A SEARCH FOR THE DIRECT RADIATIVE
CAPTURE REACTION D(d,γ)He⁴

by

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We accept this thesis as conforming to
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ABSTRACT

An experimental method for the detection of the \( \text{d(D,}\gamma)\text{He}^4 \) reaction has been developed. It involves the use of a double focusing magnetic spectrometer in conjunction with a solid state counter mounted in the focal plane of the spectrometer, the counter determining both the energy and \( dE/dx \) of the incident particles from the reaction.

The design and construction of a particle beam handling system to guide the particle beam from the Van de Graaff generator to the object point of the spectrometer has been completed and tested. Using this beam, the characteristics of the spectrometer and solid state counter have been determined and recorded.

An attempt was made to detect the \( \text{d(D,}\gamma)\text{He}^4 \) reaction but no directly useful information on the reaction crosssection was obtained. However, utilizing the knowledge gained during this experiment, it should be possible to make a more exacting attempt at the reaction crosssection determination.
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CHAPTER 1.
INTRODUCTION

The study of the nucleon-nucleon interaction (or "nuclear force") is one of the central problems of nuclear physics. It seems that one of the most direct methods of attacking this problem in the low energy (approx. up to 10 Mev.) region is through the study of nuclear scattering and reactions involving only a few nucleons (so that the problem is a "few body" problem, rather than a "Many body" problem). Reactions involving up to 4 nucleons we call "few nucleon" reactions. In this laboratory, the "few nucleon" problem has received some attention, (Warren, Griffiths et al p(D,γ)He^3 reaction) and is presently under study (Monier n,p scattering and d(D,t)p and d(D,He^3)n reactions). This thesis describes some experimental studies, also of the D,d, reaction.

The reaction to be described is the direct radiative capture reaction D(d,γ)He^4. The obvious way to study this reaction is to look for the high energy gamma rays of approximately 25 Mev. A crude calculation of the D(d,γ)He^4 crosssection, (See Appendix E), gives a crosssection of the order of $10^{-29}$ or $10^{-30}$ cm$^2$. Fowler et al $^1$ have set an ex-

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perimental upper limit on the crossection of less than $10^{-31}$ cm$^2$. However, difficulties arise due to the fact that other, highly prolific, reactions occur simultaneously and produce a very high gamma and neutron background activity. The competing reactions are D(d,He$^3$)n and D(d,t)p, and the crossections for these reactions are of the order of $10^{-27}$ cm$^2$. Also any target backing that is used will produce gamma activity and contribute to the background. It is evident that to study this reaction through gamma measurements would require the measurement of a very low gamma activity in a very high background which would tend to give spurious counts in the relevant energy region in the gamma ray spectrometer. Therefore a second method of treating the problem has been considered.

The other approach is to look for the recoil Helium ions which result from D(d,$\gamma$)He$^4$. These ions will be mainly in the ++ state and will henceforth be called alphas. If the kinematics of the reaction are considered, as in the Appendix A, it is found that for a 3 Mev. beam of incident deuterons, all the recoil alphas will emerge in a cone at an angle of less than 15° with respect to the incident beam. Using the 60° double focusing magnet spectrometer with a solid state detector at the image focus, it is possible to measure over acceptance angles of between 5° and 15° with respect to the beam. This avoids the danger of swamping the recoil alpha counter with coulomb scattered deuterons from the beam when the
recoil particles are detected at small angles to the incident beam, since the elastically scattered deuterons do not have the same trajectory in the spectrometer as the recoil alphas and therefore do not reach the counter at the spectrometer focus. Other charged particles, for example protons with the same momentum to charge ratio as the alphas have the same trajectory in the spectrometer, but with a solid state counter at the focus the energy of the particles may be measured and thus it is possible to differentiate between these particles and the recoil alphas. Upon inspection of particle trajectories in the spectrometer, (refer to Appendix D.), it is evident that a proton and alpha of the same energy have the same trajectory in the spectrometer, so that a method must be devised to differentiate between the two particles of the same energy. This is accomplished using a dE/dX technique by using a solid state counter with a low resistivity and applying a low bias voltage to it. This makes the active region of the counter small enough that the alphas are completely stopped in it and lose all their energy while the protons of the same energy penetrate through the active region and expend only part of their energy in it. The result is that the current signal received from the counter due to the protons can be made to be smaller than the signal due to the alphas of the same energy. Using this combination of solid state counter and spectrometer, the search for the recoil alphas now becomes feasible.
Before carrying out the above described experiment, three preliminary pieces of work had to be completed. First, a high flux (approx. 10 micro-amps) beam of deuterons had to be guided from the Van de Graaff generator, to the target at the object point of the spectrometer. This required the construction of a beam handling system comprised of two servo systems, namely a 17° electrostatic deflection system beam switcher followed by a two-dimensional magnetic servo lock-on system. Secondly, an exact determination of the particle trajectories in the spectrometer and its focusing characteristics was necessary to allow the mounting of the solid state counter at the optimum position for detecting the recoil alphas. Also, a baffling system had to be designed to keep scattered particles from reaching the counter. Finally, the characteristics of the solid state counter and amplifier had to be determined so that differentiation between alphas and protons could be accomplished.

In Chapter 5 a description of the experimental apparatus and procedure is recorded. Although no useful details on the reaction crosssection were obtained, information as to target thickness and stability, counter response and time dependent background will be useful in any future attempt at the crosssection measurement. With similar background conditions, assuming there will be no elastically scattered beam reaching the counter with good baffling, it should be possible to measure a crosssection of $\lesssim 10^{-32}\text{cm}^2$ with the present apparatus.
CHAPTER II
BEAM SERVO SYSTEM

The particle beam produced by the U.B.C. Van de Graff generator is to be guided by means of electrostatic and magnetic servo deflection systems and focused by electrostatic and magnetic quadrupole lenses to the object point of the sixty degree double focusing magnetic spectrometer. The beam emerges from the analysing magnet at the base of the Van de Graff and is focused on the entrance of the 17° E.S. deflector by a magnetic quadrupole lens. It is then deflected in the direction of the spectrometer object point by the 17° electrostatic deflection system and passes through the two servo steering magnets which lock the beam onto the target at the object point of the spectrometer; the steering magnets increase very considerably the latitude allowable in the tolerances on beam handling equipment preceding them. Two quadrupole lenses are placed between the deflection magnets and the target to conserve the beam intensity.

The positioning of the components of the servo system is shown in Figure 1. The approximate overall distance of travel for the beam is 34 ft. The distance of travel from deflector to target is about 25 ft. and the required stability of the beam on target is 1/25°. This is an angular stability of 1/100 degree or a stability of the 17° deflection system of about one part in two thousand. The control circuit of
that system was designed to give this stability. The horizontal and vertical steering magnets will deflect the beam up to 1° in either direction and the gain-feedback of the lock-on system is sufficient also to give a target position stability of 1/25".

17° Electrostatic Switching System

Mechanical Design:

The electrostatic deflection system consists of two concentric stainless steel plates, separated a distance of 0.375" by lucite spacers. These plates form a section of concentric cylindrical condenser with a radius of curvature 161" and an arc length four feet. The electrostatic field between the plates, when a potential difference is applied, varies as the reciprocal of the radius; therefore the fractional variation in the electric field between the plates is just the ratio of the plate separation to the radius of the curvature. This amounts to about one part in 500. The defocusing effect this has on the beam is easily corrected by the quadrupole lens which follows. Thus the electric field inside the plates can be considered constant for the purpose of calculating particle trajectories between the plates.

The system is designed to deflect up to 3.5 Mev particles from the Van de Graaff accelerator. The voltage which must be applied between the plates of the deflector to acc-
omplish this is 16.2 Kev (refer to Appendix C). It may be noted from the appendix that the voltage applied to the plates to produce a deflection will be directly proportional to the Van de Graaff potential and independent of the type of particle being accelerated.

**Circuit Design of Switching System:**

The electrical system associated with the Electrostatic deflector consists of two parts; one, the servo system, which drives, the other, the high voltage supply for the deflector plates. The servo system is activated by a signal generated when the particle beam strikes one of the beam position detectors ("sniffers" - see figure 1). The signal is amplified and fed into the control system of the high voltage generator, where it controls the voltage applied to the plates of the deflector.

The servo system itself is made up of two parts (refer to Figure 2). One part is a beam detector and the second a beam position servo. The beam detector initiates the action of the circuit driving up the deflector plate voltage. When the voltage reaches the correct magnitude, the position servo system is activated and controls the plate voltage from then on. Both parts are built around the operation of the 12AX7 double triode in a "long tailed pair" configuration. When a voltage difference is applied between the two grids the 12AX7 operates as a difference amplifier.
FIGURE 3.
and the amplified voltage difference appears across resistor $R_1$ and in turn across the output $AA'$, minus the emitter-base voltage of transistor $T_1$. The bridge and filter condenser supply the power necessary to operate the transistors as described, that is at 12 volts d.c., and 2 amps.

The output voltage $AA'$ is fed into the input of the saturable core multivibrator (Figure 3). This multivibrator is designed to operate at a frequency of 15.4 K.C. and turns out a peak voltage of 3.5 K.V., for an input of 10.5 volts d.c. This a.c. voltage is the input to a standard quadrupler which produces a d.c. output of 14 K.V. This, in turn, passes through an R.C. filter and supplies the required high voltage to the plates of the deflector. The ripple on the output of the filter was measured to be 24 volts which is about 2%.

**Beam Position Servo Operation:**

The beam position servo is activated by the beam striking two "Sniffers" which are half-moon shaped pieces of stainless steel (See Figure 1) situated about 4" past the exit of the deflection plates and electrically insulated from ground. Their straight edges extend approximately 1/16" inside the region defined by the planes tangent to the faces of the deflector plates at the exit of the deflector. When the particle beam from the Van de Graaff is passing correctly through the deflector, the deflector plate voltage $V_o$ will be
such that equal beam current will be falling on each "Sniffer". If $V_0$ drops, the beam will move onto the lower "Sniffer". This will cause a larger voltage to appear at grid $g_1$ (Refer to Figure 2). As described previously, this voltage rise will cause $V_0$ to increase and re-establish equilibrium. Similarly, if the plate voltage rises too high, the beam will strike the upper "Sniffer" and cause $V_0$ to fall. In this manner the deflector plate voltage is held such that the beam passes between the "Sniffers".

**The Beam Detector:**

The beam detector is an electrically insulated entrance aperture to the region between the deflection plates. Its function is to supply a signal which drives the deflector plate voltage up. The major portion of the beam passes through the aperture but a small portion strikes the detector. This small portion of beam current passes through diode $D_1$ (See Figure 2) since diode $D_2$ is back biased in the quiescent state. The current then passes through the resistance, selected by switch $S$, to ground. This generates a voltage at grid $g_1$ of the double triode and, as previously discussed, causes $V_0$ to rise. $V_0$ will continue to rise until a voltage appears at grid $g_2$ caused by the beam striking the upper "Sniffer". This, then, activates the second 12AX7 which lowers the voltage at point $p_1$ below ground. This forward biases diode $d_1$ and turns off the detector signal to $g_1$. The plate voltage is then held at the correct setting by the servo system.
Should some sudden fluctuation in the beam occur and cause the servo system to lose control, $V_o$ would drop and the beam detector would once again operate. This would allow the servo system to once more gain control.

It was found that if, for some reason, $V_o$ rose too high and the servo system lost control, the beam would strike the negative deflection plate. This would cause a high (up to 500 micro-amps) secondary electron emission current which would load the power supply heavily. As a result of the loading, the output voltage $V_o$ would drop and the servo system would gain control. No large secondary electron emission current results when the beam strikes the positive plate because the high electric field is biased to restrict electron emission.

Safety Precautions:

The deflection system is completely encased in a lucite box with the controls for the electronics mounted on the outside. This minimizes the probability of bodily contact with the high voltage supply.

To prevent the deflection plate voltage from rising too high and causing breakdown through the lucite spacers, a safety device was attached to the high voltage output.
This consists of two steel balls mounted on a lucite stand forming a spark gap. One ball is connected to the high voltage side and the other to the low. The distance between the balls was adjusted so that a spark would be produced when the voltage difference was greater than 15 kV.

The Two-dimensional Magnetic Servo System

To make minor corrections for fluctuations in the beam direction after it leaves the 17° electrostatic deflection system, two separate electromagnets with fields oriented at right angles to the beam and at right angles to each other are employed. These are designed to respectively deflect a 3 Mev(He⁴⁺) beam one degree in the horizontal and vertical directions and in combination to servo on a point, in much the same way as the electro-static deflector servos on a line.

The pole faces of the two electro-magnets are 4" square (See Figure 4). This ensures a reasonably homogeneous magnetic field in the middle of the pole faces. The material chosen for the magnets was ARMCO INGOT IRON because of its low residual field.

The beam travels 4" through the magnetic field and, to produce the 1° deflection of a 3 Mev(He⁴⁺), a 500 gauss magnetic field is needed. (See Appendix D). The coil used to produce the field has 200 turns of 13 guage enamelled magnet wire, and inductants of 0.017 henry and a d.c. resistance of
0.4 ohms. This corresponds to a time constant of 0.04 seconds. The current needed to produce a 500 gauss field is 5 amps which corresponds to a power dissipation of 10 watts in the coil. Two coils are needed per magnet so that each power supply must drive 0.034 henry and 0.8 ohms.

Servo Circuit:

In Figure 5 a diagram of the magnetic servo system and 6 volt power supply is shown. The servo circuit operates in much the same way as the previously described circuit for the electrostatic deflector. The 12AX7 is used as a difference amplifier. The voltage difference is amplified by the transistor circuit and applied to the base of the 2N278 power transistor, which is operating with the coil as the emitter load. The d.c. current conditions are set by adjustment of the 100 K pot until the beam is passing approximately between the two "Sniffers". The servo system then regulates the current through the magnet to keep approximately the same amount of current falling on each "Sniffer". The 6 volt power supply is needed to drive the transistors and the coil current.

The "Sniffers" are arranged in pairs adjacent to one another and separated by about \( \frac{1}{4} \)". Two pairs are needed and they are placed at right angles to each other. If the beam moves in any direction, either horizontally or vertically, it strikes one of the "Sniffers". This signal is fed back to the appropriate difference amplifier and the current in the magnet coil is
changed to move the beam back into the center of the square
formed by the four "Sniffers". Two of these groups of four
"Sniffers" are installed in the system; one about 5 feet from
the servo magnets and the other 20 feet from them, immediately
adjacent to the target assembly. The close group serves to
define the approximate direction of the beam and the far group
defines the exact placement. The first group also serves to
keep the beam on the second. Any large fluctuation in the
beam could possibly cause the group furthest away to lose con­
trol whereas the first group of "Sniffers" subtends a larger
angle and, as a result, is less likely to lose control.

The 6 Volt Supply:

The circuit drawing of the 6 volt supply for the
magnets appears in Figure 5. The supply has been designed to
deliver 5 amps at 6 volts into an inductance of 0.034 henry
with a ripple current of less than 1 part in 2000. This low
ripple is needed to attain the necessary stability in the
beam direction of 1 part in 2000.

To achieve the above design, a series transistor
regulator was used in conjunction with a 6.5 volt zener diode.
The high (3000 microfarad) output capacity for the bridge re­
ctifier is necessary to maintain the d.c. voltage above 7.5
volts, when the load is drawing 5 amps. Also, by putting
1000 microfarads on the base of the 2N301, the capacity is
effectively multiplied by the gain of the 2N301 times the gain
of the 2N278. This gives a very large effective capacity on the output. A 1 ohm resistance was connected to the emitter of the 2N278 to decrease its power dissipation.

All power transistors and rectifiers had to be mounted on copper heat-sinks and blowers used to keep the heat-sinks cool. As a safety precaution, a 35 volt thyrector was placed across the output of the transformer to remove all transients which might blow out the rectifiers in the bridge.
CHAPTER III

SURVEY OF THE 60° DOUBLE FOCUSING MAGNETIC SPECTROMETER

A preliminary investigation of the physical dimensions of the spectrometer had to be carried out in order to determine the object and image points as well as the two acceptance angles of the spectrometer. This was accomplished by employing a Wild T-2 Theodolite and a cathetometer. When the survey was complete, a monoenergetic source of protons was produced by scattering a proton beam from the Van de Graaff off a thin aluminum foil. A radioactive source of particles was not used in the trajectory surveys, since sources with sufficiently high specific activity to give the same source size energy resolution and intensity as the scattered protons are impossible to obtain. A three-dimensional survey of the focal properties of the image of the spectrometer was then carried out. The focus of the spectrometer was determined theoretically using a range of values for one adjustable parameter in the spectrometer field specifications (the extent of the fringing field on the output side of the magnet), and compared with the experimental results to determine the optimum value for this parameter. With these results, it was possible to calculate the optimum detector geometry for detecting the non-monoenergetic beam of recoil alphas which result from the D(d,α)He⁴ reaction.

See reaction kinematics in Appendix.
The Physical Dimensions of the Spectrometer:

The relevant angles of the spectrometer as measured using a cathetometer are recorded in Figure 6. These compared very favorably with the angles given in the specification. It will be assumed in all the following theoretical calculations that the angles in the specifications are correctly determined. Also, the acceptance angle of the spectrometer in the vertical direction, $\theta$ in Figure 7, may be assumed to be the angle between the horizontal plane and the vertical to the flange at the entrance to the spectrometer. The mean angle $\theta$ (i.e., the angle of the central ray) was then adjusted to 10°. Since the spectrometer accepts particles over a 10° range, centered about $\theta$, the minimum angle of acceptance is 5° and the maximum 15°.

The spectrometer has a fixed scale which determines the angular rotation $\phi$ of the spectrometer in the horizontal plane (refer to Figure 7). The zero of this scale was determined by sighting along the incident beam direction, using a transit, into the spectrometer. The spectrometer was then rotated in the horizontal plane until the plane of the pole faces was parallel to the line of sight. The reading on the spectrometer angle scale $\phi$ was recorded to be 339°. This, then, is the zero of the spectrometer.

"The Development of a Double Focusing Spectrometer".
To ensure the proper reading on the spectrometer scale the beam must always be incident in the same direction. For this purpose several points have been marked on the floor with the symbol \( \otimes \). The beam must pass vertically over these points and in the horizontal plane.

**Method of Focus Survey:**

The focusing properties of the spectrometer were measured using a monoenergetic source of particles at the object position. This monoenergetic beam was produced by scattering a 1 Mev proton beam from the Van de Graaff of a very thin evaporated aluminum target. The target was prepared by evaporating aluminum onto a very thin film of colodion. The acceptance angles of the spectrometer had been previously adjusted to be \( \Theta = 10^\circ \), \( \Phi = 0^\circ \). With this setting the spectrometer accepts particles at angles \( \Theta = 5^\circ \) to \( \Theta = 15^\circ \). In this range of angles the elastically scattered protons from the target are monoenergetic to better than 1%. To ensure that the target was at the object position the cathetometer was locked in position with the cross hairs focused on the object point of the spectrometer.

The object point of the spectrometer is shown in the specifications to be 6½" perpendicularly from the geometrical center of the front of the entrance flange. To determine this point in the laboratory a brass plate was made which fitted the entrance flange and a pointed brass rod was soldered perpendicular to the plate at its centre. When bolted onto the
entrance flange the point of the rod extended $6\frac{1}{2}''$ vertically from the flange. A second pointed rod was placed vertically upward from the axis of rotation of the spectrometer with the point of the rod at a height of $44\frac{1}{2}''$ from the floor, which is the height at which the beam emerges from the Van de Graaff. The spectrometer leveling screws were then adjusted so that the points of the two fixed rods coincided. This point of coincidence shall be referred to as the object position.

With the cathetometer locked in position with the cross-hairs focused on the object point, the target was placed to coincide with the cross-hairs. The coincidence of the target position and object position was checked repeatedly throughout the survey. A beam collimating system was set up in front of the target to ensure that the beam passed directly through the object point.

The detector used for the survey was an RCA SILICON JUNCTION ALPHA PARTICLE DETECTOR - TYPE A-4 75 VOLTS. The active surface of this counter was 2 mm in diameter. With this small active surface it was possible to detect changes in the flux of analysed particles in the image plane, i.e. in the shape of the image, over $1/10''$ intervals.

A low intensity proton beam, of the order of 0.0003 microamp, was obtained by collimating a very small amount of a low flux beam from the Van de Graaff. This beam was directed onto the target. The current through the spectrometer field
coils was adjusted to give the maximum count rate, on the elastically scattered peak, from the solid state counter placed in the approximate region of the focus. The current passing through the aluminum target was measured by means of a beam catcher placed directly behind the target and far enough away not to interfere with the beam scattered at an angle greater than $5^\circ$. The total number of counts for a preset integrated beam current was recorded.

Referring to Figure 7, the central ray, as described in the manufacturers specifications, was the normal to the plane of survey and shall be referred to as the Z axis. The plane of the survey is the X,Y plane, the X axis being parallel to the pole faces of the spectrometer and the Y axis being normal to the plane of the pole faces. The origin of the coordinate system is as shown in Figure 8.

With the spectrometer current held constant the solid-state counter was moved in the Y direction at 1/10" intervals with fixed X, Z coordinates, the number of counts for the same integrated beam current was recorded at each interval. When the survey was completed on this line the counter was moved 1/10" in the X direction. The current in the spectrometer was once again adjusted to give the maximum count rate at this point. With this current setting the survey in the Y direction was repeated. The above described method was continued until one complete plane had been surveyed.
The counter was then moved in the Z direction and a new plane was surveyed in the same fashion as the previous one. The survey was completed over a number of planes until the point of maximum counts, for the same integrated beam current, had been established.

The counts $N$ recorded by the solid state counter are due to the elastically scattered protons. That is

$$N = N(X, Y, Z, I_{\text{spec}}, \phi, \theta, I_{\text{beam}}, \xi, E)$$

Where

- $X, Y, Z =$ counter coordinates
- $I_{\text{spec}} =$ current in spectrometer field coils
- $\theta, \phi =$ spectrometer acceptance angles
- $I_{\text{beam}} =$ beam current
- $\xi =$ function describing target properties
- $E =$ beam energy

During the survey the beam energy and current and target properties remained constant. The total number of counts may be rewritten as an integral over the time of each run and over the surface of the counter. That is

$$N = K I_{\text{beam}} \int \sigma(\theta, \phi) S(X, Y, Z, I_{\text{spec}}) \, d\tau$$

where

- $K =$ a constant
- $\sigma(\theta, \phi) =$ nuclear coulomb cross section
- $S(X, Y, Z, I_{\text{spec}}) =$ function describing the focal properties of the spectrometer.
FIGURE 9.

$Y = +.1''$

$Z = +3.55''$

$I_{spec} = 19.15$ AMPS
FIGURE 10.
The survey is directed at determining the function $S$, so that, throughout the survey, it was important to hold all other functions constant. This is particularly true for $\sigma(\Theta,\Phi)$ which is the coulomb cross section and which for small acceptance angles $\Theta$ varies as $\Theta^4$. Therefore the angles of the spectrometer had to be fixed securely throughout the survey. It was found that the closest quadrupole lens could not be used since this affected the angle of incidence of the beam on the target by making the beam convergent, rather than parallel, and had a significant effect on the count rate again through the $\Theta,\Phi$ dependence of $\sigma$.

The normalized results of the survey are summarized in Figures 8-12. Figure 8 displays the count rate as a function of $Y$ for a constant $X,Z$ and spectrometer current and for different $X$ coordinates. Figure 9 displays the primary focusing quality, that is, the count rate as a function of $X$ for a constant $Y,Z$ coordinates and constant spectrometer current. The maximum count rates for each survey in the $Y$ direction, with constant $X,Z$ over the whole plane, are shown for five surfaces surveyed in Figure 10. Finally, the maximum count rate positions in each of the planes surveyed is recorded in Figures 11-12. Figure 11 shows the shape of the 2nd order focus at each point. Figure 12 shows their positions in the $X,Z$ plane and maximum count rate.

**Primary Focusing Quality:**

Over the whole volume surveyed it was found that
the size (width at half maximum of the coulomb peak) of the primary focus of the spectrometer, that is, the focus in the X direction, was of the order of, or less than, the size of the counter diameter. Figure 9 shows a typical survey of the first order focusing. This peak width did not change noticeably over the whole volume surveyed. The width of the peak is consistent with the size of the target spot and the magnification of the spectrometer. The size of the source was determined by the beam entrance aperture which was $\frac{3}{32}$". W.G. Cross gives the theoretical value for the magnification in terms of the parameters of the sector magnet. On substitution of the values corresponding to the U.B.C. 60° double focusing magnetic spectrometer, a value of 0.77 is found for the magnification. Therefore, the size of the image could be about $1/10"$, which is of the order of the size of the active region of the counter.

It may also be noted that, as the current of the spectrometer field coils is decreased, the primary focus moves in the X,Z plane toward the more positive Z and Negative X. (See Figure 12). The theoretical curve shown as a dark line is derived using a fringing field extension at the exit of 0.56" as in Figure.

Agreement between the theoretically calculated particle orbits and primary focal points for a particular spectrometer current and the experimentally observed focal points could not be established with the spectrometer char-

---

acteristics supplied by the manufacturer. The value of the magnetic field inside the spectrometer was measured using a proton resonance head, so the only remaining quality of the spectrometer not predetermined is the extent of the fringing field at the entrance and exit of the spectrometer. In the specifications for the spectrometer, the fringing field is taken into account by extending the spectrometer field by about one gap width (3/4") out from the edges of the pole faces of the spectrometer. It was found that, by decreasing the extent of the fringing field to 0.56" past the exit of the spectrometer and leaving the entrance field as specified, agreement could be established between predicted and experimentally determined primary focal points. (Refer to Figure 13).

The fringing field was changed only at the exit aperture for convenience. It is reasonable that the field should extend the same distance from both entrance and exit apertures. However, in the construction to find the distance the fringing field should extend from the edge of the gap, it was found easier to vary only the exit fringing field. When results consistent with the experiment were found by varying only the exit field, it was assumed that this would be sufficient to calculate the focal point of the alphas from the D(d,α)He⁴ reaction.

Counter Position and Baffling:

With this value of extent of fringing field it
$E_d = 2.5 \text{ MeV.}$

$R = 14 \text{ inches for } 10^\circ \text{ ray}$

$B = 5300 \text{ Gauss}$
is now possible to predict the trajectories of the particles in the spectrometer with some degree of certainty. In particular, the trajectories of the recoil alphas from the $D(d,\alpha)He^4$ reaction can be predicted. The kinematics of this reaction are calculated in Appendix A. The alphas will emerge from the target inside a cone of $15^\circ$ half angle with respect to the beam and the spectrometer, with $\Theta = 10^\circ, \Phi = 0^\circ$, will accept those particles which emerge at an angle $\Theta$ between $5^\circ$ and $15^\circ$. At any particular angle $\Theta$ there will be two energy groups of alphas. (Refer to Appendix A). The experiment will be directed at detecting only the higher energy group. These particles will have an energy speed of about 500 Kev for a 3 Mev beam of incident deuterons, the alphas at $5^\circ$ having an energy of 2.21 Mev and at $15^\circ$ having an energy of 1.41 Mev.

The predicted trajectories of these alphas are shown in Figure 14. Since they are not monoenergetic, they do not have a common focal point in the usual sense. However, a large portion of the trajectories converge in the region shown in Figure 14, which may be called a pseudo focus. The pseudo focus occurs because, at a particular beam energy, there is a unique relation between the energy of a particle entering the spectrometer, and the particular trajectory it follows. With a large counter it is possible to intercept most of these trajectories. The size of the counter used was limited by the resolution desired, since the resolution decreases proportionately to the area of the solid state counter.
A counter of length 14 mm was selected, the width to be determined by the second order focusing. This counter allows the interception of alphas that emerge between $\theta = 5^\circ$ and $\theta = 12^\circ$ which is an energy range of from 2.21 Mev to 1.65 Mev.

Also shown in Figure 14 is the baffling system designed to intercept particles which may otherwise, by multiple scattering, reach the counter. These baffles also serve to define the trajectories of the alpha particles in the spectro­meter. Lucite plate (1/8" thick) was chosen as the material from which to fabricate the baffles, primarily because of its low average nucleonic charge and resulting low coulomb scattering crossection and, secondly because of its ease of fabrication.

**Second Order Focusing:**

Second order focusing is the term used to describe the effect on particle trajectories in the direction perpendicular to the pole faces of the fringing magnetic fields. The theoretical calculation of this effect has been treated extensively by W.E.Stephens ³ and W.E.Cross ². The curvature of these fringing fields has the effect of exerting a force towards the centre of the gap on any particle incident at an angle to the edge of the pole faces. The net result is that, for a proper geometrical arrangement, the particles are focused in the Y,Z plane. This focus and the
primary focus, which in general do not co-incide, have been made to co-incide in the 60° double focusing spectrometer for a particular set of particle trajectories corresponding to a particular set of angles between trajectory and field at entrance and exit to the field. As can be seen from Figure 13, the primary focus can be moved about at will by changing the magnet current. Without the second order focusing the count rate at each primary focal point would be the same. However, the second order focusing changes with spectrometer current in a manner different from that of the first order focusing. As a result, the count rate at each primary focal point will be different. The primary focal point with the maximum count rate is referred to as the focal point of the spectrometer. At this point the primary and secondary focal points co-incide.

Second order focusing is clearly evident in Figure 8 where a sharp count rate peak can be seen in the centre of the distribution. The zero point on the Y axis corresponds to the centre of the gap. The focus is displaced 1/10" to one side because the centre of the target spot was displaced a little less than 1/10" to the other side of the object point. The position of maximum count

rate, that is the focal point, was found to be displaced slightly from the focus described by the spectrometer specifications and previous discussion of fringing field effects. (See Figure 13.)

The width of the counter needed to intercept the large majority of the beam may now be determined from Figure 11. A width of 7 mm was chosen and, as can be seen, this is sufficient to cover most of the second order focus width.
CHAPTER IV
COUNTER CHARACTERISTICS

As pointed out in the introduction, it is important that the counter be able to differentiate between protons and alphas of the same energy. For this reason the ORTEC SILICON SURFACE BARRIER DETECTOR was chosen. This detector is a large area p-n junction diode, with an extremely thin p-type layer on the sensitive side of the detector. The p-type layer is produced by the metal to semiconductor junction. The electrical contacts to the diode are made on the p-type region through a very thin (50-100 micrograms/cm$^2$) gold film and on the n-type side through an ohmic contact. At electrical equilibrium, when a reverse bias is applied to the diode, a strong electric field region (charge depleted region) is formed around the p-n junction. The region extends into the n-type material a distance $D$. This distance is dependant on the reverse bias applied and the resistivity of the material. When a charged particle enters the sensitive side of the counter it loses a small amount of energy in the "window", that is, the gold film contact, and then extends its remaining energy in the n-type region. The energy lost in the sensitive region goes into creating electron-hole pairs. These are swept out of the sensitive region by the electric field. The charge arising from this
is fed onto a capacitor. The voltage pulse arising has a height proportional to the energy the particle lost in the sensitive region.

As mentioned previously, it is important to be able to differentiate between protons and alphas of the same energy. One method of differentiation would be to make the active region just deep enough to stop alphas. A proton of the same energy would then pass through the active region and expend only a portion of its energy there. The result would be that the pulse height for the alpha particle would be much higher than for a proton. Alphas of energies up to 2 Mev are to be detected from the reaction, so that from inspection of Figure 15, the nomograph, a low resistivity counter is needed. Also, since resolution of the alpha and proton peaks is needed, a high resolution counter is necessary. The size of the counter was determined in Chapter IV to best suit the focus of the spectrometer. The detector which suited all of the above characteristics was an ORTEC SURFACE BARRIER DETECTOR. It has a resistivity of $300 \text{ ohm-cm}^2 \pm 25\%$, an active surface $7 \times 14 \text{ mm}$ and a window thickness of $50-100 \text{ micrograms/cm}^2$. This window thickness amounts to $20-40 \text{ Kev}$ for a $1.6 \text{ Mev}$ alpha. The relative response of the detector to alphas and protons was determined by detecting alphas and protons of the same energy and recording the pulse height as a function of the applied bias voltage.
Counter Testing Experimental Arrangements:

The obvious way to produce particles to test the response of the counter to alphas and protons in the energy range 1.5 to 2.0 Mev is to use the Van de Graaff beam. However, it is not possible simply to run the beam directly onto the counter since this high particle flux would destroy it. To overcome this difficulty, a much lower intensity source was made by coulomb scattering the beam off a thin homogeneous aluminum foil. The foil was prepared the same way as the foil in Chapter III. Its preparation consisted of mixing approximately equal amounts of Colodion and Amyl-acetate. Acetone was then added to this mixture as a thinner. A cylindrically-shaped container, of crossectional area a little larger than the target desired, was filled with distilled water and a few drops of the thinned mixture placed on the water surface. When the film formed on the surface had dried, it was removed by means of a wire bent to form a ring with radius equal to the desired film radius. The thickness of the film was varied by changing the amount of mixture added and the consistency controlled by the thinner. Aluminum was then evaporated onto the face of the film and the resulting foil used as the target.

The appropriate energy of the scattered beam was then resolved out by the $60^\circ$ double focusing spectrometer which had been preset with $\Theta = 10^\circ$ and $\Phi = 0^\circ$ which
SPECTROMETER CURRENT IN AMPS

HELIUM BEAM

PROTON BEAM

NUMBER OF COUNTS (x 10^-3)

FIGURE 16.
is a spread in $\theta$ of from $5^\circ$ to $15^\circ$. The energy loss by the scattered particle to the recoil nucleus in nuclear coulomb scattering is negligible at these angles. Therefore, the energy of the particles scattered from the thin aluminum foil is the same as the incident beam energy minus the energy loss due to the target thickness. The same collimation system as outlined in Chapter III was used to ensure the beam was directed onto the target at the object point of the spectrometer.

With a small beam of known energy from the Van de Graaff falling on the scattering foil the spectrometer current was varied. For current profiles see Figure 16. Referring to this diagram, when the count rate reaches a peak, the spectrometer current has been adjusted so that the counter is reading the elastically scattered beam from the foil. The low count background is due to small angle scattering of the beam from collimators along the beam path and to scattering inside the spectrometer. In the case of the alpha beam, it is expected that the current profile would have two peaks, one due to singly ionized $\text{He}^4$ and the other due to the doubly ionized. (See Figure 15). At a beam energy of 1.5 Mev. NUCLEAR DATA TABLES 1961 Pg.79 gives an expected ratio $(\text{He}^4)^+/(\text{He}^4)^{++}$ of 1 to 12. It can be seen that this ratio compares favourably with the value shown in Figure 15.
The procedure was to run a beam from the Van de Graaff onto the scattering foil and adjust the current in the spectrometer so that the counter was reading the elastically scattered peak. The pulse height of the peak was then recorded as a function of the bias applied to the solid state counter. This procedure was repeated at different energies for both alphas and protons.

The results of this survey are shown in Figures 17-19. In these graphs a correction for the aluminum foil thickness has been made. The thickness was calculated by noting the difference in spectrometer current for the same incident alpha and proton energies. The difference in spectrometer current corresponds to a difference in magnetic field in the spectrometer which, in turn, corresponds to a difference in momentum between alphas and protons emerging from the scattering foil. Knowing the incident energy of the alphas and protons, it is easy to calculate the target thickness necessary to produce this energy difference. The calculation of the Aluminum foil thickness can be found in Appendix D. The target thickness was found to be equivalent to 130 micrograms/cm² of Aluminum + 20%. The uncertainty in target thickness arises from the uncertainty in the difference of magnet currents plus the uncertainty in theoretical values of the stopping cross section for Aluminum. This target thickness for protons of 2 Mev. energy corresponds to 14.5 Kev, so that, the uncertainty in
FIGURE 17.

PROTONS

α PARTICLES

BIAS VOLTS
ENERGY IN M.E.V.

FIGURE 19.
proton energy is only of the order of 3 Kev. and is negligible compared to the proton energy.

**Window Thickness:**

The energy intercepts of Figures 18, 19, indicate the window thickness of the solid state counter. This can be seen from the curves to be less than 30 Kev. for Alpha particles of energy greater than 0.5 Mev. This checks favourably with the rated thickness of 20-40 Kev., for a 1.6 Mev. alpha.

**Linearity:**

It is expected from inspection of the nomograph Figure 15, that all alphas in the energy range 0.5 – 2 Mev., will be stopped in the active region of the solid state counter for an applied bias of 1 Volt or greater. Therefore the plot of pulse height against corrected energy should be linear for all applied biases. This is verified in Figures 18, 19.

The response of the counter to protons should be linear until the protons start penetrating past the active region of the counter. The proton curve then should depart from linearity, and the pulse height of alphas, of the same energy, should be higher than that of the protons. The point of departure of the counter from linear response to protons can be calculated from Figure 20. For example, with an applied
bias voltage of 2 Volts the counter bias will be 2.6 volts (Add 0.6 volts for contact potential). At this bias, the barrier depth D is 14 microns. A proton of energy 0.9 Mev. will penetrate to the edge of the active region, so that for higher energy, the proton will expend some energy in the inactive region. As a result, above this energy the response of the counter will be non-linear. Figure 20 is a plot of energy at which the response of the counter goes non-linear against bias voltage. The dark line is the theoretical curve and the points marked are the experimentally determined points from Figures 18,19. As can be seen, the experimental points lie on the theoretical curve, within experimental accuracy.

The variation in slope of the lines in Figures 18, 19, is due to the variation in counter capacity with bias voltage. Figure 15 shows that, as the bias voltage increases, the capacity of the counter decreases. The head amplifier used is a cascode with a grounded cathode fed back by a 4.4 pf., condenser. This amplifier was working with a gain of approximately 400. Therefore the capacity to ground, looking into the amplifier, was about 1700 pf. The current pulse generated when a particle is incident on the counter is shared between the counter capacity and the 1700 pf., head amplifier capacity. As the counter capacity changes so does the amount of current fed onto the head.
amplifier capacity and, as a result, the pulse height changes.

For example, at a 6 volt bias, the counter capacity is about 500 pf., and at 40 volts the capacity is 200 pf. (See Figure 15). The ratio of the pulse height for these two different biases should be inversely proportional to the ratio of the sums of the capacities before and after. That is:

\[
\frac{PH_1}{PH_2} = \frac{C_{amp.} + C_{\text{counter}(2)}}{C_{amp.} + C_{\text{counter}(1)}}
\]

\(PH_1\) = Pulse height for counter capacity \(C_{\text{counter}(1)}\)

\(PH_2\) = Pulse height for counter capacity \(C_{\text{counter}(2)}\)

At 1 Mev, the pulse heights are:

\(PH_1 = 145\) for 6 volts bias

\(PH_2 = 198\) for 40 volts bias.

\(C_{\text{counter}(1)} = 500\) pf.

\(C_{\text{counter}(2)} = 200\) pf.

\(C_{amp.} = 1700\) pf.

\[
\frac{C_{amp.} + C_{\text{counter}(2)}}{C_{amp.} + C_{\text{counter}(1)}} = \frac{1700 + 200}{1700 + 500} \approx 0.8
\]

\[
\frac{PH_1}{PH_2} = \frac{145}{198} \approx 0.8 = \frac{C_{amp.} + C_{\text{counter}(2)}}{C_{amp.} + C_{\text{counter}(1)}}
\]

It is evident, then, that the variation in slopes of the curves is consistent with the variation in counter capacity.
CHAPTER V.
EXPERIMENTAL, D(d,γ)He⁴ REACTION

Introduction:

A preliminary experiment in the measurement of the D(d,γ)He⁴ reaction crosssection was performed. The results of this preliminary experiment are not directly useful in the determination of the crosssection of this reaction. The reason for this appears to lie in the collimating of the bombarding beam. The collimation is sufficiently inaccurate to scatter a large number of particles from the beam directly into the spectrometer. The resulting count rate in the system is many orders of magnitude greater than what could reasonably be expected from D(d,γ)He⁴. Hence a measurement of the crosssection could not be made.

During this experiment, several measurements of relevance to the ultimate measurement of this crosssection by this method were made. They are discussed in the remainder of this chapter; they concern 1) the stability of D₂O transmission targets and 2) the time dependant background in the relevant energy region of the solid state spectrometer. A description of the preliminary experiment mentioned above is also included, since it will be useful for the analysis of the faults in the present system.
**Time Dependent Counter Background:**

Because of the deterioration of the performance of the counter described in Chapter IV, an R.C.A. 20 mm² counter was used. Its window thickness was determined to be 500 Kev., energy loss for 5.3 Mev., alpha particles by means of the differential range/energy relationships for alpha particles in air. The pulse amplitude versus energy loss in the counter calibration was determined and was consistent with the known properties of the amplifier system and the energy loss per electron-hole pair. From the reaction kinematics, the energy spectrum of the alphas resulting from the D(d,α)He⁴ which would strike the counter, was calculated, taking into account the available Van de Graaff voltage, the stopping power of the target and the orbit/energy relationships discussed in Appendix A. The "Time Dependent" background in this region of the pulse spectrum was then measured. The Van de Graaff was operated at 2.2 Mev., during this period so that the "Time Dependent" background included counts from Van de Graaff sparks and other Van de Graaff-induced events (apart from direct beam on-target produced events). The results were in the pulse amplitude region corresponding to energy losses in the counter lying between 1.5 and 1.6 Mev., which is the energy region specified above. The "Time Dependent" background was 0.2 counts/min. This count rate implies an upper limit to the smallest measurable cross-
section for the reaction. Assuming an experimental run would last not longer than approximately $3 \times 10^2$ min., the "Time Dependent" background would be 60 Counts. This background can, of course, be corrected for, but only to an accuracy of $\sqrt{\frac{1}{N}}$ where N is the number of counts. Hence, the irreducible limit to the count rate due to background is approximately 8 counts in 300 min.

The crosssection $\sigma$ is related to the number of counts in the correct energy region by :-

$$N_1 = \frac{Q}{e} N_2 \sigma \Omega$$

Where:

$Q$ = the charge in the beam striking the target = $2 \times 10^4$ microcoulombs for a 1 microamp beam for $3 \times 10^2$ min.

$e$ = electronic charge.

$N_2$ = target nuclei density in number of D nuclei/cm$^2$ which = $3 \times 10^{18}$ for a 30 Kev. thickness for a 2 Mev., deuteron.

$\Omega$ = effective detector solid angle = $4\pi \times 10^{-3}$ steradians. (effective means that transformation from centre of mass to laboratory co-ordinates has been allowed for.

This gives an upper limit to the crosssection of

$$\sigma \leq \frac{N_1 e}{QN_2 \Omega} = 2 \times 10^{-32} \text{cm}^2$$
FIGURE 21

THE TARGET ASSEMBLY
Heavy Water Transmission Target Stability:

A target of D$_2$O was laid down on a 23 x 10$^{-5}$ in. aluminum foil, cooled to liquid nitrogen temperature. The target was prepared by effusing D$_2$O vapour through a diffusing jet onto the cooled surface (See Figure 21). A beam of protons of energy 1 Mev., (corresponding to 2 Mev., deuterons in energy loss in the target) was passed through the target. The beam was approximately 1 microamp and was spread uniformly over the surface of the target. The D$_2$O target thickness was measured by magnetic analysis of the scattered protons, the target thickness being equal to the difference in energy between the protons scattered with and without D$_2$O frozen on the aluminum. The target thickness remained constant under this beam for more than 30 minutes.

Beam Scattering into Spectrometer:

In Figure 21, the collimating arrangements used at the present stage in the experiment is shown. Collimation of the incoming beam is necessary to define the target spot, and to prevent beam from striking other material than the target. Collimators are necessary on the input to the spectrometer to restrict its field of view to the target spot.

During the past measurement, beams were passed into the chamber under three conditions: a) with 23 x 10$^{-5}$ Al
foil in the target mount and b) with foil removed and c) with the aluminum foil and the beam catcher removed. In all cases, the pulse amplitude spectrum from the solid state counter was observed as a function of magnet current; that is, the particles being produced within the spectrometer's field of view were analysed for momentum and energy. In condition a) the spectrum comprised a very strong component at the energy and momentum corresponding to elastically scattered particles; at lower energies and momenta, a slightly weaker, but still very intense flux was observed.

Condition b) was then established in order to determine the source of the lower energy particles. With no aluminum foil in the target mount, there was no elastically scattered flux as in case a) but the lower energy flux continued at about the same level. Since it was considered possible that these particles were being degraded in energy and scattered into the spectrometer by the rim of the beam catcher, this was removed and condition c) established. This did not diminish the intensity of the low energy flux. It seems likely that this flux is produced in the collimating system. Further work on this is therefore necessary before the inherent capabilities of the rest of the experimental system can be realized.
APPENDIX A

D(d,γ)He⁴ REACTION KINEMATICS

The reaction considered has as its initial state an energetic deuteron incident on a stationery target deuteron. In the centre of mass (C.M.) system, both deuterons are moving toward each other with equal velocity \(v_d\), i.e:

Let

- \(m_d = \) deuteron mass
- \(E^\gamma = \) gamma energy.
- \(v^\alpha = \) velocity of the resultant alpha in C.M. system

Then

\[ v^\alpha = \frac{v_d}{2} \]

Where

- \(v_{cm} = \) velocity of C.M.
- \(v_d = \) velocity of incident deuterons in lab system.

In the centre of mass system, conservation of energy and momentum gives:

\[ T_{d_1} + T_{d_2} = 2T^\alpha = -Q + E^\gamma + E^\alpha \tag{1} \]

Where

- \(T^\alpha = \) kinetic energy in C.M. system
- \(Q = \) reaction Q value.
- \(E^\gamma = \) energy in C.M. system.
Also
\[ \mathbf{p}_A = \mathbf{p}_B \]
\[ P = \text{momentum in } C^M \text{system}. \]

Using
\[ \nu_d = \frac{1}{2} \nu_d \]

Then
\[ \nu_{d_1} = \frac{1}{2} \nu_d = \frac{1}{2} E_d \]

Substituting into 1)
\[ E^*_A = \frac{Q + E_d}{2} \]

Substituting 2) into 3)
\[ E^*_A + cP^*_B = Q + E_d \]
\[ E^*_A + \sqrt{m^2c^2 + (Q + E_d)} = 0 \]

So
\[ \sqrt{E^*_A} = \sqrt{\frac{m^2c^2}{2} + \frac{(Q + E_d)}{2}} \]

Squaring
\[ E^*_A = m^2c^2 + (Q + E_d) + \sqrt{\left(m^2c^2 \right)} + 2m^2c^2(Q + E_d) \]

Rearranging 4)
\[ E^*_A = m^2c^2 + Q + E_d + \sqrt{\left(m^2c^2 + Q + E_d \right) - (Q + E_d)} \]

From above it is evident only the minus sign is applicable.

To change to the laboratory system consider the vector relationship:
\[ \vec{v}_{cm} + \vec{v}_\alpha = \vec{v}_\alpha \]

That is
\[ \nu_\alpha^2 = \nu_\alpha^2 + \nu_{cm}^2 - 2 \nu_\alpha \nu_{cm} \cos \theta \]
\[ \nu_\alpha^2 + \nu_d^2 - \nu_d \nu_\alpha \cos \theta - \nu_\alpha^2 = 0 \]

Multiply by \( \frac{m_\alpha}{2} \)
\[ E_\alpha - \frac{m_\alpha}{2} \sqrt{E_d} \sqrt{E_\alpha \cos \theta - \left( E_\alpha - m_\alpha E_d \right)} = 0 \]
\[ \frac{\nu_d}{4 m_d} \]

Squaring, after solving for \( \sqrt{E_d} \)
\[ E_\alpha = m_\alpha E_d \cos \theta + \nu_\alpha^2 \pm \left[ \left( \frac{m_\alpha E_d \cos 2 \theta - E_\alpha}{4 m_d} \right)^2 - \left( \frac{m_\alpha E_d - E_\alpha}{4 m_d} \right)^2 \right]^{\frac{1}{2}} \] \[ \text{6) } \]

Using equations 5) and 6) it is possible to calculate the energy of the resultant alpha as a function of \( \nu_\alpha \) and \( E_d \).
APPENDIX B.
THE 17° ELECTROSTATIC DEFLECTION SYSTEM

As described in Chapter II, the system consists of a section of a concentric cylindrical condenser with:

Radius of curvature $r = 161"$
Plate separation $dr = 0.375"$
Arc length $s = 48 "$

When a particle of charge $Ze$, kinetic energy $T$, and mass $m$ is incident on the entrance aperture, tangent to the deflection plates, a voltage difference $v$ must be applied between the plates to deflect the particles 17°.

The electric field $E$ between the plates is assumed to be constant along the whole particle path between the plates. (Refer to Chapter II for discussion.) When the particles are passing correctly between the plates they will describe a circular orbit with a radius of curvature equal to the average radius of curvature of the deflection plates.

That is:

$$\frac{mv^2}{r} = ZeE$$

Where $v =$ velocity of incident particles.

But $E = \frac{v}{dr}$
\[ \frac{1}{2}mv^2 = T \]

So:

\[ \frac{2T}{r} = Zev \]

Let the potential of the Van de Graaff be \( V_o \), then:

\[ T = Zev \]

Substitute 2) into 1)

\[ \frac{2ZeV_o}{r} = \frac{ZeV}{dr} \]

Or:

\[ \frac{2V_o}{v} = \frac{r}{dr} \]

Therefore, the potential \( v \) necessary to cause the particle to move in an orbit of radius \( r \) is independent of the type of particle being accelerated and directly proportional to the Van de Graaff voltage \( V_o \).

For example, when

\[ V_o = 3.5 \text{ Mev.} \]

\[ v = 2dV_o = \frac{2(0.375)(3.5)}{161} = 16.3 \text{ Kev.} \]
ELECTRO-MAGNETIC SERVO LOCK-ON MAGNETS.

Each electro-magnet is designed to deflect a 3 Mev. He$^4^+$ up to $1^\circ$ from its incident path. The deflection takes place between the pole faces of the electro-magnet, which are 4" square and separated by a 1" gap.

The following is an approximate, although quite accurate, estimate. The time $\Delta t$ the He$^4^+$ spends in the field $\vec{B}$ is:

$$\Delta t = \frac{d}{v}$$

$d = 4''$

$v =$ velocity of incident charged particle.

The change in momentum $\Delta p$ in the time $\Delta t$ is:

$$\Delta p = F \Delta t$$

$F =$ force exerted by the field $\vec{B}$ on the charged particle.

$$F = qvB$$

where $q =$ charge on particle

Therefore

$$\Delta p = \frac{qvBd}{v} = qBd$$

The angular deflection $\Delta \theta$ for small $\Delta \theta$ is

$$\Delta \theta = \tan^{-1}(\Delta p/p) = \frac{\Delta p}{p}$$
Therefore

\[ \Delta \Theta = \frac{qBd}{2me} \]

\[ E = \text{energy of the incident particle.} \]

Using:

\[ \Delta \Theta = 1^\circ = 10^{-2} \text{radians} \]

\[ m = 4(1.66 \times 10^{-24}) \text{gms} \]

\[ q = 1.6 \times 10^{-20} \]

\[ E = 3(1.6 \times 10^{-6}) \text{ergs} \]

\[ d = 10 \text{ cm.} \]

Substituting into above expression for the maximum \( B \) necessary:

\[ B = 500 \text{ gauss} \]

It is now possible to calculate the number of amp turns necessary to produce this field in the gap. Consider an ordinary C magnet with current \( i \) in the coil and \( N \) turns. Let

\[ B_1 = \text{field inside coil.} \]

\[ B_2 = \text{field in gap.} \]

Amperes circuital law:

\[ H_i dS = Ni \]

\[ Ni = \frac{H_1 l_1 + H_2 l_2}{\mu_1} \]

\[ = \frac{B_1 l_1 + B_2 l_2}{\mu_1} \]

\[ \mu_0 \]
\[ \mu = \text{permeability} \]
\[ l_1 = \text{path in magnet} \]
\[ l_2 = \text{gap width.} \]

Let
\[ B_2 = \alpha B_1 \]
\[ \alpha = \text{leakage coefficient} = 0.6 \]

This is the usual assumption for a constant crosssection C magnet and should be an upper limit for the magnet used in the deflection system. Also, since:
\[ \frac{B_1 l_1}{\mu_1} \approx \frac{B_1 l_2}{\mu_0} \]

Therefore
\[ N_i = \frac{\alpha B_1 l_2}{\mu_0} \]

The field in the gap \( \alpha B_1 = 500 \) gauss
\[ = 500 \times 10^{-4} \text{Webers/m}^2 \]
\[ l_2 = 2.54 \text{ cm} = 0.0254 \text{ m} \]
\[ \mu_0 = 4 \times 10^{-7} \text{henry/m} \]

\( N_i = 10^3 \) amp turns.

A current of 5 amps was used which required
\[ N = 200 \text{ turns of magnet wire} \]

This number of turns was wound around a 10" diameter spindle to fit the magnet shown in Figure 4. This amounts to 167' of wire. The enameled magnet wire used was 13 gauge,
Then since

\[ L = \frac{N_i}{I} = \frac{N^2 A_2 \mu_0}{\alpha l_2} \]

Substituting the values given for above and using the fact that the area of the gap \( A_2 \) is 8\" sq.,

\[ L = 0.017 \text{ henry} \]
APPENDIX D

TARGET THICKNESS CALCULATION

In Chapter IV, a correction to the energy of the particles emerging from the scattering foil was found necessary. This correction must be applied to the incident beam energy to find the energy of the particles emerging from the foil. The effect of the foil thickness was observed by noting the difference in energy between the alphas and protons emerging when both were incident at the same energy. This energy difference was detected by the 60° double focusing spectrometer and appeared as a difference in field coil current necessary to sit on the elastically scattered peak for each particle beam. The equations of motion of the particles in the spectrometer are governed by the following:

\[ p = ZB\rho \]  \hspace{1cm} (1)

Where

- \( p \) = momentum of the particle.
- \( Z \) = charge of the particle.
- \( B \) = magnetic field between pole faces of spectrometer.
- \( \rho \) = radius of curvature while in magnetic field.

Also

\[ E = \frac{p^2}{2m} \]  \hspace{1cm} (2a)

\( E \) = particle energy.
\( m \) = particle mass.
Differentiating:
\[
\frac{dE}{E} = \frac{2dp}{p} \quad \text{(2b)}
\]
Differentiating:
\[
dp = ZpdB \quad \text{(3)}
\]
Substitute (3) into (2b):
\[
\frac{dE}{E} = \frac{2dB}{B} \quad \text{(4)}
\]
Since \( B = kI_{\text{spec}} \):
\[
k = \text{constant.}
\]
\( I_{\text{spec}} \) = spectrometer current.

4) then becomes
\[
\frac{dE}{E} = \frac{2dI_{\text{spec}}}{I_{\text{spec}}} \quad \text{(5)}
\]
Considering (1) and (2a):
\[
Bp = p = \sqrt{\frac{m(2E)}{Z}}
\]

From this it can be seen that the ratio \( m/Z \) is the same for protons and alphas, so that the orbits for protons and alphas of the same energy are equivalent.

Knowing this, it is now evident that equation (5) holds for both alphas and protons at the same time. Therefore any small energy difference \( dE \) between alpha and proton will appear as a small field coil current difference \( dI \) in the manner predicted by equation (5). For example, for incident 2.5 MeV, alphas and protons
\[
dI = I_p - I_{\text{alpha}} = 27.4 - 26.7 = 0.7 \text{ amps}
\]
\( I_p \) & \( I_{\text{alpha}} \) experimentally determined.
Therefore
\[ dE = \frac{2(o.7)^2 \times 10^3 \text{Kev.}}{27.4} = 102 \text{ Kev.} \]

Knowing this energy difference, it is now possible to calculate the target thickness necessary to give this \( dE \). From NUCLEAR DATA TABLES pg.79

\[ \frac{dE}{dx} \mid_{2 \text{ MeV proton}} = 110 \text{ Kev cm}^2/\text{mg} \]

\[ \frac{dE}{dx} \mid_{2 \text{ MeV alpha}} = 1000 \text{ Kev.cm}^2/\text{mg}. \]

Then, the energy difference between protons and alphas emerging from the target of thickness \( T \) is:

\[ T \left( \frac{dE}{dx} \right)_\alpha - \frac{dE}{dx} \pi = \Delta E \]

Using above values:

\[ T = \frac{102 \text{ Kev.} - 118 \text{ micrograms/cm}^2}{890 \text{ Kev.cm}^2/\text{mg}} \]

Similar calculations were carried out for different beam energies and are listed below:

<table>
<thead>
<tr>
<th>Beam energy</th>
<th>Exp.energy diff.</th>
<th>Calculated T</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>125</td>
<td>152</td>
</tr>
<tr>
<td>1.0</td>
<td>137</td>
<td>129</td>
</tr>
<tr>
<td>1.5</td>
<td>139</td>
<td>145</td>
</tr>
<tr>
<td>2.0</td>
<td>102</td>
<td>118</td>
</tr>
</tbody>
</table>

\( T_{\text{ave.}} = 131 \text{ micrograms/cm}^2 \)
The largest deviation from the mean is about 18%. With the accuracy quoted in NUCLEAR DATA TABLES of dE/dx of 1%, the maximum expected error in $T$ is about 19%, that is:

$$T = 131 \text{micrograms/cm}^2 \pm 26 \text{ micrograms/cm}^2.$$
APPENDIX E.

ESTIMATE OF $D(d,\sigma)He^4$ REACTION CROSSECTION

The model of the interaction to take place is the following. The deuteron is incident on the target deuteron in an $S$ wave configuration. The wave function amplitude will be attenuated due to the coulomb barrier and reflection from the nuclear potential. The particle will then be considered to pass only once across the nuclear diameter and the electro-magnetic transition must take place during this transit time. The estimate of the transition probability to be used is the usual Blatt & Weiskoff transition probability. The reaction crossection may be written:

$$\sigma = P_d \cdot T_c \cdot T_n \cdot \sigma_{sc} \cdot T_m(1) \cdot t$$

Where

$P_d$ = the probability of the excited state of the $He^4$ being formed with the appropriate spin.

$T_c$ = coulomb transmission coefficient

$T_n$ = nuclear transmission coefficient

$\sigma_{sc}$ = scattering crossection, which is an estimate of the probability of the two deuterons being close enough to interact.

$T_m(1)$ = magnetic dipole transition probability.

$t$ = length of interaction time or length of time in which the interaction may occur.
Treating each term individually, first let us consider the coulomb transmission coefficient. The electrostatic coulomb forces will be considered to be effective up to the point where the nuclear forces are appreciable. That is, the coulomb barrier $B_c$ is the potential energy of the two deuterons separated by two deuteron interaction radii, or:

$$B_c = \frac{Z^2 e^2}{r}$$

where

- $Z = 1$ for deuterons
- $e = \text{the electronic charge}$
- $r = 2 \text{ deuterons radii}$
  \[= 2(4.3 \times 10^{-13}) \text{ cm.}\]

Substituting these values into the above:

$$B_c = 0.168 \text{ Mev.}$$

Since the energy in the centre of mass system of the bombarding deuterons is 1.5 Mev., the coulomb barrier is much less than the energy of the incident deuteron. In the first approximation then, the coulomb transmission coefficient $\tau_c$ is one.

An estimate of the transmission coefficient through a discontinuity in potential, due to the attractive nuclear potential is given in Blatt & Weiskoff Pg.627 as

$$T_n = \frac{4kk}{(k+K)^2}$$

where $k=\text{wave number of the incident particle.}$
\[ K = \text{the wave number of the particle inside the nucleus.} \]

In the compound nucleus model, the energy of the particles in the nucleus is shared equally and \( K_0 \) is a constant equal to about \( 10^{+13} \text{ cms} \). Also

\[ k = \sqrt[5]{\frac{2 M E_d}{\hbar}} \]

\( M = \text{mass of the deuteron} \)
\( E_d = \text{energy of the deuteron in the centre of mass system or about 1.5 Mev.} \)

Substituting these values into the above expression:

\[ k = 2 \times 10^{12} \text{ cms} \]

OR \( k = \frac{K_0}{5} \)

Therefore;

\[ T_n = 2/3 \]

Also from Blatt & Weiskoff pg.627, an estimate of the magnetic dipole transition probability is given as:

\[ T_m(l) = \frac{1.9(l+1)}{2} \left( \frac{3}{l+3} \right)^2 \left( \frac{\hbar \omega}{197 \text{ KeV}} \right)^{2l+1} (R \text{ in } 10^{-13} \text{ cm})^2 \times 10^{-0.2l} \text{ sec}^{-1} \]

In the transition to be considered, \( l = 1 \) and is approximately a 25 Mev.gamma. The transition is to take place inside the combined deuteron radii or:

\[ l = 1 \]
\[ \hbar \omega = 25 \text{ Mev.} \]
\[ R = 8.6 \text{ Fermi} \]
Substituting these values into \( T_m(1) \) it is found \( T_m(1) \) equals \( 4 \times 10^{17} \) /second. The time of nuclear interaction of the two deuterons is assumed to be of the order of the transit time of the incident deuteron across the nucleus. Since the deuteron inside the nuclear radius is in a 25 Mev excited state, this is assumed to be approximately the kinetic energy of the deuteron in the nucleus. That is,

\[
K.E. = \frac{1}{2} Mv^2 = 25 \text{ Mev.}
\]

\[
v = \sqrt{\frac{2E}{M}}
\]

and the transit time is:

\[
t = \frac{R_{\text{nucleus}}}{v}
\]

where \( R_{\text{nucleus}} = \text{nuclear radius which} = 8.6 \times 10^{-13} \text{ cms.} \)

\[
v = \text{velocity of the deuteron in the nucleus.}
\]

therefore:

\[
t = R_{\text{nucleus}} \sqrt{\frac{M}{2E}} = 2 \times 10^{-22} \text{ sec.}
\]

The probability of the alpha being formed with spin \( J = 1 \), may be calculated with the assumption that no spin orientation is preferred over any other. Then, the number of ways any total spin \( J \) can be formed is just \( 2J+1 \). Three different spin combinations can be formed by the two spin \( J = 1 \) deuterons. They are \( J = 0, 1 \& 2 \). The probability of \( J = 1 \) being formed is the total number of ways \( J = 1 \) can
be formed divided by the total number of ways all three spins can be formed. That is:

\[ P_{df} = \frac{2J+1}{\sum_{i=0}^{3}(2J_i + 1)} = \frac{1}{3} \]

Finally, an estimate of the scattering cross-section is needed, which is an estimate of the probability that the two deuterons will come close enough to each other to interact. The usual estimate is that:

\[ \sigma_{sc} \approx \frac{4\pi}{k^2} \]

\[ k = 2 \times 10^{12}/\text{cm} \]

\[ \sigma_{sc} \approx \frac{\pi}{4} \times 10^{-24} \text{ cm}^2 \]

Using the above derived values, it is now possible to estimate the crosssection. Substituting these values into the previous equation it is found:

\[ \sigma \approx 10^{-29} \text{ cm}^2 \]

**Factors reducing the estimated crosssection:**

1) Transition may be E2

2) T_m(1) is usually found to be from 10 to 100 times too big.
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