d,n)He^4$ reaction as tritium becomes available. At low voltage and utilizing thick targets, this reaction provides an intense source of 14 MEV neutrons. The cross-section shows a resonance at 125 KEV with $\sigma_{TD}=30$ barns and at 50 KEV, the ratio of $\sigma_{TD}/\sigma_{DD} = 12$ barns/10^-2 barns $\approx 1,000$. 


II. CONSTRUCTION, DESCRIPTION AND PERFORMANCE

OF THE LOW VOLTAGE ION ACCELERATOR

A. THE VACUUM SYSTEM  (See Plate XXVI)

Vacuum is maintained in the system by means of a Distillation Products 275 l./sec oil diffusion pump backed by a Cenco Megavac mechanical pump. Pressures of $4 \times 10^{-5}$ mm. of mercury were obtainable at the inlet to diffusion pump with 25 microns in the discharge tube, as measured by a Pirani and an Ionization gauge. The inclusion of a liquid air trap now under construction will make possible lower pressures by preventing oil diffusing back into the system. The vacuum power system is protected for continuous and unattended operation. The diffusion pump has an automatic "switch off" by means of relays in case of water or power failure and a discharge mechanism which switches off pump in case of an accidental leak.

B. ION SOURCES

The choice of ion source was made on the basis of the following desirable characteristics: the highest possible ion current, a well focussed and monoenergetic beam, a high percentage of atomic ions, low gas consumption, low power consumption, high efficiency (Ions out/wattage input), low cost and ruggedness and long-life. Table II below shows the relative characteristics of various types of ion sources used by other workers.
<table>
<thead>
<tr>
<th>Type of Source</th>
<th>Canal Ray</th>
<th>Capillary Arc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&quot;Oliphant Source&quot;</td>
<td>Metal probe</td>
</tr>
<tr>
<td>Reference</td>
<td>Bouwers</td>
<td>Cragg</td>
</tr>
<tr>
<td>Pressure in Discharge (microns)</td>
<td>20</td>
<td>150</td>
</tr>
<tr>
<td>Power Input (watts)</td>
<td>2,000</td>
<td>400</td>
</tr>
<tr>
<td>Maximum Ion Current (micro-amps)</td>
<td>600</td>
<td>1800</td>
</tr>
<tr>
<td>Orifice size (mm. x mm.)</td>
<td>3 x 5</td>
<td>1.5x2.5</td>
</tr>
<tr>
<td>Percentage Atomic Ions</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Maximum Energy Spread e.v.</td>
<td>35,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Gas Consumption (c.c./min at 760 mm.)</td>
<td>3.5</td>
<td>6.5</td>
</tr>
</tbody>
</table>
ION SOURCE & PALLADIUM LEAK

Plate IV
It is clear from the table that the high frequency ion source approaches nearest to the desired characteristics. The successes of Rutherglen and Cole,\textsuperscript{11} Bayly and Ward,\textsuperscript{12} Thonemann et al\textsuperscript{13} and Hall\textsuperscript{14} in the development of the high frequency discharge ion source providing well-resolved ion beams of 500 \( \mu \) a. and containing atomic ion percentages up to 80\% of total ion current, prompted the choice of this type of source for the present research. The only disadvantages apparent are the large amount of auxiliary equipment with resultant increase in size and cost and the large power consumption. However, the latter presents no difficulty in a low voltage accelerator.

C. THE DISCHARGE TUBE (See Plate IV for construction and dimensions)

In all ion sources, the mode of ionization is the same. For example in hydrogen gas, free electrons are accelerated by a field, either D.C. or high frequency, and lose their energy in ionization by the following successive processes:

\[ \text{H}_2 \rightarrow \text{HH}^* \rightarrow \text{HH}^+ \rightarrow \text{H}^+\text{H}^+ \rightarrow \text{H}^+\text{H}^+ \]

The molecule is first ionized and then dissociated by further electron collisions. Thus the discharge will always contain a percentage of molecular ions through initial ionization or recombination. It is desirable that this percentage be kept to a minimum. Thus the first requisite is to provide a large enough H.F. voltage to give the electrons sufficient energy in one mean free path to complete dissociation. Secondly,
CIRCUIT DIAGRAM OF HF OSCILLATOR

Plate V
it is necessary to prevent recombination. The latter is achieved by:

1) A discharge tube of sufficiently large dimensions as compared to the mean free path at the tube pressure to prevent collisions with the walls.

2) Exclusion of contaminating gases, particularly air which even at low concentrations predominates in the discharge and quenches the hydrogen discharge.

3) Exclusion of all but necessary metal parts from the discharge tube.

4) Cleanliness of wall and electrode surfaces.

Pyrex has been found to be the most satisfactory material for discharge tubes as regards to recombination due to its low recombination coefficient. With quartz, the recombination probability is about six times as high, while for platinum surfaces, recombination is almost certain. For metal discharge tubes at normal power input, atomic ion percentages of 20-30% have been reported. At very high (pulsed) power inputs, these tubes have produced up to 80% atomic ions.

The discharge tube has been successfully excited by means of an oscillator-amplifier, with a 6V6 as oscillator tube and two 465-A tetrodes as amplifiers in a push-pull circuit (See Plate V). Operating frequency chosen is about 25 m.c./sec. Efficient coupling to the discharge tube (See Plate IV) has been achieved by winding the tank coil of five turns directly around the discharge tube, thus eliminating transformer coupling with its attendant matching problems. The tuning condenser is mounted
directly alongside tank coil to prevent large circulating currents in the connecting leads. Tests over a period of weeks have shown the oscillator to be very stable, since no adjustments whatever, to oscillator or tuning were required. There is some indication however that the tuning and thus the impedance of the discharge is pressure dependent as might be expected. The output of the oscillator is approximately 300 watts maximum at a peak high frequency voltage of about 1200 volts. Most of this power appears to be supplied to the excitation of the discharge since heating of coil, leads and glass envelope is found to be relatively small. These parts are air-cooled by a blower.

The colour of the discharge gives a good indication of the ion content and pressure in the tube. At high air pressures, the colour is a bricky orange which fades into a faint blue colour at low pressures. On introduction of hydrogen gas, the discharge becomes pink to rosy red depending on the degree of air and grease contamination. This red colour corresponds to the main hydrogen Balmer line and indicates a good percentage of atomic ions, H\(^+\). The red colour increases in intensity with time due to cleaning out of discharge tube, indicating an increase in the atomic ion percentage and reaches a stable condition after an hour or two of operation. At very high power input, the discharge becomes white due to outgassing of the envelope by energetic bombardment. This cleans out in time and red discharge gradually reappears. It has been possible with full power to excite sodium lines, presumably from overheated glass.
POTENTIAL DISTRIBUTION IN DISCHARGE TUBE

Plate VI
A characteristic of the discharge that is as yet not fully understood is the occasional starting trouble when the tube is hot. Since there is no trouble starting when the tube is cold, the effect is apparently temperature-pressure dependent. The increased temperature would tend to increase the pressure slightly, but due to the increased flow rate the total gas concentration would fall. Thus the probability of ionizing collisions would be reduced below that required for easy starting. If the tube is cooled the discharge recovers as would be expected on the above picture. Fortunately, at optimum pressure (20 to 30 microns) the effect is not observed.

D. EXTRACTION OF IONS

Extraction of ions is achieved by a D.C. voltage between the extractor and probe as in Plate IV. The potential distribution in the discharge takes the same general form as in a D.C. discharge. (See Plate VI). The high concentration of slowly moving ions near the cathode produces a virtual anode so that the main potential drop occurs in the last few mm. of path. Since most of the ions are produced in the main section of the tube, all ions obtain approximately the same energy. With 1200V on the probe, the energy spread in discharge has been calculated as < 100 volts on the basis of the beam spread after analysis.

The extracting cone was designed to provide a converging field towards the canal. (See Plate IV). The achievement of optimum current has required a long process of trial and error variation in the cone and tube geometry. The glass
sleeve covering the metal cathode serves to prevent recombination at the metal surface and sputtering of the metal. Also, due to the positive charge collected on its surface, it tends to shape the field in the region of the cathode, making it more convergent towards the cathode. It is found that if the sleeve is extended too far above the cathode, the ion current is reduced due to the deflection of the ions away from the canal. The focussing action of the inhomogeneous field due to the extractor geometry and the positive space charge can be understood by considering that the projecting cone and sleeve tend to form the positive space charge concave towards the canal. Since the ions in the space charge have a relatively small velocity, they will leave at right angles and follow the lines of force towards the canal opening. They attain enough velocity on reaching the defocussing field at the canal opening to be unaffected by it. The amount of current focussed into the canal will be strongly dependent on the position of the positive space charge with respect to the cone. Since this is in turn determined by the position of the main part of the discharge and therefore the oscillator coil, it was necessary to move the coil up and down for optimum current extracted. If coil is moved toward the cone from this position the current decreases rapidly while if moved away it decreases slowly with distance. This is in agreement with the assumed geometry of the space charge and the focussing field.

It was suggested that an axial magnetic field might increase the yield in two ways: firstly by increasing the charge
density by keeping the electrons moving along the field lines and secondly, due to the inhomogeneous field converging on the canal, tending to increase the concavity of the space charge sheath. The effect on the yield at the low (800 gauss) fields available has been found negligible. However, the original high frequency ion source constructed in this department by Woods, Chow and Kinnear, operating at a frequency of 250 mc/sec required fields of 300 gauss for optimum yields. The requirement of magnetic fields depends on the length of electron path before reversal, and thus the frequency used. It also depends slightly on the geometry of the extractor and the efficiency of the electrostatic focussing in the discharge. A field seems very useful at higher frequency excitation but unnecessary at 25 mc/sec.

Continuous operation of the discharge over a period of weeks results in the sputtering away of the cathode at the lip of canal and condensation on the lower glass surface. This condition may explain the fact that the total ion current available has decreased a little with time, although the atomic ion percentage has increased slightly. If this is determined to be the case, periodic disassembly and cleaning will be necessary.

Initial total extracted ion currents from hydrogen gas were measured in the first lens cylinder with a plug in the bottom (See Plate IV). The entrance is large enough to include the entire solid angle subtended by the canal. Reverse electron current was considered to be nil since there was a small positive potential between cup and extractor due to
potential drop in meter. The ion current was measured as a function of the probe voltage and probe current (as measured in the ground return of power supply, see Plate VII). The current was found to be an increasing function of the probe voltage up to the maximum voltage available. With a gas pressure of 25 microns at 3,000 volts on the probe, 7 m.a. probe current (this includes reverse electrons in discharge tube) an ion current of 500 μamps. was obtained through the canal of length 12 mm. and diameter .15 mm. Thus the extraction efficiency is approximately 15%. This might be improved by further alterations in tube geometry, but as compared to other sources reported, this is quite good.

At high extraction voltages (2500-3000 volts) a D.C. discharge is intermittently initiated due to high gas concentration near the anode. After outgassing for ten to fifteen minutes, the discharge returned to stability, although at all times a very small discharge is evident near the anode surface. A high impedance placed in the 3 KV lead to the probe was found to limit this discharge considerably.

E. THE DISCHARGE GAS SUPPLY

The gas flow rate into the system is determined by the pressure required in the discharge, the canal size, the maximum pressure allowable in the accelerator column and the pumping rate. With the present canal of dimensions, 15 mm. diameter and 12 mm. length, the flow rate at 20 microns tube
CIRCUIT DIAGRAM OF POWER SUPPLIES
pressure is .15 c.c./min of gas at atmospheric pressure. The pressure is not found to rise appreciably in the differential pumping tube until a tube pressure of 35 microns is reached. Further, measurement of the extracted beam without focussing showed it to lie mainly in the solid angle subtended by the canal so that scattering is apparently negligible in the accelerating column.

Gas has been supplied to the discharge either by means of the Palladium Leak (See Plate IV) or by means of a conventional capillary leak consisting of a pressed copper tube. Both have been successful in providing a stable, variable gas supply, although the former is most convenient. The deuterium gas used in the final tests was produced from heavy water in this laboratory by electrolysis. The apparatus is described fully in reference 44.

F. THE BEAM FOCUSSING SYSTEM (See Plate IV)

Focussing of the beam is achieved by two accelerating electrostatic cylindrical lenses. The first consists of the cylindrical protrudance of the extractor and the conical cylinder with a gap width of 1/8 inch. The second focussing gap is defined by two cylinders of equal diameter of 3/16 inch spacing. All surfaces subject to high field are highly polished and provided with corona rings. The first lens geometry indicates that it is only weakly focussing due to the difference in diameter of the two lenses and the shallowness of the extractor cylinder. The uniform geometry of the second lens indicates it to be a strong focussing lens.
The lens power supplies were designed so as to give large voltage ratios over a continuously variable range of total accelerating voltages. The maximum voltage ratings of the three power supplies are: Probe - 3KV, first lens - 18KV, second lens - 50KV. The desirability of having the beam emerge at ground potential prompted the mounting of the first two supplies on the 50 KV terminal. Thus the probe supply gives positive volts above 50 KV while the first lens supply gives negative volts below 50 KV. The 50 KV supply of course is positive for acceleration of positive ions from that voltage to ground. The arrangement is shown diagrammatically in Plate VII along with the circuit diagrams of the power supplies.

The 50KV supply is a commercial (Ferranti) oil-immersed, X-ray, half-wave rectifier set capable of supplying both positive and negative voltage. The filter is external and consists of 2 - 25KV, 1μ farad paper condensers with a 450 megohm bleeder across each. A high wattage resistor of 2 megohms is placed in series with high tension lead to limit sparking and to drop the voltage in case of accident. The resistance stack for voltage measurement consists of 6 - 10 megohm calibrated precision resistors (calibration is given in Appendix V), immersed in transformer oil to prevent corona. In series is a surge-protected milliammeter to ground as the voltage measuring instrument.

Since it is desirable, as pointed out above, that the beam emerge from accelerator at ground potential, it is necessary that the ion source, Pd leak, oscillator, power supplies and all their meters and accessories be mounted on the 50 KV terminal.
It was necessary, therefore, to include a 50 KV isolation transformer to supply 110 volts A.C. from the wall supply to these components. The power supplies, meters and controls are mounted at a high level in a wire cage (See Plate XXV) and manual operation of variacs is achieved by means of long textilite rods. All meters are protected against surge and high frequency currents by means of filters and neon tubes.

The probe voltage is supplied by a 3 KV, 15 m.a. full-wave rectifier set, the relatively high current rating being necessary to supply the probe current in the discharge.

The 18 KV supply consists of a Cockcroft-Walton voltage doubler circuit using selenium rectifiers and excited by a 6,500 KV, 56 m.a. transformer, the latter's high current rating due more to availability than design as the supply need only yield at most a milliamp to the 20 megohm bleeders. In the latter two supplies the voltage is again measured by the current through a calibrated bleeder.

As the lenses are mounted on glass spacers, observation of the ion beam was simple. The blue glow due to ionization of gas in the ion path was easily observed at all the lens gaps and at exit of accelerator. Focussing properties were also observed by allowing beam to strike an activated ZnS screen at bottom of accelerator although the latter's high activity to scattered particles led to rather misleading interpretation of beam dimensions.

The extracted beam with no focussing appeared to lie fairly well in the solid angle sustained by the canal although
the validity of this observation is limited by the light from the discharge. The first lens is found to be only weakly focusing resulting in an inability to focus beam with this lens alone, even at low probe voltages. It serves mainly as an accelerator. With 1 KV on the probe, first lens zero and a total accelerating voltage of 5.5 KV the ion beam was visible two feet below the extractor. The approximate minimum breadth was 1/4 inch. As probe voltage was raised, the accelerating voltage had to be raised to maintain the voltage ratio at the second lens for focus. This ratio remains approximately 6 up to an accelerating voltage of 15 KV. As the voltage is raised the definition improves due to less scattering of the more energetic beam. With the probe fixed at 2 KV the first lens voltage was raised in steps and the beam was refocussed with a corresponding increase in the main accelerating voltage. The definition of beam was observed to improve rapidly with the application of first lens voltage indicating that it does partially focus the beam. Observation of the beam at second gap indicated the beam to be approximately a half inch in diameter before entering the gap. This is considerably less than the solid angle subtended by the canal so that first lens with a voltage ratio of 5 accelerates and condenses the beam slightly to be finally focussed by the second lens. With 2.5 KV on probe, 8 KV on first lens and 35 KV on second lens the beam width is less than 1/16 inch in diameter. The current as measured in a narrow (3/8 inch diameter) Faraday cage at bottom of accelerator was found to increase rapidly with accelerating voltage due to the improved definition
Plate VIII

SPACE CHARGE SPREADING OF ION BEAM
of the beam-limiting ions striking the electrodes.

The above results indicate a satisfactory behaviour of the lens system. The observed weakness of the first lens suggests a possible improvement for better definition at low voltages, namely, an increase in the diameter and length of the extractor cylinder. The strengthening of this lens will also allow operation at higher probe voltages (and thus ion currents) at lower total accelerating voltages.

The effects of space charge on the spreading of the beam at low extraction voltages can be estimated. Plate VIII is a curve giving the spreading due to space charge repulsion of a beam of charged particles which are initially moving parallel to each other in a beam of radius \( r_0 \) in cms. The effective proton current \( I \) is expressed in amperes and the accelerating potential in MV. As an example, for \( I = 50 \mu A, r_0 = 1 \) mm, \( = 1600 \) volts, then \( r/r_0 = 1.1 \). Thus if probe volts is kept above 1600 volts, the space-charge spreading will be negligible.

G. THE MAGNETIC ANALYZER

The analyzer is required to mass resolve ions of mass numbers 1 to 6. Present in the deuteron beam will be the \( D^+ \), \( DD^+ \), and \( DDD^+ \) ions. If there is hydrogen contamination in the gas ions made up of \( H + D \) combinations will be present. Since the \( D^+ \) and \( HH^+ \) ions cannot be resolved it is desirable that very pure deuterium be used.

90° deflection of the beam was decided upon since a parallel beam at entrance is focussed at the exit in 90° analysis. Also it is preferable to mount the ion source vertically and the
experimental plane of scattering horizontally. As well, lower fields are required for $90^\circ$ deflection than $180^\circ$ although the linear resolution at slit is less.

$H \rho$ for masses $1, 2, 3$ and $4$ will be $3.5, 5.1, 6.1$ and $7.0 \times 10^4$ gauss cms. respectively at $60$ KV acceleration. For a radius of curvature of $11.4$ cms. the required fields for selection at $90^\circ$ exit will be $3100, 4400, 5400$ and $6200$ gauss respectively.

The $H \rho$, mass dispersion, and energy resolution are calculated in Appendix II. The mass dispersion at exit is given by the second order approximation:

$$\frac{\Delta}{\rho} = \frac{1}{2} \frac{\Delta m}{m} \left(1 + \frac{1}{4} \frac{\Delta m}{m}\right)$$

where $\Delta$ is the dispersion.

For example, consider the mass 2 component entering the slit at a radius of $11.4$ cms. Then $\Delta_1$, the dispersion of the mass 1 and $\Delta_3$ the dispersion of the mass 3 from the mass 2 are $3.25$ and $2.5$ cms. respectively. Graphically these values are $3.5$ and $2.2$ cms. respectively. Since the slit width will be of the order of $2$ mm., analysis can be expected to be complete.

The energy resolution achieved by a $2$ mm. slit is calculated by $\frac{\Delta \rho}{\rho} = \frac{1}{2} \frac{\Delta V}{V}$ where $\Delta \rho$ can be assumed equal to the slit width for $\Delta V$ small. Thus for $\rho = 11.5$ cms., $\Delta \rho = .2$ cms. and $V = 60$ KV., $\Delta V = 2,000$ volts. Similarly for $V = 6$KV: $\Delta V = 200$ volts. That is, voltage spread through slit is always a constant percentage ($\sim 2\%$) of the accelerating voltage. Better resolution is obtainable by decreasing slit width. In practice, the energy spread of the beam should be considerably less than
this since the 50 KV power supply has a ripple much less than 1% and the energy spread in the discharge has been calculated as less than 100 volts with 1200 volts on the probe.13

A maximum required field of 10,000 gauss was assumed for the design of the magnet (see Plate IX). The gap width was made 1 inch to assure a good pumping speed. The six inch diameter steel stock available fixed the pole-piece dimensions as 9 cms. by 9 cms. square. Applying A.O. Nier's "rule"18 that the fringing field increases the effective field extent by one gap width over the outside dimensions, then the effective radius of curvature is 11.5 cms. for the field measured at the centre of the pole. The complete design calculations are included in Appendix III.

A small shim was included at field entrance for adjusting the homogeneity of the field and thus the incident direction of the beam. The magnet mounting has provision for transverse and vertical adjustment by means of set screws and sylphons.

In Appendix II, it was calculated that 17 amps field current would give a field of 10,000 gauss. The hysteresis curve of Plate X shows a slight improvement over the design specifications. The commercial mild plate steel used in the construction has a very desirable low retentivity and the saturation is low in the required range of fields. A plot of the field over the face and outside the pole piece showed it to be quite inhomogeneous, dropping to 80% of the central field at the edge of pole and to 50% at a distance of 1 inch from the pole edge. Qualitatively these measurements indicate that Nier's "rule" is approximately valid.
Plate X

HYSTERESIS LOOP OF MAGNET
At present the field is controlled manually by means of a rheostat. However, it will be necessary to provide some means of stabilization for experiments that require an extended operating time. This could be achieved by means of a standard feedback current stabilization circuit. It has been calculated (See Appendix II) that for the beam to remain constantly imaged on a 2 mm. slit the current regulation $\frac{dI}{I}$ must be better than 1%.

The magnet chamber (See Plate XI) was built to conform to the assumed radius of curvature of 11.5 cms. and the magnet dimensions. Provision was made for straight through measurement of the beam (See Faraday cup, Plate XI), auxiliary pumping if necessary, and for definition of the beam by a slit at the exit. The latter was achieved by mounting a water cooled cam on two Wilson seals. Another copper tube is mounted below at exit level so that the system serves as a slit, variable from zero to 5 mm. width. The final definition of the beam into a spot of the required diameter is achieved by means of a water cooled aperture.

H. OVERALL PERFORMANCE OF ION ACCELERATOR AND MAGNETIC ANALYZER

Typical operating conditions of the ion source were as follows:

- Oscillator Power Output: 300 Watts
- Probe Voltage: 2500 Volts
- Probe Current: 15 m.a.
- Pressure: 20 microns

For current measurement, the usual precaution of biasing the Faraday cup positively with respect to ground to prevent reverse electron current was taken. Initially the total focussed ion
ASSEMBLY OF MAGNET CHAMBER & SLIT

Plate XI
current was measured in the straight through Faraday cup of the magnet box (See Plate XI) at a distance of about three feet from the source. With the above settings 400 μamps total current was obtainable. The ion current is an increasing function of oscillator power and probe voltage up to the output limit of power supplies as would be expected through increased ionization and sharper focusing of ions in the discharge tube.

Pressure dependence of source yield has not been thoroughly investigated to date due to the present lack of a Pd leak. A permanent Pd leak for this source is at present under construction. However, qualitative pressure characteristics have been determinable with the present capillary leak. It has been found that as the pressure is lowered from 30 microns, the ion current increases to a maximum and then decreases to extinction of discharge. The optimum pressure is approximately 20 microns. If the pressure is low (~10 microns), the discharge is found to become intermittent after extended operation. This effect was pointed out on page 10, and is not yet fully understood.

A test analysis of the beam was made with hydrogen in the discharge. A typical analysis was carried out under the following conditions.

<p>| | |</p>
<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Oscillator output</td>
<td>300 watts</td>
</tr>
<tr>
<td>Probe voltage</td>
<td>3,000 volts</td>
</tr>
<tr>
<td>Probe current</td>
<td>20 m.a.</td>
</tr>
<tr>
<td>Pressure</td>
<td>25 microns</td>
</tr>
<tr>
<td>Total ion current</td>
<td>350 μamps</td>
</tr>
<tr>
<td>1st lens voltage</td>
<td>8 KV</td>
</tr>
<tr>
<td>2nd lens voltage</td>
<td>40 KV</td>
</tr>
<tr>
<td>Slit Width</td>
<td>5 mm</td>
</tr>
</tbody>
</table>

Analysis of this beam showed 125 μ a. H⁺, 130 μ a. HH⁺ and 75 μ a. of HHH⁺ as well as 15 μ a. of much higher mass ions
Plate XII
indicating carbon or air contamination.

With deuterium gas produced by electrolysis in the discharge the analysis of Plate XII resulted. The operating conditions of this run were:

- Oscillator Output: 300 watts
- Probe voltage: 2500 volts
- Probe current: 16 m.a.
- Pressure: 30 microns
- Total ion current: 250 μ amps
- 1st lens voltage: 6 KV
- 2nd lens voltage: 30 KV
- Slit width: 1 mm

Ion percentages calculated on the basis of the peak ratios were

- Mass 1: 2%
- Mass 2 (D⁺): 27%
- Mass 3: 10%
- Mass 4 (DD⁺): 28%
- Mass 5: 11%
- Mass 6 (DDD⁺): 22%

The apparently high percentages of mass 1, 3, and 5 ions (containing hydrogen) is misleading. The true percentages would demand integration under the curves which would be dependent on an accurate knowledge of the beam geometry. The hydrogen content is probably considerably less than indicated by this analysis.

The presently attained atomic ion percentages are rather poor (~30%) but have been observed to improve with operating time. The fact that a high mass component is found in the beam indicates that further cleaning and extended operation will improve this percentage considerably.

The most encouraging result of this test is that a large part of the current is focussed into a 1 mm slit. Observation of the beam at exit of analyzer showed it to be approximately 1/16 inch in width and diverging, and less than 1/8 inch
in breadth. This result indicates that it will be easily possible to collimate a 100 $\mu$ a. beam into a spot of 1/8 inch diameter.

The calculated peak positions based on Nier's "rule" for the effective radius of curvature agree very well with the measured fields at the centre of the pole. These values are noted for comparison in Plate XII.

An attempt was made on the basis of the estimated beam size (3 mm.) slit geometry (1 mm.) and the half-width of the analyzer peaks (.1 amps), to determine the amount of energy spread in the beam due to varying acceleration in the discharge. An upper limit of 500 volts was established. Other workers have reported the spread to be much lower than this. In all likelihood, more rigid analysis of the present results would lower this limit considerably.

The general characteristics of the ion accelerator as indicated above are extremely satisfactory. Its stability, high current and good resolution are adequate justification of the original conception and choice of this type of source. The ability of the source to provide a very well defined analyzed beam of several hundred micro-amperes of deuterons lends considerable encouragement to the experiments proposed in the following pages and has increased the feasibility of many other experiments not formerly considered.
ANGULAR DISTRIBUTION OF PROTONS AT 50 KEV
IN THE C.M. SYSTEM

Plate XIII

THE ASYMMETRY COEFFICIENT $A(E)$
AS A FUNCTION OF ENERGY

Plate XIV
A. THEORETICAL DISCUSSION OF THE "D ON D" REACTIONS.

Owing to the simplicity of the deuteron structure, considerable progress has been made with its theoretical description. The "D on D" reaction is consequently very amenable to a fairly exact treatment. This theoretical work has been paralleled in the last few years by the accumulation of more accurate experimental data.

Early workers, Schiff and Flügge made attempts to derive an absolute value for the reaction cross-section. Flügge was successful in obtaining the right order of magnitude for the total cross-section. However, neither of these authors mentions the energy dependence of the asymmetry in the angular distribution.

These energy dependent characteristics found experimentally are indicated in Plates XIII, XIV and XV for the region of low deuteron bombarding energy (less than 125 KEV). They are equally applicable to both companion reactions, D(d,n)He$^3$ and D(d,p)H$^3$ within the accuracy of the present available data. Plate XIII shows the angular dependence of the yield (differential cross-section) which is found to fit the relation, $1 + A(E)\cos^2\phi$ in the centre of mass system at low energies. The symmetry about the 90° line follows directly from the identity of the colliding particles in the centre of mass system. The energy dependence of the asymmetry coefficient, A(E) is plotted in Plate XIV. For energies greater than 500 KEV, the introduction of higher powers of $\cos^2\phi$ is required for a fit to the distribution. Plate XV
D-D CROSS-SECTION FOR PROTON EMISSION

Plate XV
gives the total cross-section as a function of energy.

With this experimental data as a guide and similar curves tabulated by other workers, Konopinski and Teller have accounted for the energy dependence of the reaction characteristics from the relative penetrabilities of the electrostatic and centrifugal barriers. They assumed that the internucleonic forces contributed nothing to the energy dependence since strong energy variation due to nuclear interactions is usually associated with resonance effects. The latter have not been observed for the low energies under consideration. The second important assumption is that the barriers to the outgoing waves are negligible as compared to the reaction energy release. Thus, their calculation is equally applicable to neutron and proton emission from the D(d,n)He³ and D(d,p)H³ respectively, the neutron and proton spin being the same.

The procedure used by Konopinski and Teller was to set up the Schröedinger wave equation for two particles and to calculate the penetration probability \( P_l \), by the WKB approximation. This yields the expression:

\[
P_l = \exp(-C_l)
\]

where

\[
P_l = \exp(-C_l)
\]

\[
C_l = \frac{(2\mu)^{\frac{1}{2}}}{\hbar} \int_R^r \left[ \frac{e^2}{r} + \frac{\lambda(l+\frac{1}{2})}{2\mu r^2} \right] \frac{n^2}{-\hbar} \] \[ \text{dr} \]

\( \lambda \) is the reduced mass and \( e \) is the electronic charge. \( R \) is the distance to which the two deuterons may approach before nuclear forces predominate and is equal to the deuteron diameter plus the range of nuclear forces (\( \sim 7 \times 10^{-13} \text{ cm.} \). \( r_l \) is the "classical distance of closest approach" and makes the intergrand
vanish identically. \( W \) is the relative energy (one half the incident deuteron energy) and \( r \) is the relative separation of the two deuterons. \( P^l \) is the probability of barrier penetration for each of the quantum mechanical states of angular momentum of the system specified by \( l \).

It is clear from the form of the centrifugal barrier that states of higher \( l \) will have a decreasing probability of leading to a reaction. It can be inferred that the probability of \( l \)-wave penetration will decrease with energy as follows; the classical distance of approach of the deuterons in the \( l \) state is given by:

\[
r^l = \lambda l \quad (3)
\]

where \( \lambda \) is the de Broglie wave length. Since: \( \lambda \propto \frac{1}{\sqrt{l}} \propto \frac{1}{E} \), then \( r^l \) is inversely proportional to the incident deuteron energy. Assuming that the probability of penetration depends on the nearness of approach, then reactions leading from high \( l \) waves and low energies will be improbable. Thus for low energies the S and P waves only need be considered.

The allowed transitions are given by Konopinski and Teller for \( l < 2 \) as:

\[
1S_0 \rightarrow 1S_0 \quad \text{and} \quad 3P \rightarrow 3P.
\]

for low energy where spin and angular momentum is assumed to be conserved. It follows also from their argument that only \( 1/9 \) of the S collisions are in the required singlet state and \( 1/3 \) of the P collisions in the triplet state. The cross-section will be reduced accordingly by these factors \( g^l \) in the notation.

The cross-section for penetration by the \( l \) wave may be calculated by a classical argument. It will be the area in which the wave may lead to penetration multiplied by the penetration
probability, \( P_\perp \). The area from the figure and equation (3) will be:
\[
A = \pi \left( r_{\perp,1}^2 - r_{\perp,2}^2 \right) = (2 \ell + 1) \lambda^2
\]
Thus
\[
\sigma_\perp = \pi \lambda^2 (2 \ell + 1) \exp(-2C_\perp) \quad (4)
\]

Since spin and orbital angular momentum are conserved, the orbital angular momentum of the outgoing wave will have the same magnitude \( (\ell') = \ell \) and orientation \( (m' = m = 0) \) as the incident wave. The differential cross-section turns out to be
\[
d\sigma = \left| \sum_{\ell} \alpha_{\ell} \left( \int \frac{1}{r} g_{\ell} \psi_{\ell,1} \psi_{\ell,0}^* \right)^2 \right|^2 d\omega \quad (5)
\]
\( \psi_{\ell,0} \) is a normalized spherical harmonic, \( g_{\ell} \) is the weight factor depending on the multiplicity of the initial spin configuration, \( \alpha_{\ell} \) is the fraction of the penetrating \( \ell \)-waves which lead to reaction (thus on intrinsically nuclear attenuation factor, assumed above to be independent of energy) and \( \sigma_\perp \) is given by expression (4).

Considering the allowed transitions, and inserting the appropriate weight factors \( g_{\ell} \), Konopinski and Teller obtain for the differential cross-section:
\[
d\sigma = \frac{d\omega}{4\pi} \frac{\pi \lambda^2}{9} \left| \alpha_0 \right|^2 P_0 \left[ 1 + 27 \frac{\left| \alpha_1 \right|^2 P_1}{P_0} \cos^2 \phi \right] \quad (6)
\]
Also since the \( Y_{\ell m} \)'s are normalized, the integrated cross-section is
\[
\sigma = \sum_{\ell} \sigma_\perp \left| \alpha_{\ell} \right|^2 \quad (7)
\]
For the S & P waves this becomes:
\[
\sigma = C_1 P_0 \left[ 1 + C_2 \frac{P_1}{P_0} \right]
\]
A good statistical fit to the curve of Plate XV was obtained with the coefficients \( C_1 = 10 \) and \( C_2 = 7 \) at low energies.
Similarly a good fit to the curve of Plate XIV was obtained for the
asymmetry coefficient at low energies.

\[ A(E) = 27 \left| \frac{\lambda}{\lambda_0} \right|^2 \frac{P_1}{P_0} \]

The Coefficient of \( P_1/P_0 \) was obtained by fitting (6) to the curve of Plate XIII. The calculation of \( P_1/P_0 \) as the incident energy approaches zero shows that it does not vanish. This is non-vanishing only in the presence of a Coulomb field since without it, the S waves would predominate completely because an \( l \)-wave of vanishing energy requires an infinite "lever arm" to maintain its angular momentum. When the Coulomb repulsion acts, \( r_0 (= e^2/W, \) the classical distance of approach for electrostatic repulsion only) becomes greater than the lever arm for low energies. The S,P,D etc. waves are all treated alike for \( r \sim r_0 \) since the centrifugal potential is negligible in comparison to the electrostatic barrier so that the ratio \( P_1/P_0 \) does not vanish through the vanishing of \( P_1 \). This non-vanishing of the coefficient \( A(E) \) for zero energy is in agreement with the extrapolation of Plate XIV to zero energy.

From the above results it appears that quantum mechanics gives an adequate description of the reaction characteristics at low energy. For higher energies (1-5 MEV) it has been necessary to introduce terms in \( \cos^6 \phi \) up to the sixth power.\(^{25}\) Theoretical agreement is found by including the D wave and spin orbital interaction in the above calculation. A very recent extension of the results to 10 MEV shows the necessity for introducing a "\( \cos^8 \phi \)" term.\(^{26}\)

Beiduk, Pruett and Konopinski\(^{27}\) have recently carried out a calculation based on current ideas about internucleonic forces and have, by rough approximations, arrived at values for the
coefficients which are in order of magnitude agreement with the experimental values. They suggest that a more rigorous calculation is not as yet justified due to the present inaccuracy of experimental data.

It is evident that further experimentation at low energy would be useful. In all cases the statistics of the curves is random enough that considerable leeway is left in the choice of coefficients for statistical fits to the curves. Increased accuracy is particularly needed in the case of the energy dependence of the angular distribution for obtaining more accurate values for the $|\alpha_1|^2$ coefficients. These results in reference to the calculations of Beiduk et al might shed considerable light on the correctness of current ideas about nuclear forces.

There is also a need for the simultaneous measurement of the characteristics of the companion reactions. This includes the measurement of the angular distribution as a function of energy and the measurement of the energy dependence of the ratio of the reaction cross-sections of D(d,n) He$^3$ to D(d,p)H$^2$ and the angular dependence of this ratio if any. Since, until very recently, no measurements of import have been made of this ratio, there has been no theoretical consideration of the characteristic. An accurate tabulation of its energy dependence could assist in determining the relative importance of the coulomb and centrifugal barriers in nuclear reactions.

Further, the accurate measurement of the reaction ratio would establish a very useful neutron standard, since the neutrons could be accurately monitored by means of the protons from the companion reaction.
DIAGRAMMATIC TOP VIEW OF SCATTERING CHAMBER
B. DISCUSSION OF PREVIOUS WORK

The "D on D" reaction was first described by Oliphant, Harteck and Rutherford in 1933 and 1934.\textsuperscript{28,29} The last few years has seen an accelerated experimentation into the character of the reaction as a contribution to the investigation of the atomic nucleus. The following five papers covering the low energy measurements have been carefully analyzed with the object of improving on the experimental arrangements.

(1) Bretscher, French, and Seidl:\textsuperscript{3} Phys. Rev. 73, 815, 1948.

A well collimated beam of monoenergetic deuterons were directed on a fresh D\textsubscript{2}O target. The intensity of the incident beam was measured by the charge transferred to the target per unit time and the number of protons emitted from the target per unit time was counted as a function of their angle with the incident beam and as a function of the incident deuteron energy between 15 KEV and 105 KEV.

The scattering chamber used by these workers was similar to that of Plate XVI with the omission of the geiger counter. Provision was made for a well-collimated beam, "good" geometry, a fresh, uncontaminated heavy ice target, low pressure provided by auxiliary pumping and liquid air traps in the chamber, and target bias.

Their results are shown in Plates XIII, XIV and XV. The curve for the total cross-section as a function of energy is considered to be questionable due to the inaccurately known values of the rate of energy loss for the deuterons in the thick target which were used in its calculation.
UNANALYZED BEAM

COUNTER WITH PERFORATED WINDOW

CU TARGET

PEPPER'S TARGET SCHEME

Plate XVIII

T & He^3 PULSES FROM D-D REACTION

Plate XVIII
This work was obviously done with the greatest care but the maximum ion current available to these authors was 2.5 μamp­eres resulting in poor statistics at very low energies. Further the apparatus was limited to the counting of the protons only, and the counter arrangement limited the angular range within 40° to 150°.


An attempt was made to measure the ratio of the $D(d,p)H_3$ to $D(d,n)He_3$ cross-sections by counting all the charged particles from the reaction in a thin window proportional counter. The pulse sizes were sorted with a pulse analyzer. The method was good in conception but poor in execution as indicated by the large probable error in the ratio: $1.15 \pm .15$. While the results are inconclusive, the experiment proves useful in pointing out the difficulties to be encountered in this method.

The experimental arrangement is shown in Plate XVII. The target was supplied by occluded particles from the beam. The proportional counter window consisted of a .25 mg/cm\textsuperscript{2} formvar film mounted on a steel grid and presented a large solid angle (15° half angle) to the target.

Pepper found little evidence of energy dependence of the ratio in the range 15 KEV to 60 KEV. The chief source of error was apparently caused by the large straggling of $He_3$ pulses resulting in an overlapping with the $H_3$ pulses as indicated by Plate XVIII. This large energy straggling of the $He_3$'s can be attributed to several factors. The large solid angle at the window results in particles with a 15% spread in energy entering
RATIO OF THE CROSS-SECTIONS OF THE $^6\text{D(dn)}$ He$^+$ & $^6\text{D(dp)}$ H$^+$ REACTIONS AS A FUNCTION OF ENERGY

Plate XIX
the counter. (See page 3). Further, the pulses from the wide-angle particles would attain less gas amplification in the counter due to the poor counter geometry at its extremes. Compounded with these effects is the straggling of the He$^3$'s due to charge exchange in the windows. The most energetic He$^3$ would have a range of about .4 air-cms. A formvar window of .25 mg/cm$^2$ would attenuate this range by about .27 air-cms. with considerable straggling of the particles. On the basis of these compounded effects one would expect the straggling to be greatest towards the lower energies, which is borne out by Plate XVIII.


The experiments of Bretsher, French and Seidl were repeated at low energies using a high (250μA) ion current and detection by means of photographic plates. These workers have confirmed by a count of the proton tracks in the emulsion the $1 + A(E) \cos^2 \theta$ relation for the angular distribution.

(4) McNeill, Thonemann and Price$^{32}$ Nature 166, 28 (1950)

An arrangement similar to that of Pepper was used to measure the energy dependence of the reaction ratio of the "D + D" reactions. The results, which are much more reliable than Pepper's are the thick target points indicated in Plate XIX. They again used an occluded target and rather poor geometry so that the statistical error is rather high. In contradiction to Pepper's results they were able to completely resolve the He$^3$ and H$^3$ peaks in the pulse analyzer channels but had difficulty in resolving the p and H$^3$ peaks. This difference is probably due to different counter dimensions and counter pressures resulting in a different
pulse distribution. The difficulty was overcome by placing a straight through window of 4 mg/cm\(^2\) aluminum into a second counter which would count the protons only. Thus the channel counts could be assigned with an error of less than 1%. 

(5) McNeill and Keyser.\(^{33}\) Phys. Rev. 81, 602, 1951

This research was a continuation of the work of 4 above. Measurements were extended to the relative probabilities and the absolute cross sections of the "D on D" reactions in the energy range 120 KEV to 250 KEV. The work was prompted by the questionable thick target cross-sections of Bretscher et al at low energies. To overcome the thick target difficulties they used a continuous flow-gas target which approximates an ideal thin target. The counting arrangement was the same as in (4) above.

The results of McNeill and Keyser for the D(d,p)H\(^3\) cross-section are not in agreement with those of Bretscher et al even within the large statistical error (\(\pm 20\%\)) inherent in this work. Thus it seems likely that their calculation of the rate of energy loss in D\(_2\)O is badly in error. The values found for the reaction ratio are included in Plate XIX and extrapolate fairly well to the thick target results. They show a very conclusive energy dependence of the ratio. Pepper gives the average value for deuteron energies less than 60 KEV as 1.15 \(\pm\) .15 compared to the value obtained by the extrapolation of McNeill's curve of .85 \(\pm\) .05 at 60 KEV.

Despite the apparent surmounting of the thick target difficulties, the thin target and the experimental arrangement have introduced numerous other difficulties which lead to large statistical, experimental and geometrical errors. The total
maximum error is estimated as 20%.

C. PROPOSED EXPERIMENT

1. Experimental Method.

On the basis of the above experiments and an analysis of their limitations it was decided that the greatest improvement could be achieved by combining the "good" geometry and the angular measurements of Bretscher et al with some method of simultaneously counting of all the charged particles from the reaction. The availability of a deuteron beam from the ion accelerator of as much as one hundred times the intensity of that used by Bretscher makes possible a very great improvement in target and counter geometry and further, the extension of measurements to much lower energies than previously attainable. For these purposes, the experimental scattering chamber used by Bretscher et al required little modification. However, the apparent lack of resolution of the proportional counter method used by Pepper and others demanded an investigation of other methods of counting.

The use of photographic plate detection suggests itself as a possibility. The length of the tracks of 3 MEV protons, 1 MEV H³'s and .8 MEV He³'s in dry C₂ emulsion are respectively 80 microns, 10 microns and 3 microns so that detection (a one micron track can be readily identified) and resolution would be adequate. Knock-on protons due to the neutrons would be quite probable but most would arise below the emulsion surface or at an angle to the direction of viewing so could easily be discriminated. While the accuracy and dependability of the method is indisputable, the
PULSE COUNTING RATE AS A FUNCTION OF ENERGY

Plate XX

PULSE AMPLITUDE DISTRIBUTION OF PO. $\alpha$'S ON CdS PHOSPHOR

Plate XXI
time necessary for reading plates is prohibitive considering the extent of the proposed measurements and statistical accuracy required.

The increasing use of the scintillation counter as a proportional device suggested its possible application in this work. It has been used fairly successfully as a $\beta$-ray spectrometer (See Plate XX) but its resolution is seen to be poor as compared to the lens spectrometer. Plate XXI showing the pulse amplitude distribution from Polonium alpha particles on a transparent CdS. phosphor shows a broad spectrum. It is apparent that the much less energetic $\text{He}^3$'s from the $\text{^3He} + \text{^3He}$ reaction would exhibit even more straggling so that the distributions of 0.8 MEV $\text{He}^3$'s and the 1 MEV $\text{H}^3$'s would surely overlap. Carefully designed optical systems and the selection of very clean surfaced and pure phosphors might improve the resolution. However, it seemed inadvisable to try and use the method since it would represent an extended research in itself.

The difficulties apparent in the above two methods led to a reconsideration of the original proportional counter arrangement. The correction of the experimental and geometrical errors inherent in former experiments as suggested in part B might very possibly overcome the resolution difficulties. Further, if the back-angle protons corresponding to the forward $\text{H}^3$ particles were counted in coincidence with the $\text{H}^3$ pulses from the proportional counter a completely unambiguous count of the $\text{H}^3$'s would be achieved. This method demands a target thin enough to transmit the protons and the inclusion of a second counter. The
SCALER
AMPLIFIER
PULSE ANALYZER
SCALER
COINCIDENCE MIXER
LINEAR AMPLIFIER
AMPLIFIER
TARGET
GEIGER COUNTER
PROPORTIONAL COUNTER
GEIGER COUNTER

SCHEMATIC COUNTING ARRANGEMENT

Plate XXII
counting arrangement is shown in Plates XVI and XXIII and schematized in Plate XXII. If the proton and H3 peaks overlapped as found by McNeill, the inclusion of a straight through window in the proportional counter to a second counter giving a separate forward proton count (See dotted lines, Plate XXII) would eliminate all ambiguity. The presently constructed apparatus does not include this latter refinement but can be included if found necessary.

For reasons of "good" geometry and high yield at low energy a thick (heavy ice) target has been chosen. The main disadvantage of a thick target in energy-dependent measurements is the fact that the reactions arise from a complete range of particle energies due to slowing down in the target. Thus, the determination of the differential and total cross-sections and the asymmetry coefficient as a function of deuteron energy requires a knowledge of the rate of energy loss in the target, dE/dx. Unfortunately, little is known of the stopping power of gases and solids for very low energy particles. This is a serious limitation on the scope of this experiment unless this function is measured separately. However, the accurate measurement of this quantity is considered to be quite feasible with an adaption of the present scattering chamber and using the low energy beam from the ion accelerator. An experimental arrangement of this type is now under consideration in this laboratory.

2. The Scattering Chamber (Plate XXIII and Plate XXVI)

The chamber design of Bretscher, French and Seidl was adapted to the needs of the present research. The chamber includes a liquid air trap on which the target is mounted. The
whole assembly may be rotated through a Wilson seal without breaking vacuum. The counters are mounted at 180° to each other on a similar Wilson seal swivel. They are rotatable through 20° to 160° with respect to the direction of the incident beam. Also included in the assembly is an electrostatic analyzer for testing the state of neutralization of the beam, a D$_2$O bottle for spraying the target, a counter filling system for filling the thin-window counter in vacua, and ports at various angles for observation and attachment of auxiliary equipment for future neutron experiments. A fast pumping system is provided consisting of a mercury diffusion pump backed by a Duo-Seal mechanical pump. With the liquid air trap for target cooling in operation, pressures of 2 x 10^-6 mm. of mercury are attainable. Pressure in chamber is measured by means of an attached ionization gauge.

3. The Counters and Target.$^{37,38,39}$

The proportional counter was designed so as to attain the maximum resolution of the charged particle pulses. Precautions suggested by the reviewed papers are listed below. First an effort should be made to construct thinner windows (~ 0.1 mg/cm$^2$) than previously used. Thin windows made from zapon films have been successfully used in $\beta$-counter work in this department. As the windows required in the present research are an order of magnitude thicker, different techniques for producing the films will have to be developed. However, Pepper's success with formvar windows suggest that this should not be too difficult. The silicon windows suggested by Thonemann$^{40}$ and used in McNéill's work are
also applicable. If the window areas are small enough, adequate mechanical strength can be achieved without auxiliary support. The window size has been fixed as 1 mm x 5 mm by the counting rate required for low statistical error (50 counts/sec at 30 Kev with 20 μ amps deuteron current).

This small window size which has been made possible by the large ion current available has automatically overcome the resolution loss due to large angle detectors and variation of gas amplification with counter geometry. Further, considerable care has been taken to construct an accurately central wire geometry.

A gas amplification of 100 has been calculated as adequate to give a good signal to noise ratio. This can easily be achieved in an argon-alcohol gas mixture (mixture ratio, 10:1) at pressures of 5 to 10 cms. of mercury. Further this mixture has a low starting voltage which is rather important considering the relatively large dimensions of the proportional counter (2 inch diameter). The probability of knock-on protons due to neutrons is negligible at the alcohol concentration specified. A rough calculation for the ionization of the particles in the argon counter at 5 cms. pressure shows that the pulse sizes corresponding to He³, H³, and p will be in the ratio 20:5:1 respectively. This is in good agreement with the pulse distribution of Plate XVIII.

The target support is shown in Plate XXIV. It consists of a thin Al foil (.0004 inches) clamped between two copper sheets. The assembly is soldered to the liquid air trap (Plate XXIII). Calculation shows that with liquid air at -190°C in
trap and one watt power in the incident beam concentrated in a
1/8 inch central spot, the target will be maintained at -100°C. Thus there will be no difficulty in freezing a D$_2$O film on the
target.

The energy loss of the protons in the Al foil is
small enough that a relatively thick (5 mg/cm$^2$) mica window
may be used in the geiger counter to supply the necessary
strength requirements yet transmit all the back angle protons.
The counter window has the dimensions 3/8 inch by 5/8 inch, large
enough to accept all protons from a 1/8 inch diameter target area
in coincidence with the H$^3$'s counted in the proportional counter.
At the higher energies the geiger counter will have to be
advanced in the forward direction to allow for the momentum
carried off from the incident beam. This amounts to about 3°
of arc at 50 KEV energy and 90° observation. An argon-alcohol
mixture is to be used as the counter gas.

4. **Counter and Current Measuring Equipment.**

The requirements of the electronics are not very
stringent. Assuming 1% statistics, 10,000 counts will be re-
quired per reading, or three minutes operation at 50 counts/
second. At this counting rate, spurious coincidence counts
will be negligible with a resolving time as great as 10μsec
and in general the counting rate will be lower than this.

All the electronic units are available in the Nuclear
Physics Techniques Laboratory. This includes a linear amplifier
of type x "Northern Electric, Fast Linear Amplifier, A.E.P. 1444",
which is able to handle pulses as short as .5 micro-seconds.
Eighteen channels of the Marconi pulse amplitude analyzer have
been obtained, and for measurement of the total charge collected on the target a current integrator has been constructed.
XXV. Front View of Assembled Apparatus
IV CONCLUSIONS

The project proposed above for the study of the energy dependent characteristics of the "D on D" reaction at low energies has not at the time of writing reached the stage of measurement due to the lack of time. However, the construction of the apparatus has been completed and except for a few technical details is ready for initial tests. The method proposed has, with proper precautions, a potential accuracy much greater than previous work on the "D on D" reaction. The intense and highly resolved beam as reported in section II, allows the use of excellent target geometry. Tests have indicated that it will be possible to collimate a beam of 30 KEV deuterons of greater than 50μA-amperes into a 1/16 inch spot on the target. This is an order of magnitude improvement on previously produced ion beams of this energy and size. Nor are the present operating conditions optimum. From present indications, the ion current can be increased considerably by stepping up the oscillator power and probe voltage. An improvement on the focussing of the beam is also possible through redesign of the first lens resulting in an improved definition at very low energies.

The exemplary performance of the ion accelerator indicates the possibility of extending the measurements to much lower energies than previously possible. Also, the counter and target arrangement is adaptable to certain studies not considered previously, e.g. the character of the reaction ratio
as a function of angle. This latter measurement is equivalent to the determination of the difference, if any, between the behaviour of the asymmetry coefficients, $A(E)$, of the companion reactions.

The apparatus is adaptable to a large number of other experiments, either through use of the neutrons from the $(d,n)$ reactions or by direct bombardment of the targets with the ions of hydrogen, deuterium or tritium. The $(d,n)$ reactions, $^3\text{H}(d,n)^4\text{He}$, $^6\text{Li}(d,n)^7\text{Be}$, $^7\text{Li}(d,n)^8\text{Be}$ and $^{14}\text{N}(d,n)^{15}\text{O}$ merit attention in themselves and could be studied at low energies with the "D on D" apparatus with little modification. The neutrons produced from these reactions could be used in the investigation of the energy levels in many nuclei by means of the elastic and inelastic scattering of the neutrons.\textsuperscript{41}

The apparatus is also adaptable to the study of certain $(p,\gamma)$ reactions at very low energies. This information is of interest for estimating nuclear reaction rates in matter at high temperatures, as in the sun and stars. These low energy studies have recently been implemented by Fowler and co-workers\textsuperscript{42,43} with the $^{13}\text{C}(p,\gamma)^{14}\text{N}$ reaction.

Finally, the successful calculation of the cross-sections for the "D on D" reactions necessitates an accurate knowledge of the rate of energy loss of deuterons in heavy ice at low energies. This apparatus with modifications could be used successfully for the determination of $dE/dx$ for protons and deuterons at low energies in various materials.

Such examples of interesting experiments which can now be performed with the apparatus indicate that it should be a most valuable addition to the laboratory.
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APPENDIX I

The Calculation of Particle Energies as a Function of Angle of Emission for the Reactions:

\[ D^2 + D^2 \rightarrow He^3 + n + 3.28 \text{ MEV} \]
\[ D^2 + D^2 \rightarrow H^3 + P + 4.0 \text{ MEV} \]

Consider the general two-body disintegration mechanics:

\[ E_1 = \frac{1}{2} M_1 v_1^2 \quad E_2 = 0 \]
\[ P_1 = M_1 v_1 \quad P_2 = 0 \]

Before Collision \hspace{2cm} After Collision \hspace{2cm} Momentum Diagram

Fig. 1

By conservation of momentum:
\[ P_4^2 = P_1^2 + P_3^2 - 2P_1 P_3 \cos \Theta_3 \]

(2)

By conservation of energy: or
\[ E_3 + E_4 = E_1 + Q \]

(3)

If the energy of interest is that of particle M_3 (neutron), P_3 can be obtained by eliminating P_4 from (2) and (4)

This yields
\[ E_3 = E_1 \frac{M_1 M_3}{(M_3 + M_4)^2} \left\{ 2 \cos^2 \Theta_3 + \frac{M_4}{M_1 M_3} (M_3 + M_4) \right\} \]

\[ \times \left[ \frac{Q + (1 - \frac{M_1}{M_4})}{E_1} \right] + 2 \cos \Theta_3 \left[ \cos^2 \Theta_3 + \frac{M_4}{M_1 M_3} (M_3 + M_4) \left\{ \frac{Q}{E_1} + (1 - \frac{M_1}{M_4}) \right\} \right] \]

(5)

E_4 can be obtained from equation (3)
The angle at which $M_4$ appears is obtained from the momentum diagram:

$$\sin \Theta_4 = \left( \frac{M_3 \beta_3}{M_4 \beta_4} \right)^{\frac{1}{2}} \sin \Theta_3$$  \hspace{1cm} (6)

Transpose to the centre of mass system for a simplification in the calculations. This simplification arises from the fact that the energy of the particle in the centre of mass system is independent of the angle of emission $\phi$.

The sides of the $\sqrt{E}$ diagram are given by:

$$A_3 = \sqrt{\frac{M_3}{2}} \quad V_{cm} = \left( \frac{M_1 M_3}{M_1 + M_2} \right)^{\frac{1}{2}} \sqrt{E_{\text{th}}}$$ \hspace{1cm} (7)

$$B_3 = \sqrt{\frac{M_3}{2}} \quad V_3 = \left( M_2 \frac{M_4}{M_1 + M_2} \right)^{\frac{1}{2}} \sqrt{(E_1 - E_{\text{th}})^{\frac{1}{2}}} \quad \text{where} \quad E_{\text{th}} = - \frac{Q(M_1 + M_2)}{M_2}$$ \hspace{1cm} (8)

$$C_3 = \sqrt{\frac{M_3}{2}} \quad V_3' = \sqrt{E_3}$$ \hspace{1cm} (9)

Thus $E_3 = A_3^2 + B_3^2 + 2A_3 B_3 \cos \phi$ \hspace{1cm} (10)

and $\phi = \Theta_3 + \sin^{-1} \left( \frac{\sin \Theta_3}{B_3/A_3} \right)$ \hspace{1cm} (11)

1. Hanson, Taschek and Williams  KMP 21, 635, 1949
Equations (3), (7), (8), (9), (10), and (11) were applied in the preparation of table I giving the energy of the emitted particles from reactions (1) as a function of angle.

Preparation of Plate III

Using equations (7), (8) and (10), curves were plotted of $E_2$ versus $E_1$. These curves were used in combination with Plate XV for the D-D cross-section to arrive at the curves of Plate III. The ordinates $N(E)$ are proportional to the cross-section $\sigma(E)$. $\sigma(E_1)$ is plotted against $E_2$ corresponding to $E_1$. Thus the curves give the number of neutrons emitted of energy $E_2$ for a given incident energy $E$ (50 KEV and 100 KEV) at a given angle (0°, 90° and 180°). Although the calculations were carried out in the centre of mass system, they are equally applicable to the laboratory system since the difference between $\theta_2$ and $\phi$ (See Fig. II) is negligible at 50 KEV ($<1^\circ$).
APPENDIX II

1. Hρ, mass dispersion and energy resolution calculations

The equation of motion of an ion in a uniform magnetic field is:

\[ \frac{Hev}{c} = \frac{mv^2}{\rho} \]  \hspace{1cm} (1)

and the energy of a particle accelerated through a voltage \( V \) is:

\[ \frac{1}{2} mv^2 = Ve \text{ or } v = \frac{2Ve}{m} \]  \hspace{1cm} (2)

Substituting (2) in (1) gives:

\[ H\rho = \frac{mc}{e} \sqrt{\frac{2Ve}{m}} \]  \hspace{1cm} (3)

from which by differentiation and division

\[ \frac{dp}{\rho} = \frac{1}{2} \frac{dV}{V} \text{ for constant } H \text{ and } m \]  \hspace{1cm} (4)

and

\[ \frac{dp}{\rho} = \frac{1}{2} \frac{dm}{m} \text{ for constant } H \text{ and } v. \]  \hspace{1cm} (5)

Equation (4) defines the energy resolution at the slit since for

\[ \frac{dp}{\rho} \ll 1, \frac{dp}{\rho} \approx W, \text{ the slit width (See Fig.III)} \]

The first order approximation does not apply in the case of the equation for the mass dispersion of ions of mass difference one or greater since \( \frac{\Delta m}{m} \) and thus \( \frac{\Delta \rho}{\rho} \) is comparatively large.

From Fig.III, the linear separation at the slit of ions of different mass, one of which is passing through the slit, is:

\[ \Delta = \rho \left( 1 - \sqrt{1 - 2 \frac{dp}{\rho}} \right) \approx \rho \left( 1 + \frac{1}{2} \frac{dp}{\rho} \right) \]

dropping third and higher order terms. This may be written as:

\[ \frac{dp}{\rho} = \frac{\Delta}{\rho} - \frac{1}{2} \left( \frac{\Delta}{\rho} \right)^2 \text{ to a second order approximation.} \]
Therefore from (5):
\[
\frac{1}{2} \frac{\Delta m}{m} = \frac{\Delta}{\mathcal{E}} \frac{1}{2} \frac{\Delta^2}{\mathcal{E}^2}
\]
and solving for \(\frac{\Delta}{\mathcal{E}}\), the result for the mass dispersion is
\[
\Delta = \mathcal{E} \frac{\Delta m}{2m} \left( 1 + \frac{1}{4} \frac{\Delta m}{m} \right)
\]  

2. Current Stabilization:

The current or field stabilization is defined by the two equations.
\[
\frac{dI}{I} = \frac{dH}{H} = -\frac{d\mathcal{E}}{\mathcal{E}} \quad \text{for } V \text{ constant and } \tag{7}
\]
\[
\frac{dI}{I} = \frac{1}{2} \frac{dV}{V} \quad \text{for } \mathcal{E} \text{ constant} \quad \tag{8}
\]

If it is desired to maintain the beam focussed on the slit of 2 mm. width, then the beam should not shift by more than 1 mm. By (7):
\[
\frac{dI}{I} < \frac{d\mathcal{E}}{\mathcal{E}} = \frac{1}{11.5} \approx 1\%
\]

By equation (8) this would correspond to an energy resolution of
\[
\frac{dV}{V} = 0.02 \quad \text{or } 2\%
\]

For higher energy resolution a smaller slit width is required with a corresponding improvement in current stabilization.

3. Energy Spread Due to Varying Acceleration in the Discharge Tube

The beam is observed to have a width of 3 mm at analyzer exit. It is assumed that the current density is uniform over the elliptical beam area. The peak width is .1 amps or approximately 100 gauss from Plate X. Beam energy is 30 KEV and \(H = 3,000\) gauss.

From above:
\[
\frac{dH}{H} = -\frac{d\mathcal{E}}{\mathcal{E}} (V \text{ constant}); \quad \frac{d\mathcal{E}}{\mathcal{E}} = \frac{1}{2} \frac{dV}{V} (H \text{ constant}); \quad \frac{dH}{H} = \frac{1}{2} \frac{dV}{V} (\mathcal{E} \text{ const.})
\]

If the energy spread is small then to the first approximation the peak width (Plate XII) is due to the finite geometry of the beam and slit. \(d\mathcal{E}\) corresponding to the two half-current
values will therefore be 3 mm.

Thus \( \frac{d\rho}{\rho} = \frac{3}{11.5} = \frac{dH}{7,000} \) and \( dH = 75 \) gauss.

The measured \( dH = 100 \) gauss

Since modulation of the beam due to ripple is negligible, it is reasonable to assume that the excess beam straggling (25 gauss) is due to energy spread in the beam.

Thus \( \frac{1}{2} \frac{dV}{V} = \frac{25}{7,000} \) and \( dV \approx 500 \) volts.

The above rough calculation is capable of establishing no more than an order of magnitude since rather crude assumptions were made concerning the character of the ion beam. The beam width used was the visible width. There is considerable fringing current of lower intensity which would increase the effective width of the beam. However, an upper limit of energy spread appears to be about 500 volts.
Magnet Design

A required field of 10,000 gauss and a gap width of 1 inch were assumed. Assuming a leakage factor of 1.6 then the required field is increased to 16,000 gauss.

The work done carrying a unit pole across the gap

\[ = 16,000 \times (2.54) = 40,500 \text{ ergs} \]

The work done carrying a unit pole along the iron path

\[ = \frac{16,000}{1600} \left( 19 + 3(9) \right) \times 2.54 \times 10 = 1,160 \text{ ergs} \]

Total work done 42,000 ergs

where the permeability is assumed to be 1600 and the dimensions of the iron are taken from Plate IX.

Thus \( \frac{4\pi NI}{10} = 42,000 \) ergs so that \( NI = 35,000 \) ampere-turns.

At 20,000 ampere-turns/coil and 17 amps/coil, the number of turns is 1200. #13 Formel wire was calculated to supply the necessary resistive and space requirements. The resistance of a coil is 6.8 ohms so that at 17 amps, the required voltage is 116 volts which is available from the building D.C. supply. Cooling is supplied to the coils by means of two layers of 3/16 inch copper tubing wound into each coil.

---

APPENDIX IV

Table of Neutron Energies from Photo-Neutron Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Mean Energy (KEV)</th>
<th>Emax (KEV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na-Be</td>
<td>800</td>
<td>1020</td>
</tr>
<tr>
<td>Na-D20</td>
<td>220</td>
<td>320</td>
</tr>
<tr>
<td>Mn-Be</td>
<td>300</td>
<td>375</td>
</tr>
<tr>
<td></td>
<td>&lt;150&lt;</td>
<td>&lt;150</td>
</tr>
<tr>
<td>In-Be</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>&lt;150&lt;</td>
<td>&lt;150</td>
</tr>
<tr>
<td>Sb-Be</td>
<td>35</td>
<td>68</td>
</tr>
</tbody>
</table>

APPENDIX V

Calibration of the High Voltage Resistance Stack

<table>
<thead>
<tr>
<th>Resistance No.</th>
<th>Resistance in Megohms at 1 KV</th>
<th>Resistance in Megohms at 3 KV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.41</td>
<td>10.33</td>
</tr>
<tr>
<td>2</td>
<td>10.60</td>
<td>10.54</td>
</tr>
<tr>
<td>3</td>
<td>10.45</td>
<td>10.24</td>
</tr>
<tr>
<td>4</td>
<td>10.06</td>
<td>9.93</td>
</tr>
<tr>
<td>5</td>
<td>10.78</td>
<td>10.19</td>
</tr>
<tr>
<td>6</td>
<td>9.84</td>
<td>9.72</td>
</tr>
</tbody>
</table>

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2. The second energy for the reaction indicates a second neutron group.