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THE DISINTEGRATION OF BERYLLIUM BY DEUTERONS

A thesis submitted to the Faculty of The Rice Institute in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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Houston, Texas

May, 1947
THE DISINTEGRATION OF BERYLLIUM BY DEUTERONS

Introduction

Artificial disintegrations of nuclei have provided much of our information about nuclear structure. The early experiments using alpha-particles from the naturally radioactive elements aided the development of a theory of the nucleus, and permitted Gurney to predict and Pose to discover resonance phenomena in nuclear disintegrations. These phenomena are due to energy levels in the nucleus analogous to electronic energy levels of the atom, and give rise to greatly increased probabilities of disintegration for specific energies of the bombarding particle. They result in much greater yields of disintegration products near these bombarding energies, and permit emission of groups of particles of the same kind having discrete energy differences. Experiments on resonance disintegrations have provided quantitative data on nuclear energy levels, permitting extension and refinement of the early theory.

With the fundamentals of the constitution of the nucleus firmly established by the discovery of the neutron in 1932 and of the positron in 1934, the discovery of the deuteron and the development during the same period of a number of different types of apparatus for the acceleration of ions to high speeds provided valuable tools for nuclear research. In many instances the deuteron is a more effective projectile than a proton or an alpha-particle, especially for the production of neutrons. It has a low binding energy and consequently gives high excitation energy
to a nucleus capturing it, while the coulomb barrier of a nucleus is nearly the same for it as for a proton. No sharp discontinuities in yield curves were expected in disintegrations by deuterons because of the high excitation of the compound nucleus, and none were observed in early experiments. Bonner and his colleagues in 1940 first discovered sharp resonances in the yields of neutrons and of gamma-rays in the disintegration of carbon by deuterons, using thin targets and the relatively accurate control of the deuteron energies possible with a Van de Graaff electrostatic generator. Resonances were also observed for proton emission and subsequent experiments have shown resonances in the disintegration of lithium by deuterons. The present experiment was undertaken to determine the excitation functions of the disintegrations of beryllium bombarded by deuterons.

The nuclear reactions taking place when beryllium is bombarded with deuterons were studied by many investigators beginning in 1933, and by now they have been established with certainty. Identification of the reactions were relatively easy since beryllium consists of only one isotope, Be$^9$. For a number of years Be$^8$ was believed to be stable, as its mass was then believed to be less than twice the mass of Be$^4$. Nier (N1) made a careful mass spectrograph analysis of beryllium and concluded that Be$^8$ does not exist, giving an upper limit of 1 part in 10$^5$. Most recent mass values indicate that Be$^8$ is slightly unstable with respect to alpha-particle emission, and the break up of Be$^8$ into two alpha-particles has been observed. McMillan (M1) reported the radioactivity of Be$^{10}$ (produced by artificial transmutation) in 1936, and recent work
(M2, Pl, H1) has verified this. No Be\textsuperscript{10} has been observed in mass spectrograph studied of natural beryllium, although Be\textsuperscript{10} has the extremely long half-life of 2.9 \times 10^6 years (H1).

The emission of alpha-particles in the disintegration of beryllium by deuterons was first reported by Lewis, Livingstone and Lawrence (L2). This was confirmed by Oliphant, Kempton, and Rutherford (01), who in an exhaustive study identified all the Be + D reactions resulting in the emission of charged particles, and measured accurately the reaction energies. They reported the reactions:

\begin{align*}
\text{Be}^9 + D^2 &\rightarrow (\text{B}^{11})^* \rightarrow \text{Li}^7 + \text{Be}^4 + Q_\alpha \quad (1) \\
\text{Be}^9 + D^2 &\rightarrow (\text{B}^{11})^* \rightarrow \text{Be}^{10} + \text{H}^1 + Q_\beta \quad (2) \\
\text{Be}^9 + D^2 &\rightarrow (\text{B}^{11})^* \rightarrow \text{Be}^8 + \text{H}^3 + Q_t \quad (3)
\end{align*}

Groups of singly charged ions of 14 cm. and 1.4 cm. range were correctly ascribed to deuterium adsorbed by the target. A 1 cm. group of (approximately) doubly charged ions was identified as Li\textsuperscript{7} recoils from reaction (1); this was confirmed by cloud chamber photographs by Dee.

The group of singly charged ions of 8 cm. range was thought to be H\textsuperscript{3} from reaction (3), rather than protons from an excited state of Be\textsuperscript{10} or a group of nearly the same range from oxygen. Reaction (2) gave a 26 cm. group of protons, and reaction (1) gave a 3 cm. group of alpha-particles. The reaction energies reported (corrected by Livingston and Bethe (Lla)) are $Q_\alpha = 7.19 \pm .12$ Mev and $Q_\beta = 4.59 \pm .11$ Mev; Oliphant gives $Q_t = 4.5$ Mev.

The results of Oliphant were confirmed by Williams, Haxby, and Shepherd (W1). Graves (G1) investigated the alpha-particles using thin
targets and higher resolution and found two partially resolved groups with a separation of 3.1 mm., giving an excitation level of 494 kev in Li$^7$. She calculated the reaction energy to be $Q_{\alpha} = 7.093 \pm .022$ Mev. Because of this excited state of Li$^7$ formed in reaction (1), gamma-radiation would be expected to accompany the emission of alpha-particles. Pollard (P2) found a proton range of 52.6 cm. for reaction (2) using 3.1 Mev deuterons, giving $Q_p = 4.52$ Mev.

Of the above reactions, only (3) is doubtful. This has been verified somewhat indirectly by O'Neal and Goldhaber (O2) by extracting a radioactive gas identified as H$^3$ from beryllium targets previously submitted to prolonged deuteron bombardment. The gas was identified by its electron activity; careful experiments have shown that both the electron energy (15 kev) and half life (31 years) are different from those of the somewhat similar weak Be$^{10}$ activity. Some experimenters had confused the two activities. O'Neal and Goldhaber claim to have excluded the possibility of an appreciable fraction of the H$^3$ coming from the reaction D$^2(d,n)$ H$^3$.

The production of neutrons by deuteron bombardment of beryllium was first reported by Crane, Learitsen, and Soltan (C1); further work (O2) showed definitely the presence of gamma-radiation, indicating the reaction:

$$\text{Be}^9 + D^2 \rightarrow (\text{Be}^{11})^* \rightarrow \text{Be}^{10}^* + n^1 + Q_n \quad (4)$$

$$\text{Be}^{10}^* \rightarrow \text{Be}^{10} + \gamma + Q_{\gamma}$$

Simple capture of the deuteron is unlikely and no gamma-ray of the energy expected for simple capture has been reported. Bonner and Brubaker (B1) have shown that four different groups of neutrons are emitted, verifying
the reaction as written. Their accurate determination of the reaction energies $Q_n$ and $Q_\gamma$ (with their assumed range-energy relations corrected by Livingston and Bethe (I1)) give values of 4.20, 3.7, 2.2 and 0.9 Mev. This suggests energy levels in $^3$He of 0.5, 2.0, and 3.3 Mev above the ground state. These results have been corroborated by Staub and Stephens (S4) and Powell (P3).

The gamma-rays have been investigated by Crane (C3, C4) and by Kruger (K1, K2), with conflicting results. Kruger's most recent results reported thirty-one different gamma-rays ranging in energy up to 4.7 Mev; these are not justified statistically. Crane's most recent results indicate gamma-rays of 3.45 and 1 Mev; no line was observed with an energy of 2 Mev, as might be expected. The information about the gamma-rays must be regarded as incomplete, but it is definite that gamma-rays of several Mev energy are emitted.

The yields of neutrons from thick targets of beryllium have been determined roughly (due to an unresolved deuteron beam) by Crane (C1) and by Bonner and Brubaker (B2). Amaldi, Hafstad, and Tuve (A1) made accurate measurements of the relative yields from thick targets of lithium, deuterium ($^2$H), and carbon, as well as beryllium, and made a relatively accurate conversion to absolute yields. Their measurements extended from 300 Kev to 1000 Kev bombarding energy, and showed no indications of resonance phenomena. Although beryllium has been used as a target more than any other element, up to the beginning of this experiment no work has been done on the neutron emission using thin targets.
The present work is confined to the investigation of the neutrons emitted in the reaction \((4)\) and the gamma-rays accompanying the reaction \((1)\) and \((4)\). It was believed that these would give the most interesting and valuable results, and time did not permit detailed study of all the reactions. Using Kattauch's \((M3)\) values of the masses, the excitation energy of the compound nucleus \(^{11}\text{Be}\) is calculated to be 15.62 Mev (excluding the bombarding energy). Such a high excitation should, theoretically, give very broad resonances, perhaps undetectable. In addition to the predicted increase in density of levels (which holds strictly only for the heavier elements), one might expect a decrease in the lifetime of the compound nucleus with increasing excitation energy. Since the half-width \(\Delta E\) of a resonance is determined by the mean life \(\Delta t\) of the compound nucleus according to the equation \(\Delta E \cdot \Delta t = \frac{\hbar}{2}\), a short lifetime gives resonances which are broad. Sharp resonances then indicate forbidden transitions and provide information about the quantum states of the excited levels. By analogy to deuteron disintegrations of carbon and lithium, it was expected that resonances in the yield curves of beryllium might be found.

**The Detection of Neutrons.**

Measurements involving neutrons present special problems; the methods available for their detection are generally far less satisfactory than those for charged particles and photons. Observations of the latter depend on their interactions with extra-nuclear electrons and the consequent production of ions; all these interactions have relatively enormous probabilities. The neutron, being uncharged,
must make a collision with a nucleus before it can be detected;
interactions with electrons are negligible, as Dee (DL) concluded from
cloud chamber studies. Since neutron cross-sections are so small, all
methods for the detection of neutrons strive for greater efficiency;
and this can be obtained generally only by sacrificing discrimination
of the neutron energies. The methods have to contend with a background
of scattered neutrons which range in energy up to near the maximum.
For most successful application, they depend on a knowledge of the
variation with neutron energy of the particular cross section involved.

The methods fall into two general classifications determined by
the type of nuclear process resulting from the neutron collision: (1)
capture of the neutron; (2) scattering of the neutron and recoil of the
nucleus. The first process can be detected if a charged particle is
emitted or if the resultant nucleus is radioactive. In the second, the
recoiling nucleus is charged and can be detected if it is sufficiently
energetic; its methods can be applied only to fast neutrons. Methods
of the first classification generally work better with slow neutrons;
they are not suitable for measurement of fast neutron energies. In
this experiment, detection of recoils in a proportional counter was
used for reasons to be discussed.

(1) Methods involving neutron capture

Capture of neutrons by nuclei results in four general types of
disintegrations useful for their detection, leading to four general
types of methods: (a) neutron-proton disintegrations; (b) simple
capture of neutrons resulting in a radioactive nuclei; (c) neutron-
alpha-particle disintegrations; (d) neutron induced fission.

Neutron-proton disintegrations are almost always endoergic, beginning sharply at definite energies of the incident neutrons. Fast neutrons are required. The cross-sections are very small and vary with the energy of the neutron. This type is of little value for yield studies, and it is of limited applicability in the determination of neutron energies.

The simple capture type of reaction is always exoergic; it often results in the emission of gamma-radiation in addition to positrons or electrons. The radioactivity of the resultant nucleus is detected with special types of standard instruments: ionization chambers, electrosopes, proportional counters. The capture cross-section is relatively low for fast neutrons, but increases to fairly high values for slow neutrons. For slow neutrons it is inversely proportional to the neutron velocity (excluding reasonances), depending on the time spent by the neutron in traversing the range of nuclear forces. Many elements in addition exhibit resonance capture of slow neutrons. These properties make this type particularly sensitive to slow neutrons.

Fast neutrons can be slowed down, preferably in hydrogenous materials, with some loss of intensity, for detection by this method. This has been done by Amaldi (A1) and by many others, although the measurements are slow, subject to rigid restrictions, and often require elaborate techniques. A variation was used by Bonner and his colleagues (B3) in checking the neutron yield curve of the reaction

\[ {^12}_{	ext{C}} + {^2}_{	ext{D}} \rightarrow (N^{14})^* \rightarrow N^{13} + n^1 - 0.25 \text{ Mev} \]

The \( N^{13} \) formed in the production of the neutrons decays with positron
emission and gamma-radiation with a half-life of 9.93 minutes; thus the activity of the original target can be measured without activating a detector. However, as they point out, even this method is sufficiently involved and time consuming to make it impractical for extensive use with thin targets, where many determinations must be made at different bombarding energies.

The \((n,\alpha)\) disintegrations give highly ionizing alpha-particles which can easily be detected by standard instruments. Individual particles can be counted using proportional counters or ionization chambers, with less highly ionizing events biased out. Electrosopes are also used to measure the total ionization, if that due to other causes is small.

The reactions used are \(\text{Li}^6(n,\alpha)\text{H}^3\) and \(\text{Be}^{10}(n,\alpha)\text{Li}^7\). Their cross-sections for slow neutrons are inversely proportional to the velocity of the neutron, giving very high probabilities at thermal energies (the values for slow neutrons are higher than those of most elements). Boron is used as a lining for ionization chambers, or boron trifluoride gas is used to fill electrosopes or proportional counters. Relatively high efficiencies for thermal neutrons are obtained with high gas pressures (Sl); they can be increased by using boron trifluoride enriched in the \(\text{Be}^{10}\) isotope. This method was not used in this experiment primarily because it is most efficient for thermal neutrons.

Neutron induced fission is a method of potential value in neutron measurements; the highly ionizing heavy fragments can be detected with standard instruments as outlined above for the \((n,\alpha)\) reaction. The applications of these two types are very similar; they differ primarily in the reactions and their variations with neutron energy. Presumably
much work has been done on fission in the last few years, but few details have been published.

(2) Methods based on elastic scattering

Methods for making neutron measurements by detection of the recoiling nuclei in elastic scattering processes are generally better for fast neutrons than any in the first classification. The most accurate method for determining neutron energies has been the measurement of the ranges of recoil protons or helium nuclei in cloud chambers (B2). This is not suited to the investigation of yield curves because of the time required to photograph and measure the recoils. The experimental accumulation of data proceeds more rapidly using the photographic plate technique (P3); special photographic plates are exposed to neutrons, and the recoil protons in the emulsion produce latent images of tracks which can be developed. Their ranges must be measured with a microscope, and reduction of the data is difficult and tedious. Fair accuracy can be obtained for the neutron energies if a good calibration is used, but measurements of relative yields are more difficult and subject to error.

Excitation functions are determined more satisfactorily using ionization chambers, electroscopes, or proportional chambers; all three have been used with the recoil method. Here the recoiling nucleus is detected, rather than the alpha-particle as discussed in the \((n,\alpha)\) reaction. As a source of recoils, a hydrocarbonous material such as paraffin may be used as a radiator in front of a chamber or lining the walls. Alternatively, the gas filling the chamber may be used as the source.
Almost any gas can be used; experimental conditions will determine which one (or what combination) is best.

Electroscopes and ionization chambers are frequently used for detecting fast neutrons. Hydrogen at a pressure of 7 atmospheres was used (B3) in a Wulf electroscope for most of the data on the reaction $^\text{C}^{12}(d, n)^\text{H}^{13}$; the rate of discharge of the electroscope was measured. High pressures are necessary to give increased sensitivity, both by increasing the number of collisions and by ensuring that the majority of the ionization by the recoils occurs in the gas and not in the walls. As the pressure is increased, the gamma-ray effect is increased also; this is even more pronounced for heavier atoms than for hydrogen. Bailey and his co-workers (B4) used an ionization chamber filled with methane at 4 atmospheres, with a linear amplifier to count the individual pulses; they also used an argon filled chamber with a paraffin slab inside the front face. The pressure could then be varied to insure the stopping of the most energetic recoil and to permit the shortest collection time possible. Also, it was possible to bias out low energy recoils, and thus exclude detection of low energy neutrons as well as $\gamma$-rays. To detect the individual disintegrations, the pulses resulting from the collection of ions must be amplified a factor of a million or more with a linear amplifier. This extreme amplification causes great difficulty with electromagnetic pickup and microphonics.

Much of this trouble is avoided by the use of proportional counters, and other advantages are gained. The early point counter of Geiger has been developed into a modification of the Geiger-Mueller tube counter. These have been used by Korff (K3) and others for neutron
detection. A Geiger-Mueller counter consists essentially of a wire along the axis of a cylinder, with the wire at a positive potential with respect to the cylinder; any of a variety of gases at an arbitrary (but usually low) pressure fills the cylinder. Usually this is in a sealed glass tube to maintain the chosen gas constitution and pressure. At low voltages, any ions formed inside the cylinder will be collected by the wire and cylinder; the number of ions collected is the number formed, neglecting recombination. At higher voltages, the electrons will be accelerated in the high field near the wire sufficiently to produce additional ions; the slower positive ions give a space charge effect which eventually reduces the field sufficiently so that no new ions are produced. Now a larger number of ions are collected, but for a certain voltage range the number collected is proportional to the number initially formed. This is the proportional region, in which the counter acts as a proportional counter and can be used to distinguish between heavily ionizing particles and electrons and Y-rays. At higher voltages, the gas amplification is much greater and any ionizing event results in the collection of substantially the same number of ions, with essentially the same number of ions, with essentially the same mechanism stopping the discharge.

The amplification by the gas in a proportional counter permits use of a relatively low gain amplifier with the same degree of discrimination as an ionization chamber. The electrons are collected on the wire in a few microseconds, compared to a collection time of the order of hundredths of seconds for ionization chambers. This permits use of higher counting rates, and allows a higher low frequency cut-off in
the amplifier with less 60-cycle pickup. According to Barschall (B5),
the energy discrimination of a proportional counter is better. Amaldi
(A2) developed a scheme proposed earlier, capable of giving better energy
discrimination than a single proportional counter. Recoil protons from
a paraffin slab are collimated by slits to define their energy range,
and detected in a set of three proportional counters in triple coinci-
dence. The coincidence arrangement precludes the counting of particles
which did not come thru the slits. Primarily because of intensity
considerations, this method has not been successful for many experiments;
only a small fraction of the recoils have near the maximum energy, and
only a small fraction of the neutrons produce any recoil protons.

Other modifications have been suggested and used to give special
characteristics to proportional counters. Coon and Nobles (C5) have
developed a proportional counter with a hydrogen radiator inside the
cylinder but separate from the gas, giving a directional property to
a single counter. It also has good discrimination for neutrons of
different energies, with suitable standard electronic equipment. But
as Barschall and Bethe (B5) pointed out recently, any good proportional
counter can be used to count accurately the number of neutrons with
energies greater than a given amount, if the energy distribution of
these neutrons is not required.

Apparatus

Consideration of the characteristics of the various neutron
detectors discussed in the preceding section in view of the special
problems of this experiment led to the adoption of a proportional
counter for the neutron measurements. It is desirable to measure the yields of each group of neutrons separately, but preliminary experiments with coincidence proportional counters designed to record only one group at a time indicated that such a procedure would not be feasible. Adequate energy resolution over the entire range gives too low an efficiency; the many measurements necessary for a comprehensive thin target yield curve would require an unreasonable time, and the low counting rate would result in inaccurate measurements. It was decided to use a single proportional counter to count all the neutron groups.

The neutron groups from the disintegration of beryllium by deuterons correspond to reaction energies of 4.2, 3.7, 2.2, and 0.9 Mev (B2). Thus for deuteron energies from 0.5 to 1.5 Mev, the neutron groups will range in energy from 1.4 to 2.4, 2.7 to 3.7, 4.1 to 5.2, and 4.6 to 5.6 Mev, for the neutrons emitted in the forward direction. The energies \( E_R \) of the recoil nuclei are given by

\[
E_R = \frac{4M_N M_R E_N \cos^2 \theta}{(M_N + M_R)^2}
\]

where \( M_N \), \( M_R \) are the masses of the neutron and of the recoil nucleus, \( E_N \) is the energy of the incident neutron, and \( \theta \) is the angle between the directions of the incident neutron and recoil nucleus. Thus the recoils range in energy from zero up to a maximum of approximately \( 4E_N/M_R \) (for \( M_R >> M_N \)), and the counter should record all charged particles in this energy range for maximum efficiency. But for reliable measurements, it should not record ions produced by other effects.

Gamma-rays will produce pulses which can be made much smaller than the largest neutron pulses and can be biased out by the recording circuit, with loss of the small fraction of the neutron pulses smaller than this.
size. Charged particles from sources outside the counter can be kept outside by a relatively small amount of shielding material. There will be a few large pulses from natural radioactive contamination inside the counter which cannot be eliminated, but which can be reduced to a negligible fraction by avoiding contamination as much as possible. The remaining potential source of error is from neutrons from sources other than the beryllium target. Scattered neutrons from the beryllium disintegration can be kept a very small and nearly constant fraction of those produced, so that they will introduce no error. Neutrons from the disintegration of other elements are possible and require special precautions. The target is kept as free from impurities and surface contamination as possible. Other places struck by the deuteron beam are kept at a minimum, constructed of materials which give as few disintegrations as possible, (especially those resulting in neutrons and gamma-rays), kept clean, and kept as far from the target and measuring devices as possible.

In spite of all precautions taken, carbon contamination is always present, and deuteron bombardment of C¹² produces both gamma-rays and neutrons. The neutron yield of C¹² is less than 10% of that of Be⁹ (Al, B) for equal target thicknesses, so that if the target is kept reasonably clean the effect will be much smaller; the decrease in intensity with the inverse square of the distance from the source helps reduce the effect of the beam striking slits, walls, etc. The neutrons from C¹² in the forward direction have 0.7 Mev energy when produced by 1 Mev deuterons, while high energy neutrons from C¹³ are
of negligible intensity (1% of those from C\textsuperscript{12}). Thus their pulses will be small and can be biased out. This results in the loss of an appreciable fraction of the beryllium neutron recoils, but it was felt that the improved reliability of the measurements would compensate for the loss in sensitivity.

Assuming that the neutron scattering by the gas of the counter is spherically symmetric in the center of gravity system, the sensitivity of the counter as a function of the neutron energy \( E_N \) is proportional to (B5)

\[
\sigma(E_N) \cdot (1 - B/E_N)
\]

for \( E_N \geq B \). Here \( \sigma(E_N) \) is the neutron scattering cross-section of the gas, and \( B \) is neutron energy biased out; i.e., all neutrons of energy \( B \) or less are not recorded (and consequently a fraction of the recoils of neutrons with greater energy). This holds if the maximum range of the recoils biased out is small compared to the dimensions of the chamber. As the neutron energy increases above the bias energy, the counter sensitivity increases from zero rapidly and then tends to level off for high energies, if we assume \( \sigma(E_N) \) constant. Thus we have a rough approximation to constant sensitivity; at least it is better than that obtained by the neutron capture methods. For a deuteron energy of 1 Mev, biasing out 1 Mev neutrons causes losses of 53%, 31%, 22%, and 20% of the various groups of beryllium neutrons (assuming that \( \sigma(E_N) \) is constant for \( 1 < E_N < 5.1 \text{ Mev} \)). Such losses are not serious.

Different gases at various pressures were tried in counters to determine the best counter filling for this experiment. These experiments were handicapped by lack of a suitable neutron source; most tests were
made with the counters operating in the semi-proportional region, using a calibrated oscilloscope for the observations. Ethane was found to be no good; at a pressure of only 2.0 inches of mercury, the Geiger threshold was over 1600 volts. Addition of argon did not lower the threshold enough to make it useful. The efficiency of a counter rises (linearly, with best conditions) with the pressure; the voltage required for operation rises less rapidly with the pressure. Thus the efficiency of an ethane-filled counter is too low when the operating voltage is reasonable.

Hydrogen filled counters have lower thresholds at corresponding pressures, but also fewer atoms and lower efficiencies. Also, recoil protons have high energy (up to the neutron energy), while the gas has low stopping power. Most of the recoils will have a range greater than their path in the counter, so that biasing out carbon neutrons would be difficult or impossible. Furthermore, the neutron scattering cross-section for hydrogen increases sharply at low energies; this would increase the ratio of undesired pulses to desired pulses.

Helium filled counters were also tried. Voltages required with helium are low; with helium at atmospheric pressure, the Geiger threshold began at about 1200 volts. The helium recoils get a maximum energy of $(16/25) E_N$, but the stopping power of helium is low and wall effects might be undesirable. Helium has a maximum neutron scattering cross-section at about 1 Mev and the cross-section at high energies is relatively low. An attempt to fill a glass-walled counter to pressures above atmospheric proved unsuccessful.

Various pressures of argon were tried. It was found possible to use argon at atmospheric pressure; the Geiger threshold is then some-
what above 1700 volts. Addition of CCl₄ vapor to improve the voltage characteristics in the proportional region increased the operating voltage excessively; with pressures of 3.8 inches Hg of argon and 0.4 inches Hg of CCl₄, the Geiger threshold was 1500 volts. Alcohol vapor could not be used; the proton recoils from low energy neutrons would give larger pulses than argon recoils from high energy neutrons. The argon recoils get a maximum energy of 10% of the neutron energy. With 1 Mev deuterons, the most energetic recoil has a range of only 0.06 cm. in the argon gas, using the range-energy data of Blackett and Lees (B6). Thus practically the entire volume of the counter has maximum sensitivity; very few of the recoils will end their ranges in the counter wall.

The neutron counter adopted for this experiment was an Eck and Krebs β-ray counter filled with commercial argon (99.5% pure) to a pressure of 29.5 inches Hg at 27°C. The counter is thin walled glass 1.9 cm. in diameter, chemically silvered inside for a length of 7.8 cm. Glass insulators about the central wire confine the sensitive volume to a length of about 6 cm. Its sensitivity can be estimated from the expression (5) above. Assuming equal numbers of neutrons in each energy group, about 70% of the recoils will be counted with the recorder biased for 1 Mev neutrons, at a bombarding energy of 1 Mev. For the counter very close to the target, the average path length of a neutron through it may be estimated at about 1+1/2 cm. Assuming a constant scattering cross-section of 2.8 x 10²³ cm², the average probability of an elastic collision is approximately \( Lp \sigma d = 11 \times 10^{-5} \) (L is the Loschmidt number; p the pressure in atmospheres, d the neutron
path length in cm.) The theoretical efficiency is then \((0.7 \times 11 \times 10^{-5})\) 
\[\approx (1 \times 10^{-4}) = 0.01\% .\] At the operating voltage, the amplified pulses are fast and sharp; their duration is about \(2 \times 10^{-4}\) seconds. The change of pulse size with voltage is about \(1\%\) per volt.

A regulated high voltage supply similar to one described by Neher and Pickering (N3) was used for the neutron counter; the output voltage can be varied from 500 to 2000 volts. The output voltage was filtered by a two section RC filter to smooth out a 60 cycle ripple of about 0.1 volt; with the filter, the ripple was less than 0.001 volt. The regulation was adequate for the neutron counter; a change in input voltage of 1600 volts gave about 3 volts change in the output voltage. The circuit was designed and constructed to minimize slow drifts in output voltage. Wire wound resistors of adequate current capacity and thoroughly cleaned wire wound potentiometers were used in the output.

During the experiment, the coarse voltage control was not changed. One or two times it was necessary to use the fine adjustment, which had a total possible change of about 10 volts. The voltage on the neutron counter remained constant to within 2 or 3 volts, which was as close as the voltage could be read. A warm up period of a half hour or more allowed temperature equilibrium to be reached in the voltage supply.

The pulses from the neutron counter were amplified by a linear amplifier of conventional design, which had been constructed by Dr. E. E. Watt. A storage battery was used to supply voltage to the filament heater of the first stage. Other voltages came from a regulated voltage supply which was connected to a stabilized source of 115 volt AC. The amplifier controls were not changed during the experiment.
During the first part of the experiment, the amplified neutron pulses were fed into a discriminator circuit and pulse-recorder driving a Cenco recorder. The circuits were modified from a design described by Watt (W2). A stabilized source of 115V A.C. was used for the power supply. The discriminator bias could be changed from 0 to 50 volts, and was constant and reproducible to better than 1%. The control was not changed (except by accident while checking) during the experiment. The constants of the pulse recording circuit could be varied to suit the characteristics of the particular recorder used, to insure positive action in a minimum of time, to permit the highest possible counting rates. They were not changed after the initial adjustment.

Later in the experiment a scaling circuit was used for the neutron pulses to make certain that none were lost due to the relatively slow action of the recorder. This consisted of a discriminator, scale of 8, and pulse recorder built from the design of Sands. The discriminator bias was adjusted to correspond to the one previously used, and both circuits were used concurrently as a check on their action.

It would be desirable to resolve the gamma-rays and measure each component separately, or at least to separate the ones from $^{10}$B and those from $^{7}$Li. Due to the uncertainty about their energies and the probable complexity of the group, this was not attempted. The gamma-rays were counted with Geiger-Mueller counter used with an Instrument Development Laboratories scaling circuit. The latter combined a regulated voltage supply for the Geiger-Mueller counter, scale of 64 driving a Cenco recorder, and a timing circuit providing a master control of all the recording circuits. The high voltage was kept constant to
better than five volts. The Geiger-Mueller counter was the Eck and Krebs type described in the discussion of the neutron counter. For the gamma-rays, it was filled with a self-quenching mixture of 4.0 in. Hg, 99.5% commercial argon and 0.5 in. Hg of petroleum ether at 26°C, with thorough evacuation before filling. A second counter with approximately the same filling was used to finish the experiment, after the first showed signs of age. Both counters had plateaus of over 100 volts with a very rapid rise up to the plateau (less than 15 volts from no counts to a constant rate). The plateau of the first counter had a slope of 3% per 100 volts; the second had a 10% slope. No double pulses were observed with either counter for any counting rate, for voltages up to 100 volts beyond the operating voltages. The efficiencies at high counting rates were checked several times by using two radium sources. The loss of counts varied from 2% at a rate of 350 counts/second to 3% at 450 counts/second, and did not change appreciably during the period the counters were used. The highest counting rate during the experiment was 290 counts/second.

The beryllium targets were prepared by evaporation of beryllium from a hot tungsten filament on to silver disks in a high vacuum. Considerable experience was required to develop a successful technique, due to the high melting point of beryllium and the chemical activities of molten beryllium. Molten beryllium dissolves tungsten and supposedly almost all other materials of sufficiently high melting point. However, use of helixes of 30 mil tungsten rod gave successful evaporations in more than half the attempts; several evaporations can be made from the same filament. Strong (S2) has shown that a weak tungsten spectrum can be
seen when evaporating aluminum (which also dissolves tungsten) from a tungsten filament, presumably due to tungsten being carried away by the rapid evaporation; but extensive tests showed that no tungsten was deposited with the aluminum. In preparing the beryllium targets, only about half of the beryllium evaporated, to prevent evaporation of tungsten; the temperature of the filament was kept as low as possible.

The tungsten filaments were first heated in vacuum to remove any oxide present. After the helix was loaded with beryllium, the apparatus and especially the beryllium was thoroughly outgassed. The final outgassing was done near or at the melting point of beryllium, to drive off all gases and low melting point impurities, especially from the relatively cooler spots. The silver disk was protected during this operation by a mica shield which could be rotated without breaking the vacuum. Finally, the evaporation was made with the shield out of the way. The amount of beryllium deposited on the disk was determined by weighing on a micro-balance.

It is believed that the targets were free from objectionable impurities. The silver target disk was used because the silver is extremely pure and because silver itself does not give troublesome effects. The disks were cleaned carefully before being coated with beryllium. The beryllium used was labeled 95-99% pure, and impurities were given as 0.1% Fe, 0.1% Al, and 0.1% Si, with about 1% O. The Fe, Al, and Si impurities are negligible. The first two were probably reduced by the outgassing. No gamma-rays or neutrons have been reported from deuteron bombardment of silicon. Apparently beryllium can never be freed entirely of oxygen; thin films are believed to exist on the
individual grains (06), and surfaces become covered with a BeO layer. This might be important when working with thin targets of the order of 2000 atoms thick. Newson (N2) reports the reaction $^16\text{O}(d,n)^17\text{F}$, but gives its reaction energy as $-1.8$ Mev and its threshold as $2.0$ Mev. A reaction $^17\text{O}(d,n)^18\text{F}$ has been reported (D2,W4), but it is very weak, especially at energies used in this experiment; and oxygen contains only $0.04\%$ $^17\text{O}$. Other contaminants are carbon, which has already been discussed, and deuterium, which is absorbed by the target whenever deuterons are used.

**Procedure**

The Rice Institute pressure Van de Graaff generator was used to accelerate the deuterons and the atomic beam was allowed to pass thru the magnetic analyzer and energy selector to the beryllium target. A description of the apparatus has been published (B7). The potential stabilizer as described in this report was also used to hold the deuteron energy constant for each point. The current regulator system described for the magnetic analyzer was modified in that a 60 volt lead cell battery was used for the electromagnet and was not charged while data was being taken. The total charge striking the target during each measurement was measured with the current integrator described elsewhere (W3). The neutron counter $N$ was placed with its center 1.5 cm. from the target and the gamma-ray counter $G$ was placed 8.0 cm. further away to prevent too high a counting rate. The experimental arrangement is shown in Figure 1. Both counters were shielded from x-rays, light, and electrical disturbances by 1/16" brass cylinders.
closed at the ends; they were mounted on the same base and fastened to
the magnet bench to maintain their positions relative to the target
throughout the experiment. All electrical connections were well shielded
from electromagnetic disturbances, and all leads to the neutron counter
and its associated electronic equipment were kept as short as possible.

The deuteron energies were measured in terms of the analyzer
magnet currents; the latter were determined with a Leeds and Northrup
Type K potentiometer across a 0.1 ohm resistance in series with the
magnet coils, to an accuracy of better than .01%. To insure constancy
of the relationship between deuteron energy and magnet current, the
convention of always increasing the magnet current during a run was

![Diagram](image)

**Fig. 1.** Experimental arrangement showing relation of gamma-ray counter
G and neutron counter N to the target, beam defining slit, and magnetic
analyzer.
followed, and at the end of a run the magnet current was increased to 7.0 amperes before being brought back to zero. A calibration of the magnet current was determined this spring for the 440 KeV resonance of Li$^7$(p,γ)Be$^8$, and the 334 KeV and 479 KeV gamma-ray resonances of the F$^{19}$ + p reactions. These checked with more extensive measurements made last year using the F$^{19}$ + p gamma-ray resonances. Both sets of calibrations were used in plotting a calibration curve of deuteron energy as a function of magnet current. The curve had to be extended somewhat to higher energies mainly on the assumption of a nearly linear relation between magnet current and field strength. Experiments are now in progress which will provide calibration points at higher energies.

A beryllium target whose thickness was estimated from its weight to be 45 KeV for a 1 KeV deuteron was used in the first part of the experiment. With it, the yields of neutrons and of gamma-rays were measured for deuteron energies from 250 KeV to 940 KeV. It was also used for a rapid survey of the yields for deuteron energies up to 1050 KeV. Points were taken at intervals of about 2/3 the target thickness.

A master switch on the scale of 64 started the neutron recorder, gamma-ray recorder, deuteron current integrator recorder, and a timer simultaneously; after about 500-600 neutron counts, all were stopped simultaneously and the readings taken. (The two lowest energy points were taken for fewer neutron counts because of the low yield; only the gamma-ray yields are reliable here.) The number of gamma-rays counted was about 100 times the number of neutrons throughout the experiment. All points were repeated at least once (with the exception of the survey points), either in a second run, before the next point was taken, or
both. A separate run of 14 hours was made to determine the background of the neutron counter more accurately. The gamma-ray counter was checked frequently with a radium source; its counting rate remained constant to within 1%. At high voltages, background measurements were made with the beam stopped by an iron shutter and with the beam hitting the sides of the slits, to determine the effect produced by contaminants. A weak activity was noted at high voltages after the beam was turned off; its half-life was determined as 10 minutes and its initial activity estimated. It is without doubt the 9.93 minute activity of $^{13}$N, formed in the reaction $^4$C(d,n)$^{13}$N. The target was rotated several times while it was used so that a clean spot would be bombarded, in order to reduce the effect of carbon contamination on the target. The scale of $\beta$ was used with the neutron counter in the survey of the higher energies.

Further data was taken in the energy range 770 Kev to 1200 Kev with a target 22 Kev thick (for 1 Mev deuterons). The scale of $\beta$ was used with the neutron counter and the second gamma-ray counter was used for all data with this target. The experimental procedure was the same as before, except that more care was taken to minimize background effects and more frequent measurements of background were made.

Results

The thin target excitation functions for neutrons and for gamma-rays are plotted in Figure 2, data for both targets being included. The yields plotted are in arbitrary units, but are proportional (by the same factor) to the values observed directly in the experimental
Fig. 2. Gamma-ray and neutron yields from 45 keV and 22 keV targets

- - - - Gamma-rays (45 keV target)
- - - - Neutrons (45 keV target)
- - - Gamma-rays (22 keV target)
- - - Neutrons (22 keV target)
Fig. 2. Gamma-ray and neutron yields from 4.5 Kev and 22 Kev targets

- **Gamma-rays (4.5 Kev target)**
- **Neutrons (4.5 Kev target)**
- **Gamma-rays (22 Kev target)**
- **Neutrons (22 Kev target)**

**YIELDS**

**DEUTERON ENERGY (KEV)**

**MAGNET CURRENT (AMPERES)**
arrangement used. They have been plotted as a function of the analyzer magnet current, with values of the deuteron energy added from the calibration curve. Different runs on the neutron curve for the 45 KeV target have been normalized at 940 KeV, since the scale of 8 was used for the high energy points; the mean difference was 12% before normalization. The statistical errors of the neutron yields are indicated on the graph; most of the points checked well within these limits.

All the data from the 45 KeV target has been corrected for background. This was important at the low yields encountered at the lowest energies, but very small in the medium energies; carbon effects at the high energies amounted to a few percent. The estimated effect of carbon gamma-rays was several times that of carbon neutrons, so most of the carbon neutrons were biased out as planned.

The data plotted for the 22 KeV target has not been corrected for background. Excluding effects of contamination, the background effect is very small at these yields and roughly constant. The effects due to contamination are difficult to estimate accurately for each point, due to changes in beam current, periods of erratic action, and changes in amount of contamination with time. A careful analysis of these factors was made with the data available on backgrounds, and a consistent correction determined. When applied, it had a negligible effect on the shape of the curve. The height was reduced 5–to 10% and the scatter of most (but not all) of the points was improved slightly. Especially in view of the negligible change of shape, it was felt that the corrections were more doubtful than the uncorrected data, and were omitted in the results given here.
Both neutron and gamma-ray curves exhibit an approximately exponential increase with deuteron energy at the low energies, as is expected of the penetration of the coulomb barrier of the nucleus by the charged deuteron. The rise becomes steeper at about 850 Kev indicating increased probability of penetration by the deuteron, and a resonance is observed at 970 Kev indicating an energy level in the excited compound nucleus $^7$B. The steep rise occurring again at 1200 Kev almost certainly indicates a resonance lying somewhat higher than this.

The neutron curves and gamma-ray curves are similar over the energy range investigated, except for a slight dip in the neutron curve about 750 Kev, which may be due to experimental error. The two curves might easily differ; the gamma-rays from $^7$Li could have a different excitation function from those from $^9$Be, or the different neutron groups might vary in relative intensity with bombarding energy. However, the general similarity of the experimental curves indicates a similarity of the excitation functions for the reactions $^9$Be$(d,n)^{10}$B and $^9$Be$(d,\alpha)^7$Li, unless the gamma-ray intensity from one of the reactions is too weak to influence the curve.

The possibility of a systematic experimental error (to explain the shallow dip in the neutron curve) has not been rigorously eliminated. Vacuum tube characteristics may change with time. More important, the measured neutron intensity may be decreased by high intensities of gamma-rays; the almost continuous ionization produced in the counter by these might lower the average field strength in the counter, decreasing the gas amplification for some of the pulses and thus the counting rate. Neutron capture, reported for $^{40}\text{A}(S3)$, is not likely to affect
the results; its cross-section is very small.

It is believed that impurities have not affected the curves obtained, as explained in the discussion of the preparation of the targets. Only carbon, and possibly adsorbed deuterium, give measurable effects. The D-D reaction gives neutrons of approximately 3 Mev energy, but no gamma-rays. The thin target yield (B8) is smooth, showing no resonances for deuteron energies between 0.5 Mev and 1.8 Mev, and the rise with energy is small. Deuterium contamination could not produce or appreciably affect the Be\(^9\)(d,n) resonances obtained. There may be some effect at low energies; the cross-section for the D(d,n) reaction is larger than that of the Be(d,n) reaction at low energies, but the latter rises much more rapidly with energy (A2). Carbon has been discussed to some extent previously. There certainly is an effect, but comparison of the thin target yield curves (B3, B9) shows no similarity with those given here.

The 45 Kev target data has been plotted on a larger scale in Figure 3 to investigate the coulomb barrier penetration. An attempt was made to compare this with the thick neutron yields of Amaldi (A2), but these could not be reduced to thin target yields from the published curves with sufficient accuracy.

Bethe (B10) has given a discussion of the theories of nuclear disintegrations. For low energies far from resonances (the "penetrability region"), the disintegration cross-section \( \sigma \) may be written

\[
\sigma \propto \frac{P_P P_Q}{E},
\]

where \( P_P \) is the penetrability for the incident particle of energy \( E \)
(in the center of gravity system) and $P_{q}$ is that for the emitted particle. For particles of zero orbital momentum, the penetrabilities are given by

$$P = \exp \left[ -\frac{\mu}{2} \cdot \gamma \left( \frac{E}{B} \right) \right],$$

(B10, eq. 600) where

$$\mu = 0.375 \left[ \frac{2Za/(A+a)}{A} \right]^{\frac{3}{2}} A \gamma,$$

$$\gamma \left( \frac{E}{B} \right) - \gamma(x) = x^{\frac{1}{2}} \arccos x^{\frac{1}{2}} - (1-x)^{\frac{1}{2}},$$

$$B = 0.70 Z(A+a)A^{-1/2} \text{Mev}.$$  

Here $Z$, $z$ and $A$, $a$ are the atomic numbers and masses of the nucleus and particle. $B$ is the barrier height of the nucleus for the incident particle, and $g$ is the critical orbital momentum of the particle. For particles with orbital momentum $l \neq 0$, the penetrability is

$$P = \exp \left[ -2C \mu \right],$$

where

$$C = \frac{1}{2} x^{\frac{1}{2}} \left( \frac{\mu}{2} \right)^{\frac{1}{2}} \arcsin \left( \frac{1-2x}{1+4xy} \right) - (y+1-x)^{\frac{1}{2}}$$

$$+ y^{\frac{1}{2}} \log \left[ \frac{1+2y^{\frac{1}{2}} \left( y^{\frac{1}{2}} + (y+1-x)^{\frac{1}{2}} \right)}{(y+1-x)^{\frac{1}{2}}} \right]$$

The effective orbital momentum $l_c$ is given by

$$l_c + \frac{1}{2} = (\frac{\mu}{2})^{\frac{1}{2}} (1-x)^{-\frac{1}{2}}$$

and represents the value of $l$ for which $P_l$ has fallen to a value $P_o/e$; particles of higher orbital momentum have negligible penetrabilities.

For deuterons incident on beryllium, the barrier height $B$ is 1.64 Mev and the critical orbital momentum $g$ is 1.38. The effective orbital momenta are approximately, for deuteron energies 0 and 1.64 Mev,

$$l_c(0) = 0.83, \text{ and } l_c(1.64) = 1.13.$$  

Thus deuterons of orbital momenta greater than 1 are predicted to have little effect on the beryllium
FIG. 3. Experimental and theoretical excitation functions for gamma-rays and neutrons from 145 KeV target.

- Experimental gamma-ray yields
- Experimental neutron yields
- Theoretical gamma-ray yields ($\ell=0$)
- Theoretical gamma-ray yields ($\ell=1$)
nucleus, for the energy range of this experiment.

For the emission of neutrons (and of gamma-rays), no barrier is penetrated, and $P_{0qq} = 1$. Using this, the penetrabilities and cross-sections for $l = 0$ and $l = 1$ have been calculated, and the values given in Table I. The cross-sections $\sigma_{on}$ and $\sigma_{ln}$ listed are the values of $\sigma_1$ and $\sigma_0$ normalized to the gamma-ray yield function of Be + D at 600 Kev. They are included in Figure 3.

TABLE I

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<th>$E_D$</th>
<th>$P_0$</th>
<th>$P_1$</th>
<th>$\sigma_0$</th>
<th>$\sigma_1$</th>
<th>$\sigma_{on}$</th>
<th>$\sigma_{ln}$</th>
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<td>.00093</td>
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<td>.032</td>
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<td>.111</td>
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<td>.01367</td>
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<td>.01503</td>
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<td>.0310</td>
<td>.907</td>
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<td>.332</td>
<td>.0537</td>
<td>1.37</td>
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The curve for $\sigma_{on}$ is a reasonably good fit of the experimental yield curve for low energies; the curve for $\sigma_{ln}$ rises too steeply.

Another argument that the observed effects are principally due to $s$-deuterons is the fact that the yield of this reaction is quite large, and $\sigma_0$ is much larger than $\sigma_1$. Deuterons of orbital momenta 0 and 1 may both participate in the reaction; $(\sigma_0 + \sigma_1)_n$ is very nearly the
same as $\sigma_{\text{on}}$. Near the resonance at 970 Kev, the experimental points rise much more rapidly than the theoretical curve, as is expected, even though it is still far from the top of the barrier. The theoretical excitation curve is not supposed to hold exactly for a nucleus as light as Be$^9$, but it is better than that of the Oppenheimer-Phillips theory.

The data for the 22 Kev target has been plotted on an enlarged scale in Figure 4. The general rise of the gamma-ray excitation function in the region of the 970 Kev resonance has been estimated (ignoring possible resonances above 970 Kev) and is shown as the dotted curve. Subtracting this from the gamma-ray excitation function gives the resonance curve shown at the bottom of the graph. A value of 0.1 unit should be subtracted from the marked values of the ordinates to obtain the proper values for this resonance curve, since its zero has been drawn on the ordinate 0.1.

The resonance at 970 Kev is certain, but nothing definite can be said about the region between it and the probable beginning of a resonance at 1200 Kev. A complex structure is indicated; the points vary more than can be accounted for wholly by experimental error. However, the resolution and statistics are poor. Trouble with the voltage regulator introduced considerable scatter in the gamma-ray points in this region (but no uncertainty in the deuteron energy); the points below 900 Kev were generally reproducible to better than 1/2. This region should be explored carefully with a thinner target.

The derived resonance curve shows the shape of the 970 Kev resonance much better than the original curve, although the points on the high energy side still have too much scatter. The curve rises more
Fig. 4. Gamma-ray and neutron yields from 22 kev target for Be-D

- Gamma-rays
- Neutrons
- Gamma-ray resonance

YIELD OF GAMMA-RAYS AND NEUTRONS (ARBITRARY UNITS)

ENERGY OF DEUTERONS (KEV)

ANALYZER MAGNET CURRENT (AMPERES)
rapidly than it falls; this either shows a decided asymmetry of the 
resonance or indicates strongly other unresolved resonances on the 
high energy side. The curve drawn has a half-width of 100 Kev. A 
symmetrically drawn curve gives a half-width of 75 Kev for the 970 
Kev resonance; weak unresolved resonances on either side would, if 
resolved, decrease the apparent width slightly. The half-width is 
definitely greater than the target thickness at this bombarding energy. 

Another resonance in both the gamma-ray yield and the neutron yield 
at a deuteron energy slightly greater than 1200 Kev is almost certain.

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