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Resonances for Carbon Bombarded 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, 1948
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INTRODUCTION

A nuclear reaction is now generally thought to occur in two steps, in a manner first suggested by Niels Bohr. First a compound nucleus is formed which is composed of the incident bombarding particle (proton, neutron, deuteron, or alpha-particle) and the target nucleus (any element). The compound nucleus so formed is not stable, but it does exist for a longer time than the time required for the incident particle to traverse a distance of nuclear dimension. The compound nucleus has gained an excitation energy equal to the kinetic energy of the incident particle plus the binding energy of the incident particle in the compound nucleus. All nuclei have a smaller mass than the sum of the masses of the individual protons and neutrons which form the nucleus. This difference in mass, converted into energy, is the total binding energy of the nucleus. The binding energy per particle in a nucleus amounts to about six to eight million electron volts.

When all or part of the excitation energy, which has been shared by the neutrons and protons in the nucleus, concentrates on a particular nuclear particle, the second part of the nuclear reaction takes place with the emission of the particle. Emission of the same kind of particle
as the bombarding particle is always a possible reaction. This process is called elastic scattering, or inelastic scattering, according as the emitted particle has the same, or less, energy relative to the residual nucleus as the incident particle had relative to the target nucleus. The excess energy left with the residual nucleus when inelastic scattering occurs is given off as a gamma-ray; or if the excess is sufficient, another particle may be emitted.

In addition to emission of a particle of the same kind as the incident particle, sufficient energy for emission may concentrate on another type of particle. In a general nuclear reaction all types of particle emission, consistent with conservation laws, compete with each other and with gamma-ray emission. However, gamma-ray emission is almost impossible if particle emission is possible. (1) The yield, or number of emitted particles of one kind produced by a given number of bombarding particles, is proportional to the probability of formation of the compound nucleus and the probability of emission of the particle.

No completely satisfactory model or set of mathematical rules has as yet been developed which can predict the experimental results of nuclear disintegrations. One of the observable characteristics of artificial disintegrations giving most promise for a better understanding of nuclear structure is the phenomenon of resonance. Here it is observed that the yields for one or several types of
particle emission show a marked increase extending over a definite range of bombarding particle energy. Often the bombarding particle energy range covered by a resonance as small as 500 to 10,000 electron volts. (See reference (32) for examples occurring under proton bombardment of various light nuclei.) From an experimental standpoint the small energy spread of some resonances makes it necessary to confine the energy spread of the bombarding beam of ions to an even smaller magnitude. This requirement retarded close examination of the properties of narrow resonances until the development during the past ten years of ion accelerators capable of the necessary resolution.

Nuclear yields are given quantitative expression in terms of the quantity cross-section. This quantity may be defined as the probability that a bombarding particle incident on one square centimeter will have a reaction with a target nucleus placed somewhere in the square centimeter, or alternatively as the effective area of a target nucleus presented to a bombarding particle.

Any theoretical attempts to explain resonances in artificial nuclear disintegrations must be made on the basis of the following experimentally observable quantities:

(1) The cross-section

(2) The bombarding energy at which the resonance occurs
(3) The sharpness of the resonance (This is expressed in terms of the energy width at half maximum yield.)

(4) The shape of the resonance curve

(5) The types of possible emitted particles or gamma-rays which show resonance yield at a given bombarding energy

(6) The angular distribution of the emitted particles at resonance.

(See figures 1, 2, 5 for illustrative resonance curves.)

If an observed resonance is comparatively isolated, so that interference effects of other possible excited energy levels of the compound nucleus may be neglected, some of the above observables may be interpreted. Expressions for the cross section near such an isolated resonance are given in the form,

\[ \sigma = \frac{\gamma^2 \gamma^2}{(E-E_0)^2 + \frac{\gamma^2}{4}} \]  \hspace{1cm} (reference 3 formula 12)

where \( \gamma / \gamma_n \) is the total probability per unit time of disintegration of the compound nucleus formed by bombardment with particles of energy \( E \). It is equal to the sum of the probabilities for disintegration into all the possible types of emitted particles.

where \( \gamma^2 / \gamma_n \) is the probability for emission of particles of the same kind as the incident particle.
where $\gamma/\eta$ is the probability for the emission of a particle of type $\beta$.

$\Gamma$ depends on the wave length of the incident particle. Then the energy of the incident particle, $E$, is equal to $E_0$ the cross section is a maximum. From the value of $E_0$ the excitation energy of the resonance energy level of the compound nucleus may be obtained.

$E_0 = \text{Energy of resonance level} + \text{Binding energy of incident particle.}$

When $E = E_0$, $\gamma = \Gamma$, the true energy width of the resonance level. The width, $\Gamma$, is connected with the mean life of the compound energy state by the indeterminancy relation, $\Gamma = \frac{\hbar}{\tau}$. Thus a narrow resonance means that the compound nucleus exists for a long time. For example a resonance state with a width of 200 electron volts would exist approximately $10^{-9}$ seconds. This is quite long compared to the $10^{-21}$ seconds a bombarding particle would spend traversing a distance of nuclear dimensions.

Interpretations of yield energy curves for resonance levels close enough together to overlap cannot be made until better nuclear models and a better understanding of the forces between nuclear particles is obtained. Peaks in experimental yield-energy curves no longer
indicate the position of levels in the compound nucleus with the precision obtainable in the isolated level case. (5) The shape of an experimental resonance curve sometimes shows the effect of nearby interfering levels. (See curves (1) and (5).)

HISTORY OF THE CARBON REACTION

Resonance yields occurring in a deuteron reaction were first observed in 1940 by Bennett and Bonner for the deuteron bombardment of carbon. (6) In a series of experiments extending through 1941, the yields of the various disintegration products, protons, neutrons, and gamma-rays were determined. The reactions for the carbon isotope of carbon, C^{12}, which were shown to exhibit resonance yields are,

\[ C^{12} + d \rightarrow H^{13} + p + Q_1 \]  (1)
\[ C^{13} + n \rightarrow p + Q_2 \text{ and } C^{13} \rightarrow C^{13} + \gamma \]  (2)
\[ p^{15} + n + Q_3 \]  (3)

The Q values have been determined to be,

\[ Q_1 = +2.71 \text{ Mev. (reference (10))} \]
\[ Q_2 = -0.52 \text{ Mev. (reference (9))} \]
\[ Q_3 = -0.27 \text{ Mev. (reference (11))} \]

The high energy protons emitted in reaction (1) were observed in an ion chamber connected to a linear amplifier. (9) Resonance yield peaks were observed at 0.92 Mev, 1.16 Mev,
1.25 MeV, and possibly at 1.7 MeV. (See figure (7).)

The gamma-rays coming from the excited $^{13}\text{C}^*$ of reaction (2) were observed with a Gulf electrometer filled to a pressure of 70 atmospheres of Argon. (6) Resonances were observed at 0.92, 1.13, 1.3, 1.43, and 1.74 MeV. At each of these resonance energies the energy of the gamma-rays was determined using Geiger counters in coincidence and placing aluminum absorbers between them.

The absorber vs. thickness of aluminum curves showed that a high intensity gamma-ray of about 5.0 MeV. was causing most of the coincidence counts. However, the end point of the curve indicated that there was a low intensity gamma-ray with an energy of 5.1 MeV. present. It was found possible to attribute this higher energy gamma-ray to the $^{13}\text{C}$ isotope by using targets enriched in $^{15}\text{C}$ and noting the increased intensity of the 5.1 MeV. gammas. Cloud chamber studies by Donner, Becker, Rubin and Streib using normal and enriched carbon targets confirmed this conclusion and gave gamma-ray energies of 3.0 MeV. and 5.5 MeV. The $^{13}\text{C}$ reaction involved is,

$$^{13}\text{C} + ^{1}\text{H} \rightarrow ^{15}\text{N}^* \rightarrow ^{14}\text{N} + n + 0.4 \text{ MeV}.$$  

A direct determination of the energy of the short range protons of reaction (2) was made by observing them in a cloud chamber filled with Helium. From the observed
range of these protons a Q value of \(-0.52\) MeV. was calculated. A proton reaction of this Q value leaves \(^{13}\text{C}\) excited to 3.24 MeV, which agrees well enough with the experimentally observed gamma-ray energy of 3.0 MeV.

The 1941 determination of the neutron excitation curve was made with a Wulf type electrometer filled with hydrogen to a pressure of 7 atmospheres. Since both gamma-rays and recoil protons contribute to the ionization, it was necessary to correct for the ionization caused by the gamma-rays. After applying the correction resonances for the yield of neutrons were found to occur at 0.82, 1.16, 1.35, 1.52 MeV., and also a doubtful resonance at 1.74 MeV. The Wulf electrometer was placed to observe the yield of neutrons at 0° to the deuteron beam.

The number of \(^{13}\text{N}\) residual nucloi formed in reaction (5) is equal to the number of neutrons emitted. \(^{13}\text{N}\) is positron radioactive with a half-life of 9.05 sec. (13) Thus it was possible to obtain the yield of neutrons by observing the number of positrons from \(^{13}\text{N}\). The same resonances were observed for the positron yields, which are proportional to the neutron yield over all angles, as for forward direction neutrons. However, the relative intensities of the resonance peaks were different, suggesting that the yield of neutrons varied with angle of emission. (9)
Of particular interest among the resonances observed was the gamma-ray resonance found at deuteron energies of about 1.43 kev. For this resonance a width of 10 kev was measured. The spread in energy of the Rice Institute's Van de Graaff beam at the time of this measurement was also about 10 kev. Thus the true width of the resonance might have been less. Such a narrow level occurring in so highly excited a compound nucleus was unexpected. Indeed, resonances resulting from deuteron bombardment were not expected at all because the small binding energy of the deuteron gives high excitation to any deuteron produced compound nucleus. For example the excitation energy of $^9_{14^3}$ formed by a deuteron combining with $^3_{12}$ would be 10.3 kev plus the relative kinetic energy of the deuteron. This is much higher excitation than the 7.6 kev which would exist in a $^9_{14^3}$ compound nucleus formed by proton bombardment of $^3_{13}$. The high energy protons of reaction (1) and the neutrons of reaction (2) did not seem to show a resonance yield at 1.43 deuteron energy. However, there was some doubt about the non-resonance yield of neutrons since a correction had to be made to allow for the effect of the gamma-rays in the Wulf electroscope. One of the purposes of the present experiment was to investigate the neutron yield with a device insensitive to gamma-rays.
A particularly careful check was made in 1941 of the energy of the gamma-ray involved in the 1.43 Mev. resonance. Coincidence Geiger counters were used with sufficient absorber between them to prevent 3 Mev. gamma-rays from giving coincidence counts. No resonance yield was observed. A similar experiment was performed with sufficient absorber to prevent gamma-rays of less than 2.8 Mev. from giving coincidence counts. With this arrangement the resonance was observed and so the gamma-rays were concluded to be the 3 Mev. rays from reaction (3).

Bailey, Phillips, and Williams studied the yield of neutrons from reaction (3) using a 37g chamber as a neutron detector. They reported neutron resonance yields at 0.91, 1.20, 1.6, and 2.3 Mev. (See table 7.)

Very recently, Bailey, Schrier, and Williams reported an investigation of the yield of gamma-rays and neutrons from reactions (2) and (3) extended to deuteron bombarding energies of 5.2 Mev. Neutron yields were observed both in the forward direction and at 90° to the deuteron beam. The yield energy curves at these two angles showed very different characteristics. The cross sections per unit laboratory solid angle for neutrons observed at 90° were in general much smaller than the cross sections for neutrons at 0°. Also, some
resonances appeared for the $^{16}$O neutrons which appeared
absent for $^{20}$O neutrons. Another phenomenon observed by
these authors was a difference between gamma-ray and
neutron resonance peaks for the same excited level of the
$^{16}$O nucleus. These shifts occurred at higher bombarding
energies than are covered in this paper.

OBJECTIVE OF THE PRESENT INVESTIGATION

The observations reported in this thesis were
undertaken for the purpose of obtaining neutron yields
with an apparatus insensitive to gamma-ray background,
and in particular to investigate neutron and gamma-ray
yields in the neighborhood of the narrow resonance appear-
ing at about 145 kev. deuteron energy.

The Rice Institute's Van de Graaff ion accelerator
now has finer resolution of the spread in energy of the
bombarding ion beam than was obtainable at the time of
the 1941 measurements of the width of the narrow resonance.
Very thin carbon targets were prepared in order to take
full advantage of the resolution of the ion beam and the
width has been determined accurately.

Narrow resonances are used throughout the country
as standards for the calibration of bombarding particle
energies. For this reason a careful energy calibration
was made just before one of the several observations of the narrow resonance. A value of 1417 kev. was obtained for the deuteron energy at which the resonance maximum appears.

As the experiment progressed lack of a definite neutron resonance yield, for forward direction neutrons in the neighborhood of the gamma-ray resonance at 1160 kev., made it desirable to investigate the total yield of neutrons over all angles. (See figure 2) This was done by observing the yield of positrons produced in the radioactive decay of $^13_1$ formed by the reaction

$$^12_1 + ^1_1 \rightarrow ^{14}_1 \rightarrow ^{13}_1 + ^1_1.$$  (2)

Positron yield observations have the added advantage of making possible rather precise calculations of cross-section, and thus give yield measurements a quantitative value.

Angular distribution measurements have been made of neutron yields for the three lowest energy resonances. (See figure (6).) These results are incomplete but they indicate a very remarkable asymmetry in the angular distribution.

APPARATUS

A general description of the Rice Institute Van de Graaff ion accelerator has not been published. It is
similar in design to the accelerator described by Horb, Parkinson, and Kerst.\textsuperscript{(20)} The recently added voltage stabilizer, which makes possible the investigation of narrow resonances, has been described by Bennett, Donner, Sandeville, and Watt.\textsuperscript{(19)} This apparatus has given this year highly resolved deuteron bombarding currents ranging from 0.1 to 0.6 micro amperes. The current is observed on an electronic microammeter connected to the metal target backing through a current integrating device. The integrator causes a count to be recorded on a mechanical register for each 0.0416 micro coulombs of deuteron charge collected at the target. A description of this device has been published by Dr. E. T. Watt.\textsuperscript{(19)} Whenever the deuteron beam current exceeded 0.5 micro-amperes an additional charging capacitance of 1000 mmf. was placed in parallel with the original charging capacitance of 1000 mmf., described in reference (19). The additional capacitance reduced the sensitivity to one count per 0.0861 micro coulombs and so reduced the counting rate of the mechanical register by a factor of two. The mechanical register could not respond faster than about 10 counts per second.

Full resolution of the ion beam has been estimated as \(\pm 0.05\%\) of the total bombarding energy. Thus in the neighborhood of the narrow resonance at 1417 kev, the
uncertainty in the energy is about 1500 electron volts.

Four factors determine the resolution of the beam. (a) The field of the magnetic analyser must be kept steady, (See Figure (3).) A bank of batteries supplying 60 volts provides an initially steady current to the field coils of the analyser. In addition, high frequency voltage fluctuations across the coils are compensated by an electronic device, while slow changes in the magnet coil current caused by battery fluctuations or coil heating are manually corrected by slightly modifying the voltage across the coils. The current through the magnet coils was constantly observed by means of a potentiometer measuring the voltage across a standard 0.1 ohm resistance. When precision energy control was desired, as in the examination of the 1417 resonance, the magnet current was held constant to within .05 milliamperes out of 4.3 amperes total current. (b) The slits defining the emergent beam from the analyser must be as narrow as possible yet still allow a fairly large deuteron beam to strike the target. (c) Also the beam must be kept centered on the slits. This is accomplished by sending electrons back the accelerating tube in the opposite direction to the deuteron beam. The number of electrons sent back the tube is modulated by the proportion of beam charge falling on one side of the slit as compared to the other side. More deuteron
current falling on the high energy side of the slit causes more electrons to be sent back to the positive potential at the deuteron source. Less electrons are sent back the accelerating tube if the beam falls on the low energy side of the slits. A visual inspection of the beam made by observing its fluorescent image on pyrex glass showed that the beam was held centered to within about one tenth of the slit width. The slit width at the time of this observation was .615 cm. (d) A small energy spread is caused by an internal voltage at the ion source used to draw the deuteron ions through a small capillary tube into the large potential drop existing along the accelerating tube. This voltage was of the order of 500 volts during the course of the present experiment.

TARGET PREPARATION

In all nuclear disintegration studies and more especially in resonance disintegration study, the preparation of targets is of primary importance. For a preliminary survey of the variation in yield with bombarding energy a relatively thick target is most desirable. The thickness of a target is a measure of the number of disintegrable nuclei per square centimeter which a bombarding particle sees. Thus larger intensities are obtained the thicker the target. Thickness is generally denoted in
terms of grams per sq. cm. or in units of energy loss suffered by the bombarding particle in traversing the target. For example, in this experiment targets of cereais wax ranging in thickness from 2.1 micrograms per sq. cm. to 3 micrograms per sq. cm. were used. After a preliminary survey has been made, and the approximate shape of the yield-energy curve determined, closer study may be made with thinner targets of the resonance regions revealed in the survey.

Since a deuteron making a disintegrating collision at the front surface of the cereain target will have more energy than a deuteron making a collision deeper in the target, an uncertainty equal to the energy loss of the deuteron in passing through the target will be introduced into the energy. An experimental yield-energy curve gives an observed width at half maximum yield according to the relation,

\[
\Gamma_{\text{observed}} = \sqrt{\Gamma_{\text{actual}}^2 + W^2}
\]

where \( \Gamma \) is the energy width at half maximum intensity (see figure 5).

\( W \) is the spread in energy of the bombarding deuterons introduced by target thickness and lack of resolution of the ion beam.

In order to obtain the actual width of the 1417 kev.
resonance, $W$, had to be made as small as possible. For this purpose the 3 microgram per sq. cm. target was prepared. This has a calculated thickness of about 1000 electron volts.

All targets were prepared by evaporating in a vacuum small pieces of ceresin wax onto a highly polished silver disk of 6 sq. cm. area. The ceresin was held in a small porcelain crucible cover which was electrically heated with a tungsten wire coiled under the cover. The evaporation was carried to completion in about 20 minutes. Practice showed that a one millimeter cube of ceresin would deposit a layer of 3 micrograms per sq. cm. on the silver disk placed 6 centimeters from the ceresin. This proportion of volume of ceresin to amount deposited was constant. Silver was chosen as a backing because it is inactive under bombardment in the energy range covered in this experiment.

The silver disk was balanced on a micro-balance against a like disk before and after deposition of the ceresin. Also the disk was balanced, both before and after deposition, against a disk coated with ceresin on one side. This procedure gave a check on the slightly differing amounts of water adsorbed by the silver and by the ceresin side of the disk.
Carbon targets prepared by depositing soot from a flame on a tantalum disk have been used by Williams. (16) These targets had to be electrically heated during the time of bombardment in order to prevent absorption of deuterium. The ceraein targets do not absorb deuterium to any noticeable extent. Twenty or so hours of deuteron bombardment during the time of four separate runs over the 1417 kev. resonance region gave no indication of increased neutron yield resulting from the reaction,

\[ ^3D + D^2 \rightarrow ^3He + n^1 . \]

A calculation of the loss of energy experienced by a deuteron passing through a given thickness of ceraein may be made using the 1936 revised range-energy curves of Herb, Parkinson, Bellamy, andudson and the stopping power curves given by Livingston and Bethe, (21) for carbon and hydrogen. Assuming that the average molecule of ceraein is \( C_{30}H_{48} \), the stopping power per half molecule is 20.93 for deuterons of 1.4 kev. energy. One microgram per sq. cm. is equivalent to a column of \( C_{30}H_{42} \) gas 5.63 \( \times 10^{-5} \) cm. long. A deuteron of 1.4 kev. will lose 0.346 kev. per cm. of path in air and so will lose 20.95 \( \times 0.346 \times 5.63 \times 10^{-5} \) or 468 ev. passing through one microgram per sq. cm. of ceraein. Both the stopping power and the energy loss per cm. increase as the particle energy decreases. For example, a target giving an energy loss of 1000 ev. for deuteron energies of 1.4 kev. would
give an energy loss of 1900 eV for deuterons of 0.7 keV. This means that targets suitable for use at high energies are often too thick for the close examination of resonances at low energies.

DETECTION OF NEUTRONS

Methods of detecting fast neutrons with any degree of efficiency have not been developed to the satisfactory extent that detection of charged particles and gamma-rays has reached. Neutrons do not interact with the electrons in matter and so their detection is accomplished by observing their interaction with nuclei. These interactions have a very small probability as compared to charged particle interaction with electrons.

For this experiment a method was devised which gave reasonably high efficiency for a fast neutron detector, and which had an almost constant sensitivity over the range of neutron energies covered.

It is possible for a neutron to give up any fraction of its energy to the recoil proton produced in a collision between a neutron and an hydrogen atom. The ionization produced by the recoil proton may be detected with standard methods. The general expression for the energy given to a recoiling nucleus in a collision is,

\[ E_p = \frac{E_1 M_p}{M_1 + M_p} \cos^2 \theta \left( \frac{M_1 + M_p}{E_1} \right)^2 \]
where \( E_r, E_i \) are the kinetic energies of the recoil nucleus and incident particle measured in the laboratory system; \( M_r, M_i \) are their masses; \( \theta \) is the angle between the direction of the incident particle and the recoil nucleus measured in the system in which the center of gravity is at rest.

In order to detect the recoil protons caused by neutrons from reaction (5), a standard Eck and Krebs glass gamma-ray counter was filled with ethane to a pressure of 43 cm. of Hg. The counter is a glass cylinder chemically silvered on its inner surface. A length of 6 cm. of the 4 mil. center wire is effective for collecting electrons. The counter has an inner diameter of 1.64 cm. and an active volume of 12.6 c.c. This counter was operated at such a voltage, 2200 volts, that electrons set free along the path of the ionizing proton migrated toward the wire and produced several more electrons per electron in the stronger electric field near the wire. Counters operating in this way are said to be operating in the proportional region because the number of electrons collected at the center wire and hence the voltage pulse produced is proportional to the number of ions produced by the recoil proton. In spite of the amplification produced by this electron multiplication the voltage pulses produced by a recoil are only about 100 micro-volts.

A high gain amplifier using battery operated filament brought the voltage pulses to a usable 10 to 20
volts. This amplifier was used to observe the yields pictured in the neutron $\theta^0$ curve of figures (1) and (2). The yields of figures (3) and (5) were observed using an Atomic Instrument Development Company amplifier which gave amplified pulses up to 100 volts before limiting. After amplification the pulses were sent through a discriminator and thence to a scale of 64 and mechanical register. The discriminator, a device to exclude pulses less than a set voltage, made it possible to make the counter completely insensitive to gamma-ray effects, and also made it possible to maintain a constant sensitivity over a wide range of neutron energies. It was just this possibility of excluding gamma-ray effects which made the use of a proportional counter desirable for the experiment, since the gamma-rays from the competing reaction $C^{12} + D^2 \rightarrow C^{13} + H^1$ can interfere with observations of neutron yields.

The fact that pulses below a certain size are not counted means, according to formula 3, that proton recoils give a countable pulse only if they are within a cone with a vortex at the point of collision and an axis along the direction of the incident neutron. As the deuteron energy is increased in the reaction $C^{12} + D^2 \rightarrow N^{13} + n^1$, the neutron energy increases, and the angular opening of the proton recoil cone also increases. Thus a greater fraction
of the incident neutrons cause a count to be registered. This fact in itself would cause the counter to be somewhat unsatisfactory since its sensitivity would change rapidly as the neutron energy increased. If the recoil path length of the smallest recoil which can be observed is small compared to the counter dimensions, then the sensitivity is proportional to

\[ \sigma(\varepsilon) (1 - \frac{\varepsilon}{E}) \]

where \( \sigma(\varepsilon) \) is the scattering cross section of protons for neutrons, \( B \) is the smallest energy recoil which may be counted for a given discriminator bias setting, and \( E \) is the energy of the neutrons. Formula (7) holds only for isotropic scattering. Neutron-proton scattering has been shown to be isotropic in the center of mass system. (22)(23) Fortunately, as Baroshall and Beths have pointed out, (24) from the fact that \( \sigma(\varepsilon) \) varies approximately as \( \varepsilon^{-1} \) for neutron-proton scattering, there results a sensitivity function which is constant within 25% over an energy range from 1.63 to 9.6 B.

Ethane gas was used in the counter in order to get as many hydrogen nuclei per cubic centimeter as possible. However, the use of ethane has the disadvantage of requiring rather high voltages for counter operation in the proportional region. It was necessary to use 2200 volts on the counter described.

Minor dielectric breakdowns and small corona discharges at these voltages give a spurious pulse which can
be mistaken for a true count. To eliminate this difficulty all electrical parts had to have a high voltage rating, and all wires carrying a high voltage had to have large diameter and be well separated from ground potential. Amphenol connectors were avoided on all high voltage leads. The counter was coated with coloresin to prevent surface moisture from causing surface electrical leakage. An RG59U coax cable carried the high voltage to the counter. The coupling capacitance to the amplifier, the 1 megohm load resistor, and its by-pass capacitance were all mounted in a brass box directly beneath the counter. The coupling capacitance was a Centralab Hi-Vo-Kap of 1000 nuf. with a voltage rating of 10,000 V.V.D.C. The by-pass capacitance was a .01 μf. Glassmike of 5000 V.V.D.C.

A regulated power supply similar to one described (25) supplied the 2200 volt counter voltage. The output voltage was filtered by a two section RC filter to help eliminate 60 cycle pickup.

As used, the counter was not operating under optimum conditions. The energy of the smallest recoil proton counted, with the standard discriminator bias chosen, was estimated by observing the number of counts recorded as the bias was changed. This smallest recoil energy was found to be about 0.3 Mev. It is also the energy of the slowest neutron which may produce a count. The smallest track length in the counter which will give a count is
then 0.7 cm. A maximum sensitivity occurs for neutrons of 0.9 Mev. corresponding to a deuteron bombarding energy of 1.6 Mev. At a deuteron bombarding energy of 1.5 Mev. the sensitivity for neutron detection is about 35% of maximum while for 1.8 Mev. deuterons the sensitivity is 95% of maximum as may be seen from formula (7) using $\alpha (E) \sim E^{-\frac{3}{2}}$.

For the discriminator setting used, recoiling carbon nuclei began to count at deuteron energies of about 1.4 Mev., corresponding to neutron energies of about 1.1 Mev. However, even at deuteron energies of 1.6 Mev. the number of counts which could be attributed to recoiling carbon nuclei only amounted to 10% of the total number of counts. This computation was made on the basis of approximately equal neutron cross sections for hydrogen and carbon. (See ref. (26) pages 396 and 407.)

**EXPERIMENTAL USE OF NEUTRON COUNTER**

The neutron counter described above was used to determine the neutron yield from the reaction

$$^9\text{Li} + ^3\text{He} \rightarrow ^7\text{Be} + ^1\text{n}$$

for deuteron energies in the range 0.75 Mev. to 1.6 Mev. (See figure (2) curve labeled Neutrons at 0°.) The counter was placed at 0° to the direction of the deuteron beam and as close to the target as possible. (See figure (3).) Paraffin blocks were
placed about the counter as indicated in figure (3) to slow down any fast neutrons which might enter the counter. Fast neutrons originate in the ever present carbon contamination found on the slits, in the magnet path, etc., the neutrons so slowed, and also the slow neutron atmosphere always found in a closed laboratory when neutrons are being produced, do not have enough energy to be counted. A check on the overall gain of the system, counter plus amplifier, was made each day by reducing the discriminator bias to a value small enough to detect gamma-rays. The gain of the amplifier was slightly changed if the number of gamma-ray counts, produced by a standard radium source, varied. By this means it was found possible to reproduce neutron yields each day to within 1%. All critical electrical equipment such as the current integrator, amplifier, and power supply were given at least an hour warm up before use.

At least two sets of observations were made at each deuteron energy shown in figure (2). Each observation represents the detection of 640 neutrons.

Particular attention was paid to the gamma resonance level at 1417 kev. Neutron yields were observed for deuteron energies taken in 1 kev. or 2 kev. steps over an energy range from 1385 kev. to 1455 kev. using a target 16 kev. thick. There was absolutely no indication of a resonance in the yield of neutrons. This confirms the
result of the 1940 experiments of Bonnar, Budapeh, and Bennett.

(7) It may be noticed from an examination of the 0° neutron curve of figure (3) that there is no pronounced resonance in the vicinity of 1140 kev. (See also references (6) and (17).) However, earlier studies of the production of the A\(^{15}\) nucleus produced in the same reactor that gives the neutrons had shown a resonance at this energy. (6) In order to check this resonance in the production of A\(^{15}\) a similar experiment has been performed this year.

The A\(^{15}\) nucleus produced in the reaction, 
\[ ^{12}C + d \rightarrow A^{15} + n \], is positron radioactive with a half-life of 10 minutes. Thus it is possible to measure the yield of neutrons by observing the positron yields from the equal number of A\(^{15}\) nuclei formed. It may be noted here that the A\(^{15}\) yields observed are equivalent to the neutron yield over all angles.

In order to obtain the neutron cross section by this indirect method, a quantity of A\(^{15}\) was produced by deuteron bombardment. Then bombardment was stopped and positron activity was measured.

For 600 seconds the carbon target was bombarded holding the deuteron current as constant as possible. Every 100 seconds during the 600 seconds an integrator reading was taken. This reading gave a measure of the total deuteron charge collected during the 100 seconds.
The number of $^\text{13}$ atoms remaining at the end of the first 100 seconds is $\frac{C_{100}}{\lambda} \left( 1 - e^{-\lambda_{100}} \right)$, of which number $\frac{C_{100}}{\lambda} \left( 1 - e^{-\lambda_{100}} \right) e^{-\lambda_{500}}$ will remain at the end of the bombarding period. The number at 200 seconds resulting from bombardment from 100 to 200 seconds is $\frac{C_{200}}{\lambda} \left( 1 - e^{-\lambda_{100}} \right)$ of which $\frac{C_{200}}{\lambda} \left( 1 - e^{-\lambda_{100}} \right) e^{-\lambda_{400}}$ will remain at the end of the bombardment period. Here $C_{200}$ represents the number of $^\text{13}$ atoms created per second in the interval between 100 and 200 seconds, and $\lambda$ is the decay constant ($\lambda = \frac{1693}{600}$ per second). The total number of $^\text{13}$ nuclei remaining at the end of the 200 second bombarding period is,

$$m_{200} = \frac{1}{\lambda} \left( 1 - e^{-\lambda_{100}} \right) \left( C_{100} e^{-\lambda_{500}} + C_{200} e^{-\lambda_{400}} + C_{300} e^{-\lambda_{300}} + C_{400} e^{-\lambda_{200}} + C_{500} e^{-\lambda_{100}} + C_{600} \right)$$

If $C_{100} = C_{200} = \cdots = C_{600} = C$, this formula reduces to

$$m_{200} = \frac{C}{\lambda} \left( 1 - e^{-\lambda_{100}} \right) = \frac{C}{2\lambda}$$

The quantity $m_{200} \lambda$ is the number of $^\text{13}$ atoms decaying per second by positron emission just at the instant deuteron bombardment is stopped.

The second step in the cross-section determination was the experimental measurement of $m_{200} \lambda$. Once this quantity has been found the cross section may be calculated since any of the $C$'s is given by $C = \frac{1}{m_{13}} \text{(no. of carbon atoms per } \mu\text{gn) times (no. of deuterons per integrator count) } k$.

where 100 $k$ is the number of integrator counts in the 100 second bombarding interval concerned.
where $\sigma_{N^3}$ = cross section for the formation of $^N_{13}$ = cross section for emission of a neutron.

In order to calculate $\eta_{bom}$, the number of positrons emitted in a small solid angle was measured by means of a thin walled Geiger counter for many 100 second intervals after the 600 second bombardment period. The logarithm of the number of positron counts per 100 second interval plotted against time gave a straight line. Every 50 seconds the number of positron counts should decrease by a factor of two since the measured half life of the $^N_{13}$ decay is almost exactly 10 minutes. Knowledge of this fact, which determines the slope of the line on the logarithmic plot, made it possible to draw the best straight line through the experimental points. Experimental points were plotted for time intervals 100 seconds apart beginning with a time 50 seconds from the cessation of bombardment. This means that the points are plotted at times very close to the time at which the average number of counts per second over an 100 second interval would be expected. (Actually the time at which the average number would occur is 53.5 seconds from the beginning of the interval.)

Before any of the experimental points were plotted three corrections had to be made. The background counts due to cosmic rays and the normal radioactivity in the laboratory and in the counter walls were subtracted from the observed number of positron counts.
Also 7% of the counts recorded were caused by annihilation radiation. If this effect were neglected, the effective solid angle subtended by the counter would be unknown. The positrons themselves have to enter the counter through a small aperture. (See figure (4).) The amount of annihilation radiation was a constant percentage of the amount of positron activity. The figure 7% was obtained by blocking positron entry to the counter with a thin lead sheet and observing the decay of annihilation radiation alone.

In addition to these corrections, allowance had to be made for residual radioactivity remaining in the carbon target from previous bombardment periods. This effect was not completely negligible since bombarding voltage was changed, and a complete new determination of positron yield was made every 3000 seconds, (five half lives).

The final form of the equation used to determine the cross section at each voltage is,

\[ \sigma_{N^1} = \frac{\text{number of counts per sec. at } t = 600}{100} \times \left( \frac{\text{number of integrator counts per deuteron}}{\text{relative solid angle}} \right) \left( \frac{1}{Q} \right) \times \left( \frac{1}{\text{transmission of positrons}} \right) \]

where

\[ Q = \left( 1 - e^{-\lambda_{100}} - e^{-\lambda_{200}} + k_{200} e^{-\lambda_{400}} + k_{300} e^{-\lambda_{300}} + k_{400} e^{-\lambda_{200}} + k_{500} e^{-\lambda_{100}} \right) \]
and

$$k = \text{no. of integrator counts in the 1cc sec. interval concerned}$$

Time was measured from the start of deuteron bombardment.
All of the quantities on the right hand side of the equation
are experimentally observed or can be calculated from the
experimental findings of others. The efficiency of the
thin walled Geiger counter is taken as 100% for the detection
of positrons. For a 10 minute half life the value of $\lambda$ is
$0.115$. In order to calculate the transmission of positrons
through the thin aluminum foil covering the small aperture
of the target assembly, and through the glass counter walls,
the air gap, and the black paper which lie between the
target and the sensitive volume of the counter, it was
necessary to know the energy distribution of the positrons.
This information has been published in the form of a graph
by A. A. Townsend.

The absorber thickness between target and counter
was $0.047$ gms/cm$^2$ aluminum foil, $0.0106$ gms/cm$^2$ paper,
$0.01$ gms/cm$^2$ air, and $0.054$ gms/cm$^2$ glass, giving a total of
$0.070$ gms/cm$^2$. This thickness of absorber removes all posi-
trons with an energy less than $0.27$ Mev. (26) A graphical
integration of Townsend's energy distribution curve between
the limits $0.27$ Mev. to the highest energy positron, $1.2$
Mev., shows that $74\%$ of the positrons pass through the
absorber. In this way the cross section for neutron
emission over all angles was found to be $6.256 \times 10^{-24}$ cm$^2$
for deuterons of $1.14$ Mev.
Once the cross section has been found at a given energy, the cross section at all other energies is known by a comparison of the relative yields. The curve labeled \( N^{13} \) in figure (3) was obtained using a different experimental setup than the one just described. In this case a carbon target 58 micrograms/cm\(^2\) was placed on a thin silver backing 0.109 grs/cm\(^2\) thick. Positrons were counted by a Geiger counter placed about 10 centimeters directly in front of the target. The thickness of the absorbing material and its nearness to the target made it difficult to get an accurate estimate of the number of positrons transmitted. However, relative yields are correct in figure (3) and so the cross section at any deuteron energy may be found using \( 0.26 \times 10^{-24} \text{ cm}^2 \) as the cross section at 1.14 kev., or \( 0.40 \times 10^{-24} \text{ cm}^2 \) as the cross section at the peak of the resonance at 1300 kev.

The defining cross section measurements were made with a ceresin target of 43.1 micrograms/cm\(^2\).

In addition to the points indicated on the \( N^{15} \) curve of figure (3), nine additional positron yields were measured with the apparatus shown in figure (4) over the deuteron energy interval between 1140 kev. and 1320 kev. The relative yields were the same as those of figure (3).

**YIELD OF GAMMA-RAYS**

In order to study the gamma-rays which accompany the short range proton group from the reaction
\[ ^{12}\text{C} + ^{2}\text{D} \rightarrow ^{13}\text{C}^* + ^{1}\text{H} , \ \ ^{13}\text{C}^* \rightarrow ^{13}\text{C} + \text{hv} \] an Argon

filled Geiger counter was used. This was an Eck and Krebs

counter, identical to the neutron proportional counter

already described, but filled with Argon and 96% petroleum

ether to 10 cm. of Hg, and operated in the Geiger region

instead of the proportional region. (In the Geiger region

all voltage pulses are the same size whether caused by one

electron or a heavily ionizing recoil nucleus.) The

voltage required was 1340 volts. The counter was placed

about 6 cm. from the center of the target and at about 90°

to the direction of the deuteron beam. Large lead blocks

were used to shield the counter from stray gamma-rays

coming from carbon contamination along the beam path, (see

Figure 3). About an inch of lead was placed around the

counter to absorb scattered X-rays coming from the high

voltage electrode of the Van de Graaff generator.

The counting rate of the Geiger counter became too

great as the high yield gamma resonance at 1700 kev. was

approached. The simple expedient of moving the counter

farther from the target was avoided because it was

desirable to keep the proportion of gamma counts from the

target high with respect to scattered background radiation.

Thus at 1500 kev. deuteron energies a small Herbach and

Rademan Geiger counter with only 15% of the sensitive

volume of the original counter was substituted. This

counter was also an Argon plus quenching gas counter. It
was operated at 978 volts well within the Geiger plateau of about 75 volts. Tested for counting loss, the new counter showed less than 1/4 loss for 500 counts per second. It was found possible to move the small counter to a distance of 4.5 cm. from the target center to the counter center. The counter was enclosed in a lead jacket 1.5 cm. thick. All the remainder of the gamma-ray yield curve from 1500 kev. to 1900 kev. was obtained with this counter arrangement. A careful "tie in" with the previous yield measurements was made by repeating several old yield measurements with the new counter.

All of the gamma-ray yield measurements were taken using an Instrument Development Laboratories scale of 64 unit.

Background determinations were made by allowing the entire beam to fall on the low energy side of the slit, thus blocking the beam from the target, but giving essentially the same amount of radiation from carbon contamination elsewhere along the beam path.

THE NARROW GAMMA-RAY RESONANCE AT 1417 KEV

Resolution of the very narrow gamma-ray resonance at 1417 kev. was accomplished by changing bombarding energies in 1 kev. steps. Two days before the observations shown in figure (1) were taken, an energy calibration of the magnetic analyser was made. This was done by
plotting the known energy at which a standard group of narrow Fluorine resonances occur for proton bombardment, against the magnet current necessary to focus the proton beam on the target. The narrow resonances used for atomic hydrogen bombardment were at 927, 1325, 1363 kev. and for molecular hydrogen bombardment the resonances at 479, 660, 862, and 927 kev. were observed. These observations gave the magnet currents necessary to analyze deuterons of 462, 667, 891, 988, 1326, 1724, and 1934 kev. respectively. Thus the energy at which the resonance appears (1417 kev.) is given with good precision, and the energy may be used as a convenient value for future calibrations. The curve of figure (1) was obtained using a target approximately 6 kev. thick. Since the resonance width appeared almost this small it was necessary to prepare an even thinner target of 1 kev. thickness. The thickness of this very thin target was checked by comparing its positron yield with the positron yield of a 30 kev. target, which could be weighed more accurately. The check was made with the apparatus illustrated in figure (4). However, the width of 6300 ev. obtained was not very much different from the 6800 ev. found with the thicker target. (See figures (1) and (5).) The 6 kev. target must have been somewhat thinner than had been estimated. (See formula (5).)
COMPUTATION OF CROSS SECTIONS FOR GAMMA RAYS

A cross section calculation may be made at a given energy for the reaction \( ^{12}C + d \rightarrow ^{13}N + p \), if the efficiency of the Geiger counter for gamma-rays is known. A comprehensive survey of counter efficiencies has been made by Folke Norling, who gives an efficiency of about 1.85 per unit solid angle for a counter surrounded by brass and about 3° for a counter surrounded by lead.

Then if \( \sigma \) is the cross section, \( N \) the number of carbon atoms per \( cm^2 \) in the target, and \( n \) is the chance for a deuteron to produce a gamma-ray (or short range proton) we have,

\[
N = \sigma \cdot n
\]

where \( n \) may be written,

\[
n = \frac{\text{no. of gamma-counts per integrator count}}{\text{no. of integrator counts per deuteron}} \cdot \frac{4\pi}{\text{solid angle subtended by the counter}} \cdot \frac{1}{\text{transmission of gamma-rays}}
\]

An exact computation of the cross section of a resonance as narrow as 0.5 kev. is made difficult because a target sufficiently thin to resolve the resonance cannot be weighed accurately. Three independent methods have been used to get an estimate of the cross section of the narrow resonance at 1417 kev.

A direct calculation, assuming that \( N \) (see formula (8)) was accurately determined by weighing, gave a cross
section at resonance peak of $0.73 \times 10^{-34} \text{ cm}^2$. For this
calculation the yield at peak of the resonance (see figure
(5).) was converted into the number of gamma-rays per
deuterom by using an efficiency of 1.0% and a value of 49% for
the transmission of the 3 kev. gamma-rays through the
1.4 cm. lead shield which enclosed the counter.

The value for the transmission of gamma rays through
the lead shielding was obtained experimentally by using
the 3.6 kev. gamma-rays from a source containing ThC$^-$ and
observing the decrease of counting rate when the counter
was shielded. A calculation of the percentage transmission
using 0.46 per cm. as the absorption coefficient for 3 kev.
gamma-rays in lead gave a value of 49% transmission. (26)

A comparison of the efficiency of the small Herbach and
Kademan counter used in the above computation to the
efficiency of the larger Zok and Breake counter previously
described gave a ratio of 0.93. For the sake of internal
consistency, the efficiency of the small counter was taken
as 1.0% since the efficiency of the large counter has been
chosen as 2%. (See ref. (3).)

Another value for the cross section at 1417 kev.
was obtained by comparing the yield of an 8 kev. target
to the thin target curve of figure (5). The thickness
of the 8 kev. target was determined by comparing the
width of 0.9 kev. observed using this target with the true
width 0.3 kev. (See formula (5).) A yield of $4.3 \times 10^{-7}$
gamma-ray/deuteron was observed for the 9 kev. target.
This yield was taken as the integrated yield over an
interval of 4 kev. on either side of the peak of the thin
target curve of figure (5). A graphical integration
resulted in the value $0.63 \times 10^{-24}$ cm$^2$ for the cross section
at resonance maximum. This sort of computation is based
on the assumption that the curve of figure (5) is a very
good approximation to the true thin target curve. (A true
thin target cross section is the cross section which would
be obtained for a target that introduces no energy loss
to the deuteron beam; i.e., a target so thin that only
one carbon nucleus per cm$^2$ is presented to the neutrons.)

A third method has also been used to compute the
cross section. The gamma ray yield at the 1300 kev.
resonance was obtained using the thin 1 kev. target. The
ratio of the yield at 1417 kev. to the yield at 1300 kev.
was observed to be 1.86. As will be explained in the
following paragraphs, the cross section at 1300 kev. was
estimated as $0.42 \times 10^{-24}$ cm$^2$. Thus this third calculation
of the cross section at 1417 kev. gives the result
$0.50 \times 10^{-24}$ cm$^2$.

None of the above calculations may be expected to
be more accurate than the 10% or 20% error likely in the
estimation of the Geiger counter efficiency.
A rough check on the ratio of the number of gamma-rays to the number of neutrons may be made at the 1300 kev. resonance. A gamma-ray yield using a 56.3 microgram/cm² target was taken during the 600 second bombarding period preceding each positron yield determination pictured in the N¹³ curve of figure (2). The cross section at the maximum of the 1300 resonance has been calculated as $0.42 \times 10^{-24}$ cm² for the gamma-ray reaction, using 0.44 per cm. as the absorption coefficient of the inch of lead which was placed between the counter and the target to stop annihilation radiation and positrons. The cross section for neutrons at this point obtained from the positron yields was found to be $0.4 \times 10^{-24}$ cm². Thus the two reactions seem equally probable at 1300 kev. This result is consistent with the result of Bennett and Bonner, who found the number of long range protons from reaction (1) essentially the same at 0.92 kev. and 1.6 kev. They also found that the number of gammas was equal to the number of long range protons at 1.6 kev., and that the number of long range protons was 1.9 times as great as the number of N¹³ formed deuterons of 0.92 kev. A glance at figure (2) shows that the number of gamma-rays at 1.6 kev. is also about twice the number of gammas at 0.92 kev. Thus the gamma-ray reaction and the neutron reaction should be about equally probable at 0.92 kev.
Figure (2) then serves to indicate that if the two reactions are equally probable at 0.32 kev, they are also equally probable at 1.3 kev., as has also been shown in this experiment.

Another check on the order of magnitude of the cross section for gamma-rays at 1300 kev. was made by assuming that the gamma-ray curve, shown in figure (2), is an approximation to the shape of the true thin target excitation curve. Bennett and Donner (9) have reported that the gamma-ray yield from a thick graphite target (a target thick enough to bring to rest all the bombarding deuterons) is $17 \times 10^6$ quanta per micro-coulomb of deuterons for a deuteron energy of 1.0 kev. A graphical integration of the yield curve of figure (2) has been made according to the relation,

$$\int_{1.0 \text{ kev}}^{1.0 \text{ kev}} \frac{e^{-\gamma(E)}}{\delta(E)} \, dE = \frac{17 \times 10^6}{0.25 \times 10^3} = \text{number of quanta per deuteron}$$

$$\delta(E) = \frac{\text{energy loss per cm. of path in graphite}}{\text{no. of disintegrating atoms per cm}^2}$$

The quantity $\delta(E)$ changes with the energy and so must be calculated for each small energy interval used in the graphical integration. The integration determined the ordinate in terms of cm$^2$ for a thin target. Assuming that relative yields are correct for the gamma-ray yields of figure (2), the calculated cross section at the 1300 kev. resonance maximum is $0.43 \times 10^{-24}$ cm$^2$. 
ANGULAR DISTRIBUTION OF NEUTRONS

One of the most remarkable phenomena observed in the investigation of the deuteron-carbon reaction has unfortunately been discovered too recently for complete presentation in this thesis of an exhaustive experimental survey. A very marked asymmetry has been observed, at three resonance energies, in the yield of neutrons at various angles to the deuteron beam. (See figures (6a) (6b).) The majority of the neutrons seem to be emitted in the backward direction at the resonance energies 1140 kev. and 1360 kev. at the 900 kev. resonance energy; however, the neutron yield exhibits a slight predominance of forward direction neutrons but is almost symmetric about a plane perpendicular to the direction of the deuteron beam.

In order to observe the angular distribution of neutrons it was necessary to construct a neutron counter of slightly greater efficiency than the one previously described. Otherwise the neutron counting rate above background would have been too small at the greater counter distances from the target necessary to define a fairly small solid angle. The counter constructed operated on the same principle as the proportional counter previously described. However, it had five times the sensitive volume and was filled with one atmosphere of hydrogen plus
25 methane instead of ethane. To achieve the larger volume and still keep the operating voltage low, a one mil wire 4.5 cm. long was used in a metal counter of 4 cm. diameter.

The discovery of large backward direction cross sections may explain a discrepancy which seems to exist between the cross sections observed in this experiment for H13 and the cross sections obtained by Williams (17) for neutrons at 0°. Williams has obtained cross sections of \(0.03 \times 10^{-24} \text{ cm}^2\) per unit laboratory solid angle at the 13.5 kev. resonance. The results of the present experiment for the neutron cross section over all angles, if converted to cross section per unit solid angle, give a cross section at 13.5 kev. of \(0.03 \times 10^{-24} \text{ cm}^2\).

An entire excitation curve for neutron emission in the backward direction would be of interest as the resonance levels would likely appear more definite. Also there is a possibility that the neutrons in the neighborhood of the 1417 kev. resonance might indicate a resonance yield. As yet no explanation can be given for the lack of neutron resonance yield at 1417 kev. The yield in the neighborhood of 1140 kev. would undoubtedly show a more positive resonance for backward direction neutrons than the yield which has been observed for forward direction neutrons at this energy, since the total neutron yield over all angles does indicate a resonance. (See figure (2).)
The experiments of Williams gave no indication of resonance yield at 1140 kev. for either 0° neutrons or 90°
neutrons. This result seems consistent with the present
data as may be seen from figure (6A). In the figure the
neutron yield is minimum at these angles.

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Mr. J. P. Van der Neust and Mr. P. CoVries, we owe the
successful operation of our equipment.
NARROW RESONANCE AS OBSERVED WITH A 6 KEV TARGET
Neutron and gamma yields observed with 200 micro gram per cm$^2$ target
Positrons from $^13$N observed from 56 micro gram per cm$^2$ target
Yields are expressed in different arbitrary units
NOTE TO USERS

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Fig 3

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UMI
EXPERIMENTAL SETUP USED WITH 200 MICRO GRAM PER CM$^2$ CERESIN TARGET
TARGET ASSEMBLY USED TO DETERMINE YIELD OF $^{13}_N$

$$^{12}_C + ^2D \rightarrow ^{14}_N \rightarrow ^{13}_N + ^1n$$

$$^{13}_N \rightarrow ^{13}_C + e^+$$

(FULL SCALE)
GAMMA RAY YIELD

VS

ANALYSER CURRENT

\[ ^{12}C + p \rightarrow ^{13}N + H^1 \]

\[ ^{13}N \rightarrow ^{13}C + \text{hv} \]

PEAK 1417 kev.

WIDTH 6.3 kev.

TARGET 1 kev.

(1 milliamperes = 575 ev)
\( ^{12}\text{C} + ^{1}\text{H}^2 \)

NEUTRON ANGULAR DISTRIBUTION
AT DEUTERON ENERGY 1.14 M.E.V.

DEFINITION ± 8°
<table>
<thead>
<tr>
<th>Energy of Resonance Mev.</th>
<th>Present Data</th>
<th>Ref (9)</th>
<th>Ref (17)</th>
<th>Reactions Showing Resonance</th>
<th>Cross Sections in Units of $10^{-24}$ cm$^2$</th>
<th>Neutrons over all Angles</th>
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</thead>
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<td>0.90</td>
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<td>.92</td>
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</table>

C$^{13}$ + H$^2$ → C$^{15}$ + H$^1$  
C$^{13}$ + H$^1$  
$^n$ + 4 n

*Resonance observed only for neutron yields over all angles.

#Present Data and Ref (9) only.
REFERENCES

(1) Bowler, Lauritsen, and Lauritsen, Rev. Mod. Phys. 20, 236 (1948)

(2) Breit and Wigner, Phys. Rev. 49, 519 (1936)

(3) Bethe and Placzek, Phys. Rev. 51, 450 (1937)

(4) Kalckar, Oppenheimer, and Gerber, Phys. Rev. 52, 273 (1937)

(5) Breit, Phys. Rev. 68, 308 (1940)

(6) Bennett and Bonner, Phys. Rev. 50, 103 (1940)

(7) Bonner, Hudspeth, and Bennett, Phys. Rev. 50, 185 (1940)

(8) Rogers, Bennett, Bonner, and Hudspeth, Phys. Rev. 50, 186 (1940)

(9) Bennett, Bonner, Hudspeth, Richards, and Watt, Phys. Rev. 59, 731 (1941)


(11) Bennett and Richards, Phys. Rev. 71, 565 (1947)

(12) Bonner, Becker, Rubin, and Streib, Phys. Rev. 59, 215 (1941)


(14) Bethe, Rev. Mod. Phys. 9, 89 (1937) page 190

(15) Watanouch, Nuclear Physics Tables, Interscience Publishers Inc., 1941

(16) Bailey, Hillips, and Williams, Phys. Rev. 62, 80 (1942)

(17) Bailey, Freier, and Williams, Phys. Rev. 75, 274 (1949)

(18) Bennett, Bonner, Sandeville, and Watt, Phys. Rev. 70, 832 (1946)

(20) Herb, Parkinson, and Kerst, Phys. Rev. 51, 75 (1937)
(21) Livingston, and Bethe, Rev. Mod. Phys. 9, 245 (1937)
   page 274
   (1944)
(23) Tatel, Phys. Rev. 61, 450 (1942)
(24) Barschall, and Bethe, Rev. Sci. Instr. 18, 147 (1947)
(26) The Science and Engineering of Nuclear Power, Addison- 
    Wesley Press Inc., 1947
    No. 9 (1945)
(28) Bernet, Herb, and Parkinson, Phys. Rev. 54, 398 (1938)
(29) Townsend, Proc. Roy. Soc. 177, 357 (1941)
(30) Norling, Arkive for Matematik, Astronomi och Fysik,
    B and 27 Hafte 4
(31) Bohr, Nature, 137, 344 (1936)
(32) Roald Tangen, Experimental Investigations of Proton 
    Videnskabers Selskabs Skrifter, 1946 Nr1
(33) Bernet, Herb, and Parkinson, Phys. Rev. 54, 398 (1938)