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MAGNETIC ANALYSIS OF THE CHARGED PARTICLE GROUPS PRODUCED BY THE BOMBARDMENT OF CARBON, BERYLLIUM, AND OXYGEN WITH DEUTERONS

by

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INTRODUCTION

In the study of nuclear energy levels, there are certain similarities with the methods used for the determination of atomic energy levels. However, in considering nuclear processes in general there is a marked difference from the case of atomic collisions, a fact which was first pointed out by Bohr. According to him, the two-body theory of atomic collisions must be replaced by a many-body treatment in which account is taken of the exchange of energy between the many distinct particles which make up the nucleus.

The basic fact is that the forces between nuclear particles are short-range forces, as opposed to the long-range inverse square electrostatic forces involved in atomic collisions. The distances between neighboring nuclear particles are of the same order as the range of the forces, and the forces between the neighboring particles are comparable with the forces between one of them and the rest of the nucleus. As a result, a particle which strikes a heavy nucleus cannot pass through as a fast electron passes through the extra-nuclear structure of an atom. It must instead lose energy by collisions with the closely-packed nuclear particles, and its energy is soon shared among the particles making up the nucleus.

The combination of the incident particle and the initial nucleus is called the compound nucleus. According
to Bohr's picture, the compound nucleus remains similar to an ordinary nucleus in a high state of excitation until by a fluctuation the excess energy is again concentrated in one particle, which can then escape. The state of the compound nucleus is very quickly no longer dependent on the way it was formed, and it could have been produced by another particle with corresponding energy incident on a suitable nucleus. Its decay into an emitted particle and a residual nucleus is thus independent of what happened before. From this point of view a nuclear reaction can be divided into two well separated states; the formation of the compound nucleus, and its disintegration.

Like an ordinary stable nucleus, may be expected to have a spectrum of quantized energy levels. So far no definite regularity has been found in the spacing of these levels. The distance between the lowest levels of an ordinary stable nucleus is of the order of magnitude of 1 Mev. As the excitation energy becomes higher the level density becomes greater. This increase should be the larger the more particles there are in the nucleus. Since we are dealing with a system of several particles, any one of which has nearly all the excitation energy only very rarely, excited states, called virtual levels, can exist above the disintegration energy for times sufficient to
permit radiation. Another consequence of this fact is that the energy levels of the nucleus as a whole will be very numerous and closely spaced.

The nuclear energy levels can be investigated by several means. The excitation energy to form the compound nucleus can be provided by γ-rays, charged particles, or neutrons. The energy furnished by the addition of a particle to the nucleus, disregarding its initial kinetic energy, is equal to the binding energy of the particle in the compound nucleus and is of the order of 8 Mev for neutrons and protons.

The width of a low-lying level is purely a radiation width as long as the excitation energy is lower than the lowest binding energy of a particle. The mean lifetime of a state, \( \tau \), is connected with its width, \( \Delta \), by the relation

\[ \tau \Delta = \hbar \]

With sufficient excitation energy, a particle can be emitted with different energies corresponding to the different states in which the residual nucleus can be left. The widths of the levels increase with higher excitation energy since more particles can be emitted, more states of the residual nucleus are possible, and the probability of emission of a
particle increases with its velocity. At some value of the excitation energy the widths of the levels become larger than the level distances, and the levels overlap.

In the excitation of a nucleus by a particle, the absorption of the particle by the nucleus should be appreciable only if the sum of the binding energy and kinetic energy of the particle is equal to or within the width of an excitation level of the compound nucleus. For this case, as one changes the energy of the bombarding particles, he should observe typical resonance phenomena. Thus if one has a source of monoenergetic particles, he can, by varying the energy of the beam, investigate the levels of the compound nucleus above the binding energy of the particle used as a projectile. Such resonance levels have been observed with alpha particle and proton bombardment on light elements up to aluminum. A particularly good particle to use in resonance absorption studies is the thermal neutron. Since it is not charged, the neutron can penetrate the nucleus easily even at low energy, and this makes possible the study of resonance absorption even for heavy nuclei.

Another method of studying nuclear energy levels is the measurement of the energy differences of emitted particle groups. The energy distribution of such groups consists of a series of peaks which are a picture of the
spectrum of the residual nucleus, the highest energy corresponding to the lowest level of the residual nucleus. If the emitted particles are charged, their momentum distribution can be measured with a large annular magnet. Such a magnet was first designed by Cockcroft\(^1\) and used by Rutherford\(^2\) and his co-workers to measure accurately the energies of the natural alpha particle groups. In the case of neutron emission, the residual nuclei can be examined with an annular magnet, although the problem in this case is complicated by the fact that the nuclei can have various charges and thus one will obtain several peaks for a given energy of the residual nucleus.

A magnet similar to the one used by Rutherford is being used at the Massachusetts Institute of Technology by W. W. Buechner and his associates\(^3\) in studying nuclear energy levels as discussed above. A modification of this design has been made at The Rice Institute, and a magnet has been constructed and put into operation here. The performance of this instrument has been checked by using

1) J. D. Cockcroft, J. Sci. Inst. 10, 71, (1933)
it to measure the $Q$ values of several nuclear reactions previously investigated by the M. I. T. group. The $Q$ of a reaction is the total energy evolved in the reaction.

In the present measurements, a beam of deuterons is incident on a thin foil of the material under investigation at an angle of $45^\circ$ with respect to the foil. The foil is placed in the center of the region of uniform field of the magnet, and those charged particles which come off the foil at an angle of $45^\circ$ with respect to it and $90^\circ$ with respect to the incident beam are deflected by the magnetic field and brought to a focus $180^\circ$ around from the target at which point they pass through an energy resolution slit and then are counted. Because the incident deuteron beam must be brought in to the target through the field of the annular magnet, the angle at which it strikes the foil is not quite $45^\circ$, and this effect must be taken into account. Knowledge of the magnetic field necessary to deflect the emitted particles through the slit together with the incident deuteron energy enables one to calculate

4) W. W. Buechner, E. N. Strait, S. Sperduto, and R. Malm, Phys. Rev. 76, 1543, (1949) and

W. W. Buechner and E. N. Strait, Phys. Rev. 76, 1547, (1949)
7.

the Q value of the reaction under consideration.

In the experiments to be described, both the method used for determining the energy of the incident particles and that for measuring the field of the magnet are different from those used by Professor Buschner. In the M. I. T. work, the energy of the incident deuterons was measured by the magnetic analysis of deuterons elastically scattered from thin foils placed in the target positions. The magnetic field was measured by means of a fluxmeter calibrated in terms of polonium $\alpha$-particles. In the present work the energy of the incident beam was determined by means of the $0.8735$ Mev. $^9\text{F} \left( p \alpha^1, \gamma \right) ^{16}\text{O}^5$ resonance as measured by Herb and his associates. The magnetic field was measured in terms of the magnetic moment of the proton.

II
DETAILS OF MAGNET CONSTRUCTION

The annular magnet was constructed of A. I. S. I. 4815 forging steel. This steel has satisfactory magnetic properties and excellent machining characteristics. The annular region has an inside diameter of 25.56 inches and an outside diameter of 29.50 inches. The gap used in the present experiments was 0.562 inches, but the magnet is so designed that the gap can be increased to 2 inches if it becomes desirable to use an inhomogeneous magnetic field in later experiments. The drawings of the magnet are given in Figure 1.

The magnet is energized by means of four water-cooled coils, each of about 1400 turns, wound with #14 double vacuum impregnated and baked after Vitrotex wire. The coils were a winding. They can dissipate about 3 kilowatts with water cooling alone, and at this power level a magnetic field of about 15 kilograms is obtained with the present gap.

The magnet rests on non-magnetic ball bearings when in use and can be rotated about its axis of symmetry perpendicular to the plane of the gap by this means. Rotation about the two mutually perpendicular axes parallel to the plane of the gap is accomplished by means of four screw jacks at the bottom of the table supporting the magnet. The magnet was constructed by the Cameron Iron Works of Houston and presented by them to The Rice Institute.

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1. Drill 2" deep.
2. Tap 1\(\frac{1}{8}\)" BNS-2 - \(\frac{1}{2}\)" full thread.
3. 1 hole at center.

Relief:

Tapping:

No. 25 (1495) drill
Tap No. 10-24, 2
82° C.S. 10° dia., 1
8° B.C. equally

Top ring - 1 req'd.
3 holes, eq. spaced on 2 7/64 dia. - 1/16
hole circle - 2.01 (fl) drill - 5/32 dp
trap 1/8 - 20 n6 - 2 - 1/8 dp

5 (1495) drill - 1" deep
no. 16 - 24 - 1/2 full thd
5 1/16 dia. - 4 holes on
- equally spaced.
Spacer Washer - 1 Req'd
TOP RING - 1 REQ'D

29.504 Dia
29.994

16\frac{1}{2} Dia \pm \frac{1}{64}

\frac{1}{8} \times 45°

22\frac{1}{2} ± \frac{3}{64} Pitch Dia.

27.501
27.999 Pitch Dia.

30.500 ± \frac{3}{64} Dia.

BOTTOM RING - 1 REQ'D

* THESE THICKNESSES TO BE GRIND BOTH SPACERS
- NOT OVER 250 RMS
- NOT OVER 50 RMS
- NOT OVER 20 RMS

(ENGINEERING DRAWING BOTTOM RING)
5(1495) Drill - 1" Deep
No. 10-24 - 3/4" Full Thd.
5, 3/8 Dia. - 4 Holes on equally spaced.

Finish cut on this groove and corresponding groove in Pt No. 90956 must be made with same tool.

Furnish:
1 - Lifting Eye - Pt. No. 11849
4 - Machine Screws - Flat Head
*10 - 1/2" x 3/4" Long.
1 - Pc 9620 - 1" Ø x 3 FT Long

Ness to be equal. Surface 4 spacers at same time
250 RMS Microinches
50 RMS Microinches
20 RMS Microinches
Figure 1. **Annular Magnet**

**Pt. No. 11849**

Ø x 5 FT long.

*SAE 4815 Steel - No.*

MAKE FROM FORGING
1. **Annular Magnet**

SAE 4815 steel - Normalize & Anneal

Make from forging No 90947-30
A: $4,000 \pm 0.010$
B: Dim A $\pm 0.0002$ (Dim A Measured After Machining)
C: $12,000 \pm 0.010$
D: Dim C $\pm 0.000$ (Dim C Measured After Machining)
FINISH CUT ON THIS GROOVE AND CORRESPONDING GROOVE IN PT NO 90956 MUST BE MADE WITH SAME TOOL.

FURNISH:
1 - LIFTING EYE - PT NO 11849
4 - MACHINE SCREWS - FLAT HEAD
*10 - TWO x 3/4 LONG.
1 - PC 4620 - 16 x 3 FT LON.
Figure 1. Annular Magn.

SAE 4815 Steel - NOM.

MAKE FROM FORGING.

Property of Cameron Iron Works, Inc., Houston, Texas.

| Property | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W | X | Y | Z |
|          |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
Annular Magnet

SAE 4815 STEEL - NORMALIZE & ANNEAL

Make From Forging No 90947-30
9.

III.

DETAILS OF VACUUM SYSTEM

The vacuum system connecting the target and counter assemblies was made by bending into an arc of a circle and than flattening copper tubing of 2 inches outside diameter and 1/16 inch wall thickness. This work was done by the Texas Pipe Bending Co. Inc. of Houston. The ends of this tube were silver soldered to the machined brass target and counter assemblies, drawings of which are given in Figure 2 and Figure 3. These assemblies were made vacuum-tight by waxing on phosphor bronze lids .020 inch thick which were held in place by 2-56 brass screws. A line passing over the center of the target, the center of the magnet, and the center of slit in front of the counter was scribed on top of the system. The line of the circular edge of the pole piece was also scribed on top of the target assembly, and these lines together with 180° lines scribed on the surface of the top pole piece, were used to line the vacuum system up accurately with respect to the pole pieces. The entire assembly was prevented from moving with respect to the pole pieces by sheets of dentists rubber dam placed both below and above the target and counter assemblies.
The target assembly consisted of a pair of .010 inch washer-shaped silver rings at right angles to each other soldered to the end of a .034 inch phosphor bronze rod. One ring carried a circular quartz plate on which was glued a quartz fiber coated with phosphorescent zinc sulfide. The other ring carried the beryllium foil, cemented on with shellac. The vacuum seal of the rod was made through a tapered teflon fitting, and stops were provided for the positions in which the quartz and the beryllium target respectively were presented to the deuteron beam. The target holder just described was surrounded by a cylinder of .010 inch silver which collected the deuteron beam passing through the target. The target and silver cylinder assemblies were insulated electrically from the rest of the vacuum system by means of a lucite plate and lucite bushings on the screws holding the end plate in place. This enabled one to connect the beam collector to the current integrator and thus measure the total charge passing through the target in each run. The end plate carrying the target assembly was sealed to the rest of the vacuum system by means of "O" rings, and accurate reproducibility of target position was obtained by the use of lapped spacing washers which limited the compression of the "O" rings. The .010 inch silver box in front of the target holder was held at 150
The particle counter used had an active volume of 3/8 x 3/8 x 1 3/8 inches. It had a .005 inch tungsten center wire tipped with a glass bead, and it was operated as a proportioned counter. The mica window if the counter was waxed into place. The counter was provided with a system by means of which the regions on both sides of the window can be evacuated simultaneously and then the counter filled to a low pressure with an appropriate gas, thus permitting the use of very thin windows. In the present experiments, half an atmosphere of a mixture of 95% tank argon and 5% tank carbon dioxide was used as the counter filling. A milled slot on the diameter of the magnet passing through the center of the target was provided in the counter assembly for the insertion of aluminum plates with slits of various widths for setting the energy resolution of the instrument. In the present work a slit .175 cm. wide was used for the 1% data and one .875 cm. wide was used for the ½% data.

The target assembly was connected to the main vacuum system of the Van de Graaff generator by means of a set of
two sylphon bellows at the ends of a section of straight brass tubing. The distance between the gaps of the analyzing and annular magnets was 21\(\frac{\pi}{4}\) inches.

IV

MEASUREMENT OF \(\rho\) AND OF \(\cos \Theta\)

The radius of curvature, \(\rho\), of the particles analyzed by the annular magnet was measured by means of the calibrated screw on a large milling machine before the top plates of the target and counter assemblies were put in place. A fixed pointer was used, and the assembly was adjusted until the pointer passed directly over the center of the silver target ring and the centers of the milled slot in front of the counter window. When the table of the machine was moved along its ways.

The distance from the target to each end of the slot was then measured by means of the calibrated screw on the machine. At the conclusion of the experiments, the top plates were removed and the distance was again measured in terms of the screw on the milling machine. This time a fixed optical telescope was used to sight on the edges of the slot at the counter and on the top of the quartz fiber. The distance
between the quartz fiber and the center of the carbon deposit made on the beryllium target by the deuteron beam had been measured previously by means of a cathetometer. This measurement was made on the beryllium foil used in the run with 1% energy resolution. It was made necessary because the quartz fiber was not in the same plane as the beryllium foil and because the deuteron beam was centered on the shadow of the quartz fiber rather than on the fiber itself. The intensity of the zinc sulfide fluorescence burned off, and it was unsatisfactory for centering the beam. The correction applied to the measured \( \rho \) of 34.895 cm. due to this effect was 0.053 cm.

The angle which the direction of the incident deuterons made with the direction of the outgoing particles moving along the central path of the annular region, \( \Theta \), was measured in the following manner. The deuteron beam was made to pass through a slit placed on the line joining the target and its focal point and in the region of the uniform field of the annular magnet. If the distance between this slit and the target is \( d \) and the radius of the curvature of the path of the deuterons in the uniform field of the annular magnet is \( r \), then we have to the first order that

\[
\cos \Theta = -\frac{d}{2r}
\]
The quantity \( r \) was calculated from the known energy of the deuterons and the known magnetic field of the annular magnet.

V.

MEASUREMENT OF \( H \)

The magnetic field of the annular magnet, \( H \), was both measured and held constant by means of a proton magnetic moment regulator constructed by Richard D. Jones and discussed in detail in his thesis submitted for the degree of Master of Arts at The Rice Institute in May, 1950. The proton magnetic moment absorption signal was presented on an oscilloscope screen and was used to monitor visually the constancy of the magnetic field during the runs of the present experiments. Resistances in series with the magnet coils could be varied manually to provide for large changes of current to the coils.

The frequency of the oscillator used to provide the energy at the Larmor frequency of the protons was measured and checked by means of a U. S. Army Signal Corps Frequency
Meter Model # BC-221-D. The oscillator frequency was checked frequently at the ends of runs, which lasted about 10 minutes and it was found that the drift of the oscillator during a run was of the order of a few thousand cycles per second.

The wave meter was checked by beating its signal with that of radio station WWV by means of a short-wave receiver. This test was made before the experiments and immediately upon the conclusion of the measurements, and it was found that the wave meter was correct to the smallest marked division on its vernier.

The widths of the oscilloscope sweeps used at the fields corresponding to the three proton peaks studied were measured at the end of the experiment, and it was found that the total sweep width was about 6 gauss. The resonance pattern was in the center 1/6 of the sweep on the average; thus the magnetic field was held constant to about \( \pm 1.5 \) gauss during the runs.
VI.

EXPERIMENTAL METHOD

The monoenergetic deuterons used in these experiments were furnished by the Rice Institute pressurized Van de Graaff accelerator. 7) The energy of the deuterons was determined in terms of the accurately measured 0.8735 Mev \((p \alpha^1, \gamma)\) resonance in fluorine. 5) For this purpose the accelerator was modified by removing the gas bottle with palladium leak in the high voltage electrode and replacing it with a simple palladium leak connected to a saran tube which was fed through one of the main textolite supports of the accelerator. The saran tube passed through a seal in the wall of the pressure tank of the Van de Graaff at the ground end of the textolite and was connected to a copper manifold which could be filled with hydrogen or deuterium at will. It has been found possible with this arrangement to change from a beam of protons to one of deuterons in a few minutes. To minimize sparking in the gas in the saran tubing the pressure inside the saran was kept about equal to that of the insulating air outside the tubing.

For the energy calibration of the Van de Graaff, a target of zinc fluoride evaporated on a silver disc was

7) Bennett, Bonner, Mandeville, and Watt, Phys. Rev. 70, 882, (1946)
supported by a rod passing through a tapered teflon fitting in such a manner that the target could be placed in position perpendicular to the accelerated beam to intercept it or parallel to the beam and at one side to allow the beam to pass. The target was located about an inch behind the jaws of the analyzing magnet, and a lead-shielded Geiger counter was placed about 2 inches from it.

The target of zinc fluoride was about 2 Kev thick for the incident protons. The shape of the \( (p\alpha^1, \gamma) \) resonance was established by determining the \( \gamma \)-ray counting rate per current integrator\(^8\) count to the target for 5 ma steps in the analyzing magnet current. After the shape was determined in this manner, for each run points were taken at increasing analyzing magnet currents until a counting rate equal to that at the peak of the resonance curve was obtained. The magnet current was then held constant manually at this value while the system was changed over from the acceleration of a molecular proton beam to the acceleration of an atomic deuteron beam and the \((d,p)\) or \((d,\alpha)\) reaction under investigation was run. At the conclusion of a measurement, protons were again accelerated and the \( \gamma \)-ray counting rate was again determined.

The energy calibrations as described above were made with the exciting current of the annular magnet turned

off. It was found that when the annular magnet was on, since its field was of such a direction as to buck out the field of the analyzing magnet, the energy of the deuterons for a given analyzing magnet current was decreased. It was thought that this effect would be negligible; however, experimentally it was discovered that it was larger than expected by about a factor of 20. To correct for the effect, curves of the \( \gamma \)-ray counting rate per integrator count as a function of analyzing magnet current were run at each of the annular magnet fields corresponding to the 3 proton groups under consideration. In this way the shift of the resonance due to the field of the annular magnet was measured, and the incident deuteron energy was corrected for this effect, the correction being of the order of 20 Kev.

The following procedure was used in studying the \((d, p)\) and \((d, \alpha)\) reactions being investigated. The deuteron beam was positioned on the quartz disk by centering the shadow of the quartz fiber on the blue fluorescent pattern made by the beam on the quartz disk. Then the target holder was rotated to move away the quartz and bring the beryllium foil into position. The proton or alpha particle counts per microcoulomb of charge passing through the target were then measured for various fields of the annular magnet.

The field of the annular magnet was influenced by that of the analyzing magnet, and an experiment was done
to give the correction to the observed frequencies due to this effect and to the inhomogeneities in the field of the annular magnet along the path of the particles from the target to the counter. The largest inhomogeneity found in the field of the annular magnet was about 20 gauss out of 10,000. The correction was found by placing the probe of the proton moment regulator in turn at the position in which it was used during the experiments and at one of three other positions; the target position, the counter position, and half-way in between. The ratio of the frequencies at which the proton signal was found was established relative to the measuring position for each of the three positions at the analyzing magnet field used in the proton experiments and the annular magnet fields corresponding to the carbon and beryllium proton peaks. It was found that by repeated cycles reliable values for these ratios could be obtained even though the field of the annular magnet was not being held constant by a regulator. The ratio at the central point of the path between target and counter was weighted twice as heavily as those at the end positions in computing the final correction factors for the observed frequencies, which were of the order of 1.001.

The counter used for detecting the protons and alpha particles was calibrated by means of alpha particles of known
range. The voltage output per unit energy loss in the counter was determined, and this information was used in selecting the proper counter voltage, amplifier gain, and discriminator bias for the (d, p) and the (d, α) runs. The energies of the protons to be expected were calculated from the data of Suechner, and from this their energy loss in the counter could be determined. It was found possible to discriminate completely against γ-ray pileups so that the background counting rate was that of the natural α activity of the counter, about 0.3 counts per minute. The mica window of the counter was of sufficient thickness to stop the elastically scattered deuterons.
REDUCTION OF DATA

The data obtained with a beryllium target and 1% energy resolution are shown in Figure 4. The thickness of the target was about 50 micrograms per cm². It was kindly supplied to us by Dr. Hugh Bradner of the Radiation Laboratory of the University of California. The positively identified peaks are marked with their respective nuclear reactions. The three lowest energy peaks are most likely proton groups from excited states of oxygen 17 or nitrogen 15. Alpha particles of the energies corresponding to these peaks would not be able to penetrate the counter window. Wyly has reported a Q value for $^{14}\text{(d,p)}^{15}\text{N}$ of $1.4 \pm 0.1$ Mev.

From this Q we obtain a proton energy of

$$E_2 = \frac{M_3}{M_2 + M_3} Q - \frac{M_1 - M_3}{M_2 + M_3} E_1 = \frac{15}{16}(1.4) - \frac{-13}{16} 1.732 = 2.72 \text{ Mev.}$$

The measured energy of the lowest unknown group is 2.76 Mev.

One would expect there to be a thin layer of adsorbed nitrogen on the surface of the target, and the protons from such a layer would be observed if the cross section for the (d,p) reaction is large enough.

9) L. D. Wyly, Phys. Rev. 75, 316, (1949)
FIGURE 4 FREQUENCY IN MEGACYCLES/SEC.
The final data for the (d,p) reactions which were obtained with 1/2% energy resolution/which were that used for the calculations of the (d,p) Q values are shown in Figure 5. In these data, the beryllium protons were looked at first, before a carbon deposit built up on the target. After 3.2 hours of running time with beam on the beryllium target, the carbon protons were measured. Probably the best way of obtaining a uniform thin target of carbon for the present measurements is by the action of the deuteron beam on a thin metallic foil. However, to use such a target one must bombard the foil long enough before measuring the carbon protons that the target does not grow appreciably as the high energy edge of the peak is being established. The thickness of a carbon deposit obtained by the action of the beam can be estimated roughly by its appearance. The points indicated by solid circles on Figure 5 are those obtained with the carbon protons before the points indicated by open circles. Determining the position of the carbon peak required 3.3 hours of running time, after which the oxygen protons were investigated. The oxygen on the beryllium is presumably in a protective oxide coating on the surface formed as the beryllium was exposed to air after being evaporated in vacuum.

The criterion used for determining the proton energy to be associated with the observed peaks was that given by
Rutherford\textsuperscript{2). The point one-third the height of the peak on the high velocity side is that taken to represent the energy of the proton group. Wooster\textsuperscript{10) has given an analysis of the motion of charged particles in a uniform magnetic field. He has shown that no matter how wide the slit which determines the maximum angles of particles accepted by the instrument from a point source is, the line formed by a beam of point $180^\circ$ from the source has a definite sharply-defined limit at the large $\rho$ end and that most of the paths are concentrated into this edge.

Wooster has also calculated the intensity curves along the focal line for flat sources parallel to the magnetic field and used these to compute the line shape for the case of a magnetic spectrometer in which a slit is placed in front of the detecting device and the magnetic field is varied. The analysis yields a similar line shape for an infinitely narrow source and a cylindrical source .05 cm. in diameter. The line shape obtained is of the following kind:

It is shown that increasing the size of the limiting slit near the source merely augments the tail of the line, PQ. As the width of the slit in front of the detector is decreased, the flat portion of the line becomes smaller without decreasing its height, and when the slit is equal to the width of the line (defined below) Q coincides with R and there is no straight portion. As the slit is further reduced, the curve P Q R S becomes identical with the spectrum line. The width of the line, \( y \), is given by the following relation:

\[
y = \frac{2r^2}{x} \sin^2 \theta
\]

where \( r \) is the radius of curvature of the circular trajectory of the particles. \( \theta \) is the angle at the source which the tangent of the track passing through the edge of the defining slit makes with the tangent of the track passing through the center of the slit. \( x \) is the distance from the limiting slit to the head of the line.

For our instrument, the value of the line width \( y \) was about 0.27 cm. Thus our slits were smaller than the line width and an undistorted leading edge R S of the line should have been obtained. From the above analysis one sees that the correct \( H \) to assign to a particle group is that corresponding to the point S. However, the ideal line shape is never quite realized, and Rutherford found that the point one-third of the height of the peak is very little affected
by imperfections in the shape of the peak.

It was found that the frequencies corresponding to the various peaks could be determined to four figures, the last place varying by at most two units when the line through the experimental points was shifted visually to positions which clearly misrepresented the data. From the observed positions of the peaks, the non-relativistic energies of the protons were calculated by means of the following expression

\[ E_2 = \frac{2 \gamma^2}{10^{14}} \frac{\nu_c}{\nu_L} \frac{1}{y} \mathcal{J}^2 f^2, \quad E_2 \text{ in MeV.} \]

where \( \frac{\nu_c}{\nu_L} \) is the ratio of the cyclotron frequency of the proton to the nuclear resonance frequency of the proton. The value used, 0.358064, is that given by Hipple. \( \gamma \) is the gyromagnetic ratio of the proton. The value used, \( 2.67528 \pm 0.00006 \times 10^4 \text{ sec}^{-1} \text{ gauss}^{-1} \), is that given by Thomas et al.

\( \mathcal{J} \) is the radius of curvature of the protons in the field of the annular magnet.

\( f \) is the observed position of the proton or alpha particle peak in cycles/second.

The energies of the alpha particle groups were obtained from the above expression with an additional factor

11) J. A. Hipple, Private Communication
of four times the ratio of the mass of the proton to the mass of the alpha particle.

The relativistic correction to the energy of the emitted particles is given by

\[ \frac{E_2^2}{2m_0c^2} \]

where \( m_0c^2 \) is the rest energy of the emitted particle. The proton and alpha particle masses used, 1.0081374 and 4.003910 atomic mass units, are those given by Tollestrup et al.\(^{13}\). The energy equivalence of 1 atomic mass unit, 931.04 \( \pm 0.07 \) Mev, is that given by DuMond and Cohen.\(^{14}\)

The Q values of the reactions investigated were calculated from the following formula given by Livingston and Bethe.\(^{15}\)

\[ Q = \left( \frac{M_1 - M_3}{M_3} \right) E_1 + \left( \frac{M_2 + M_3}{M_3} \right) E_2 - \frac{2}{M_3} \left( M_1 M_2 E_1 E_2 \right)^{1/2} \cos \Theta \]

where the subscript 1 refers to the incident particle, the deuteron. The subscript 2 refers to the produced particle, the proton or alpha particle. The subscript 3 refers to the

15) M. Stanley Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 277, (1937)
residual nucleus.

The M's refer to the masses of the particles in question. The values of the masses were taken from Tollestrup et al. 13)

The angle $\Theta$ is that between the directions of motion of the incident and produced particle.

The angle between the direction of the incident particles and that of the emitted particles which traveled along the central path in the annular region (we will call this path the central ray) was calculated for each observed peak in the following manner. The quantity $r$, the radius of curvature of the incident deuterons in the uniform field, $H$, of the annular magnet, is given by

$$ r = \frac{1}{2M_1} \frac{\sqrt{1.60199}}{e} \times 10^{-3} \sqrt{E_1} $$

where $M_1$ is the mass of the deuteron. The value used, $2.014726$ a. m. u., is that given by Tollestrup et al. 13)

$e$ is the charge on the deuteron. The value used, $1.60199 \pm 0.00016 \times 10^{-20}$ e. s. u., is that given by DuMond and Cohen 14).

$E_1$ is the energy of the incident deuterons in Mev.

The field $H$ was calculated from the relation

$$ H = \frac{2\pi f}{\gamma} $$

and the value of $\cos \Theta$ was calculated from the expression given previously,

$$ \cos \Theta = -\frac{d}{2r} $$
The values of $\Theta$ are tabulated below.

Proton  Carbon  92.268°  Beryllium  Ground state  92.652°
Beryllium  92.682  alpha particles  Excited state  92.574
Oxygen  92.074

Particles whose direction of motion made a greater angle than $\Theta$ with the direction of motion of the incident beam could not pass through the slit in front of the counter because their energy was smaller than those moving along the central ray and their radius of curvature too small to enable them to pass through the slit. Particles making a smaller angle with the incident beam had a larger energy than those moving along the central ray and could pass through the slit. The maximum angle such particles could make with the central ray and still be detected was determined by the width of the vacuum chamber at a point 90° around from the target toward the counter. This angle, $\chi$, at the target between the tangents to the paths of the particles traveling along the central ray and those just striking the wall of the vacuum chamber was 4.25°. The average angle between the directions of incident and emitted particles was then $\Theta = \frac{\chi}{2}$.

These average angles for the various particle groups measured are as follows:
29.

Protons Carbon \(90.14^\circ\)  Beryllium Alpha Ground state \(90.53^\circ\)
Beryllium \(90.56\)     Particles    Excited state \(90.45\)
Oxygen   \(89.95\)

Thus to a very good approximation the average angle between incident and emitted particles in the present experiments was \(90^\circ\), and since the sign of \(\cos \Theta\) changes about \(\Theta = 90^\circ\) the \(Q\) values for the reactions were calculated for an angle of \(90^\circ\). The value of \(\rho\) used in the calculation of \(E_2\) was that of the average path, not the \(\rho\) as measured for the central ray. This correction factor to \(\rho\) was 1.0007.

The uncertainty in the \(Q\)'s obtained due to the deviation of the average angle from \(90^\circ\) was calculated in each case from the following expression

\[
\Delta Q = \frac{2}{M_3} (M_1M_2E_1E_2)^{\frac{1}{2}} d\Theta,
\]

where \(d\Theta\) is the deviation of the average angle between incident and emitted particles from \(90^\circ\). In combining this uncertainty with the others involved in the measurement of \(Q\), the whole \(\Delta Q\) (instead of \(\frac{1}{2}\) of it) as calculated above was included in the probable error because of the uncertainty in the measurement of the angle \(\chi\).

The other probable errors associated with the various measurements of these experiments are discussed below. In each case the calculation for the proton group from carbon will be given. The calculations for the other groups are
similar except as noted otherwise.

2. Measurement of the magnetic field \( H \). The position of the resonance signal on the oscilloscope sweep was kept constant to \( \pm 1.5 \) gauss. The oscillator frequency was constant to \( \pm 5000 \) cycles/sec. or 1.17 gauss, as calculated from the expression relating field and frequency which was given above. Thus the error due to both of these effects is 
\[
\sqrt{(1.5)^2 + (1.17)^2} = \pm 1.90 \text{ gauss.}
\]
The relative error is 1.90 parts in 8187, since a field of 8187 gauss corresponded to the point on the high energy side of the peak at a height one-third of the height of the proton peak for carbon. The energy of the protons is proportional to the square of the magnetic field; thus the error in the energy is 3.80 parts in 8187. The proton energy was 3895 kev, so the uncertainty in it is

\[
\frac{3.80}{8187} (3895) \text{ or } 1.81 \text{ kev.}
\]
The error in \( Q \) is then 
\[
\frac{M_2 + M_3}{M_3} \triangle E_2 \text{ or } \frac{14}{13} (1.81) = 1.95 \text{ kev.}
\]

3. The measurement of the radius of curvature, \( \rho \), was good to about 1 part in 35,000. A correction of .05 cm. was made because of the method of positioning the beam, and it is assumed the correction was measured to 10%. Thus has a probable error of about 5 parts in 35,000. The energy of the protons is proportional to \( \rho^2 \), so the uncertainty
in $E_2$ is 10 parts in 35,000.

\[ \frac{10}{35,000} (38.95) = 1.1 \text{ Kev, and } \frac{14}{13} (1.1) = 1.2 \text{ Kev for } \Delta Q. \]

4. Measurement of bombarding energy. The zinc fluoride target used was 2 Kev. thick for the incident protons. A 1 Kev correction for target thickness was applied, and a correction of 15 Kev was made because of the effect of the field of the annular magnet on that of the analyzing magnet. Assuming both corrections are good to 10%, the probable error in the bombarding energy is 1.6 Kev and in $Q$ is \[ \frac{M_2 - M_1}{M_3} \Delta E_1 = \frac{11}{13}(1.6) \]

= 1.4 Kev. In the case of the beryllium proton group, a 20 Kev correction was made for the effect of the field of the annular magnet. A target about 30 Kev thick was used in the $(d, \alpha )$ runs, and the corrections to $E_1$ were correspondingly larger. Also, a drift in energy of the deuteron beam was noticed in these runs and this drift was added to the uncertainty in $E_1$.

5. Determination of peak location. It is estimated the positions of the points one-third of the heights of the peaks were measured to ±10 kilocycles/sec., and that the correction made for the field of the analyzing magnet was good to 20%, i.e., to 2 parts in 10,000. Then the uncertainty due to the field of the analyzing magnet was

\[ \frac{2}{10,000} (3.486) = 6.97 \text{ kilocycles/sec.} \]
The combined effect of the two uncertainties is 
\[ \sqrt{(10)^2 + \left(\frac{2.7}{6197}\right)^2} \]
= 12.2 kilocycles/sec. The relative error is 12.2 parts in
34860, and since $E_2$ is proportional to $f^2$, the error is $\frac{24.4}{34860}(3895)$
= 2.7 Kev. Thus $\Delta Q = \left(\frac{14}{13}\right)(2.7) = 2.9$ Kev. In the case
of the oxygen protons, it is estimated the position of the
peak was known to $\pm 20$ kilocycles/sec.

6. Target Contamination. Since the beryllium (d,p)
data were taken with a new, previously unbombarded target,
no contamination error was assigned. The carbon (d,p) data
obtained with the carbon deposited on the target by the
action of the beam were likewise subject to no error of
this sort. The oxygen(d,p) data were taken at the end of
the run, and in this case the probable error due to the
carbon layer is estimated to be $\pm 4$ Kev, considering the
length of time the target had been bombarded and the appear-
ance of the target. A similar estimate was made for the
(d,α) data, and in this case the effect was more serious
since the target was thicker for the alpha particles than
for the protons.

7. Error in the determination of the energy of the
$^{19}\text{F}(p,\alpha)^{16}\text{O}$ resonance. The value of the resonance energy
is given by Herb\(^5\) et al. as 873.5 $\pm 0.9$ Kev. Thus the
uncertainty in $E_1$ is 1.746 Kev and in $Q$ is $\frac{11}{13}(1.746) = 1.5$ Kev.
8. Uncertainties in the constants used in the calculation of $E_2$. The probable error in $\gamma$ is given as 6 parts in 268,000. The probable error in $\frac{\gamma_C}{\gamma_L}$ is estimated to be 1 part in 50,000. Thus

$$\frac{1}{268,000} (3895) = .09 \text{ Kev} \quad \text{and} \quad \frac{1}{50,000} (3895) = .08 \text{ Kev}$$

$$\sqrt{(.0873)^2 + (.0779)^2} = .12 \text{ Kev.}$$ Finally, $\Delta Q = .12(\frac{14}{13}) = .13 \text{ Kev.}$

9. Energy resolution slit. For the proton runs, a $\frac{1}{2}$% energy resolution slit was used. It was assumed that the uncertainty in the position of a peak is 1/5 the width of the peak. This is probably too conservative an estimate; and since it is the largest uncertainty, it may lead to somewhat too large values for the given net probable errors of the present measurements. Thus the 1/10% uncertainty for the case of the carbon protons whose energy was 3.8 Mev was 3.8 Kev. $(3.895)(\frac{14}{13}) = 4.2 \text{ Kev.}$ For the alpha runs, the energy resolution was 1%.

The probable errors calculated as outlined above are given below in tabular form:
<table>
<thead>
<tr>
<th>Energy Resolution</th>
<th>Energy Resolution</th>
<th>Energy Resolution</th>
<th>Energy Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.6</td>
<td>17.6</td>
<td>17.6</td>
<td>17.6</td>
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<tr>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>4.3</td>
<td>4.3</td>
<td>4.3</td>
<td>4.3</td>
</tr>
</tbody>
</table>

**Error in Values of α Energy**

**Target Preparation**

**Error in Determination**

**Determination of peak location**

**Measurement of incident particle energies**

**Measurement of H and mitted particles**

**Uncertainty in angle**

**Ground State**

**Excited State**

**Carbon Oxygen**

From d, ∞, on Be, α Particles
VIII.
RESULTS OBTAINED

The Q values obtained in these experiments are given below:

<table>
<thead>
<tr>
<th>Protons</th>
<th>Carbon</th>
<th>2.732 ± 0.006</th>
<th>Mev</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beryllium</td>
<td>4.591 ± 0.008</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Oxygen</td>
<td>1.919 ± 0.008</td>
<td></td>
</tr>
</tbody>
</table>

Alpha Particles from
Ground State       7.191 ± 0.024
Excited State      6.705 ± 0.022
(d, α) on Be⁹

The values given by Buechner are as follows

<table>
<thead>
<tr>
<th>Protons</th>
<th>Carbon</th>
<th>2.729 ± 0.009</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beryllium</td>
<td>4.576 ± 0.012</td>
</tr>
<tr>
<td></td>
<td>Oxygen</td>
<td>1.925 ± 0.008</td>
</tr>
</tbody>
</table>

Alpha Particles
Ground State       7.145 ± 0.024
Excited State      6.663

A new set of Q's for the (d, p) reactions has been obtained by Buechner

<table>
<thead>
<tr>
<th>Carbon</th>
<th>2.716 ± 0.005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beryllium</td>
<td>4.592 ± 0.008</td>
</tr>
<tr>
<td>Oxygen</td>
<td>1.917 ± 0.005</td>
</tr>
</tbody>
</table>

16) W. W. Buechner, Private Communication
From the measured $Q$'s of the $(d, p)$ reactions we can calculate the masses of $^{13}C$, $^{10}Be$, and $^{17}O$. We take the conversion of $1mM = 0.9311$ Mev. and the masses of $^{12}C$, $^{9}Be$, $^{1}H$, and $^{2}H$ given by Tollestrup et al. We have

$$^{12}C + ^{2}H \rightarrow ^{13}C + ^{1}H + Q_1$$

$Q_1 = 2.732$ Mev = 2.934 m M. Thus

$$^{13}C = 12.003900 + 2.014726 - 1.0081374 - 0.002934$$

$$= 13.007555$$

Similarly,

$$^{10}Be = 9.015098 + 2.014726 - 1.0081374 - 0.004931$$

$$= 10.016756$$

and

$$^{17}O = 16.000000 + 2.014726 - 1.0081374 - 0.002601$$

$$= 17.004528$$

The values of these masses as given by Tollestrup et al are

$$^{13}C = 13.007554, \ ^{10}Be = 10.016774, \ ^{17}O = 17.004515.$$  

We can also calculate the neutron-proton mass difference from the present $(d, p)$ data for carbon and the data obtained for the $Q$'s of a closed cycle of reactions involving $^{12}C$ and $^{13}C$ by others-workers. We consider the following reactions:
(1) \( ^{12}C + H^2 \rightarrow ^{13}C + H^1 + Q_1 \) and

(2) \( ^{12}C + H^2 \rightarrow ^{13}N + n^1 + Q_2 \)

\( ^{13}N \) decays to \( ^{13}C \) by positron emission with an energy release of \( Q_3 \), where

\[
Q_3 = ^{13}N - ^{13}C - 2m_e^+ \quad \text{thus}
\]

(3) \( ^{13}N \rightarrow Q_3 + ^{13}C + 2m_e^+ \)

Subtracting (3) from (1), we obtain

(4) \( ^{12}C - ^{13}N \rightarrow ^{13}C + H^2 + H^1 + Q_1 - Q_3 - ^{13}C - 2m_e^+ \)

Rewriting (2), we have

(5) \( ^{12}C - ^{13}N \rightarrow n^1 + Q_2 - H^2 \)

Subtracting (5) from (4) yields

\[
0 = H^1 + Q_1 - H^2 - 2m_e - Q_3 - n^1 - Q_2 + H^2
\]

and finally

\[
(n^1 - H^1) = Q_1 - Q_2 - Q_3 - 2m_e
\]

The present measurements give a value of \( Q_1 \) of \( 2.732 \pm 0.006 \) Mev.

\( Q_2 \) has been measured by Bonner et al as \( -0.281 \pm 0.003 \) Mev.

\[17\) T. W. Bonner, J. E. Evans, and J. E. Hill, Phys Rev. 75, 1398, (1949)\]
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UMI
Q has been measured by Hornyak et al. as \(1.202 \pm 0.005\) Mev.\(^{14}\)

The value of \(m_e\) is given by DuMond and Cohen as
\[0.51079 \pm 0.00006\) Mev. Thus

\[(n^1 - H^1) = 0.789 \pm 0.008\) Mev.

This value is to be compared with the weighted mean obtained from eight such cycles as given by Tollestrup et al. as \(0.782 \pm 0.001\) Mev. The \((n^1 - H^1)\) mass difference from Mier's value for the \((2H^1 - H^2)\) doublet and Bell and Elliott's value of \(Q = 2.230 \pm 0.007\) for \(H^1(\gamma, n)H^2\) as given by Tollestrup et al. is \(0.788\) Mev.

The value obtained in the present work for the first excited state in \(Li^7\) is \(7.191 - 6.705 = 486\) Kev. The value obtained for this level from measurement of the \(\gamma\)-ray is \(476.7 \pm 1\) Kev as given by Hornyak et al. The value found by measurements of the energies of protons inelastically scattered by \(Li^7\) is \(479.0 \pm 1\) Kev as given by Fowler and Lauritsen.


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