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CROSS SECTIONS FOR PRODUCTS OF 90 MEV NEUTRONS ON CARBON

D. A. Kellogg

(thesis)

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CROSS SECTIONS FOR PRODUCTS OF 90 MEV NEUTRONS ON CARBON

D. A. Kellogg

ABSTRACT

Determinations have been made of the cross sections for the products of 90 Mev neutrons on carbon in the case of practically all reactions that occur. Beta counting of the activities generated in a rotating polyethylene disc yielded cross sections for the production of some heavy fragments, identified as to isotope and atomic number. Cloud chamber study yielded cross sections for almost all reactions, but resulted in the identification of most of the heavy fragments only by atomic number. The rotating disc method cross sections were normalized to the $C^{12}(n,2n)C^{11}$ cross section, and the cloud chamber method cross sections were normalized to the n-p cross section.

The relative and absolute yields of protons, deuterons, and tritons of high energies were determined by the cloud chamber method and compared with the results of Hadley and York⁽⁶⁾; the agreement was excellent.

CROSS SECTIONS FOR PRODUCTS OF 90 MEV NEUTRONS ON CARBON

D. A. Kellogg

I. INTRODUCTION

Study of the nuclear reactions of carbon is necessary for the analysis of events occurring during irradiation of organic tissues. Furthermore, the symmetric nuclear constitution and possible α -particle substructure of carbon 12 make its nuclear reactions hold special interest. In particular, reactions of carbon with neutrons of 90 Mev are studied because the theory of the compound nucleus is not valid at this energy, and information may be gained concerning knock-on interactions and spallations.

In recent years Cook et al.⁽¹⁾ and DeJuren and Knable⁽²⁾ have determined the total and inelastic cross sections for 90 Mev neutrons on carbon, but there has been little data made available on specific neutron reactions with carbon at this energy. Two notable exceptions are (1) the reaction $C^{12}(n;2n)C^{11}$ which has been studied theoretically by Heckrotte and Wolff⁽⁴⁾, and experimentally by McMillan and York⁽⁵⁾ and (2) the ejection of protons, deuterons and tritons studied by Hadley and York⁽⁶⁾. It is to be noted that the work of Hadley and York cannot designate the specific nuclear reactions involved without ambiguity, since singly charged particles may be ejected from carbon leaving a variety of residual nuclei. Furthermore, their experimental method placed limitations on the lowest energy that a detectable ejected particle may have.

The object of the present work is to determine relative and absolute cross sections, as far as possible, for all reactions that occur in carbon bombarded by 90 Mev neutrons. The general plan is to accept the present values of the cross sections for the two following processes:

- (1) $C^{12} (n;2n) C^{11}$ cross section 22 ± 4 millibarns
(McMillan and York⁽⁵⁾)
- (2) n-p scattering cross section 77 ± 1.5 millibarns
(Composite value from work of Hadley et al.⁽⁷⁾,
DeJuren and Knable⁽²⁾ and Cook et al.⁽¹⁷⁾)

These values are used as monitors to put all cross sections that are measured upon an absolute scale. For further comparison and checks, the present best values for the elastic, inelastic and total carbon cross sections are also used.

At the outset it is to be noted that the "90 Mev" neutrons used in bombarding carbon are produced by 190 Mev deuteron bombardment of a half-inch beryllium target (Serber stripping⁽⁸⁾) in the 184-inch cyclotron. The resulting neutrons have an energy spectrum measured experimentally by Hadley et al.⁽⁷⁾ and Brueckner et al.⁽⁹⁾ as having a peak with a maximum at about 90 Mev, and a half-width of 25 to 30 Mev. However, all cross sections used for comparison and normalization or measured in this work were determined with this same neutron beam. In a few cases, differing average detection energies (83 to 95 Mev) have made extrapolation or interpolation to 90 Mev necessary. Henceforth in this work it is to be assumed that all reactions and cross sections mentioned are for the typical 90 Mev spectrum just described, unless specifically indicated otherwise.

It is also necessary to define the word "reaction" as it will be used here, with regard to time and mechanism. In this work, the time after collision at which an event is described and classified is arbitrarily set at 10^{-3} to 10^{-2} second because of the experimental limitations of the methods used. This means that the ejection of a Be^8 nucleus from carbon with its subsequent breakup into two alpha particles in 10^{-14} or less of a second⁽¹⁰⁾ is described as the ejection of two alpha particles directly from the nucleus, even though there is evidence that the actual mechanism is probably through Be^8 in most cases⁽¹¹⁾. Likewise, ejection of particles from the nucleus after a very short delay rather than as immediate knockouts is not detected.

Lastly, an arbitrary but ill-defined boundary between heavy and light fragments produced from carbon nuclei is set at the element Helium as a matter of terminology.

Some of the specific points of interest to be investigated are as follows:

1. Measurement of the $\text{C}^{12}(\text{n;p})\text{B}^{12}$ cross section, which is of interest because it tells the probability of a proton knockout with the neutron remaining trapped in the nucleus long enough for a subsequent beta decay ($T_{1/2} = 0.025$ seconds).

2. The mechanisms by which high and low energy protons, deuterons and tritons are produced - i.e., knock-on or pick-up versus spallation.

3. The presence of Li^8 as a residual nucleus. This has been confirmed by two experimenters, but doubt has been cast indirectly by a third.

4. The splitting of carbon into three alpha particles at this neutron energy.

5. The reaction $C^{12}(n;3n)C^{10}$

6. The reaction $C^{12}(n;?)He^6$

7. The reaction $C^{12}(n;?)Be^7$

8. The possibility of splitting of the carbon nucleus into two roughly equal fragments by neutrons.

9. Remeasuring the relative and absolute yields of protons, deuterons and tritons as reported by Hadley and York⁽⁶⁾, and Brueckner and Powell⁽¹²⁾ for possible improvement in the accuracy thereof and extension of the data to lower energies.

10. Determination of the inelastic neutron cross section for carbon.

11. Summarizing all known reaction cross sections of 90 Mev neutrons on carbon and comparing the sum to the total carbon cross section.

A basic difficulty is that of attempting simultaneous identification of the light fragments and of the heavy residual nucleus resulting from any given interaction. It is hard to think of any plausible method of doing so in any but isolated special cases. However, as will be seen, positive statements can be made concerning the identity of all products of a given reaction in some cases.

II. PRINCIPLES OF EXPERIMENTAL METHODS

The two methods employed to identify reaction products and measure cross sections are:

1. Identification and counting of the beta-particle activities of the heavy residual nuclei produced from carbon.
2. Identification and counting of the prongs of carbon stars photographed in a cloud chamber.

The beta activity method identifies and counts specific isotopes of heavy residual nuclei, but gives no direct information about light fragments. The cloud chamber method identifies and counts light fragments by isotope, but identifies heavy residual nuclei only by atomic number in most cases. The two methods are therefore complementary. There are some cross checks possible, and between the two experiments much can be learned about carbon reactions.

Both methods are time consuming - the beta activity method, because of the computations involved in unscrambling six activities, and the cloud chamber method because it requires identification of fragments one at a time for every single collision investigated.

A. The Beta Activity (Rotating Disc) Method

Following the design principle used by Becker and Gaerttner⁽¹³⁾ for the determination of the half-life of Boron 12, a rotating disc of polyethylene was bombarded at one circular area near the rim by a well collimated neutron beam of 90 Mev neutrons. This process quickly built up equilibrium concentrations of each of the short-lived beta activities that are generated from carbon. These concentrations have

a steady value (assuming constant rotation speed, uniform disc thickness and a neutron beam of uniform time and position intensity) at each point of the disc as that point reaches a given angular position in rotation. This means that manually-timed counts of minutes' duration may be taken at given angular positions on activities whose half-lives are quite short (0.025 to 0.88 second), provided that the equilibrium is maintained. A plot of activity against angular position is then equivalent to the usual plot of activity against time made for artificially radioactive samples counted after bombardment instead of during bombardment. A complicating factor is the gradual build-up of any activity whose half-life is of the order of or longer than the time used for "warm-up" to equilibrium. In this case the $C^{12}(n;2n)C^{11}$ beta activity ($T_{1/2} = 20.5$ minutes) requires either a "warm-up" period of well over an hour for a reasonable approach to equilibrium, or else a determination of the build-up rate of this activity and correction of every counter reading by subtraction of the appropriate C^{11} activity. The first plan simplifies computation but wastes cyclotron time; the second saves running time but complicates computation.

The C^{11} activity furnishes the essential normalization needed to place measured cross sections on an absolute scale, since the C^{11} cross section is known. However, since the various beta activities produced in carbon have maximum beta energies ranging from 1 to 13 Mev, a determination of self-absorption factors is necessary to determine true relative production ratio. This can be done by using discs of varying thicknesses.

The separation of the beta activities present is facilitated by using several rotation speeds; as will be shown later, a given activity can be brought into relative predominance over others at certain angular positions by making the rotation speed roughly equal to the mean life of the activity in question. The longer lived activities can also be counted conventionally; i.e., with the neutron beam turned off. Selective beta-absorption can be used to separate activities whose half-lives are nearly identical - provided the beta-energy end-points differ sufficiently.

B. The Cloud Chamber Method

This method of study consists of passing a pulsed, collimated 90 Mev neutron beam of about half maximum intensity through a large cloud chamber placed in a high magnetic field and filled with a mixture of methane and hydrogen gasses. The cloud chamber is expanded shortly before each pulse, and a stereoscopic pair of photographs is taken shortly after the pulse. The photographs can be examined through a stereoscopic viewer and can also be reprojected onto a glass plate as life-size, three-dimensional images. The inelastic interactions of neutrons with carbon are seen as stars of two or more prongs. The individual prongs, or fragment tracks, may be identified by using radius of curvature, specific ionization, and range. Normalization of yields for various reactions with carbon to absolute cross sections can be accomplished by counting the number of proton recoils (generated by neutrons) corresponding to a given number of carbon events. Corrections must be made for the short proton recoils that are lost because they

are indistinguishable from background and from elastic neutron scatters from carbon. Also, correction is necessary for the small amount of oxygen that is present in the water vapor required for cloud chamber operation.

III. DETAILS OF APPARATUS AND METHOD - ROTATING

DISC BETA ACTIVITY METHOD

A. Details of Apparatus

The rotating disc apparatus (Fig. 1) consists basically of interchangeable polyethylene discs of 21-inch diameter, stiffened at the center by exterior discs of bakelite of 15-inch diameter, mounted on a half-inch diameter shaft. Either of two motors may be used to supply power to this shaft; a fan-cooled variable speed one-half horse power motor used for speeds of 600 rpm to 2,400 rpm, and a constant speed one-half horsepower motor operating through a gear-box and pulley drive used for a speed of 60 rpm. (Fig. 2). The shaft has a coupling joint to permit interchange of discs and uncoupling of the 60 rpm motor; the high speed motor is always coupled to the shaft and furnishes a fixed reference point for positioning the discs accurately with respect to the fixed planes of the apparatus.

The discs are made of circles cut from flat sheets of one-sixteenth inch thick polyethylene; some are single thickness, and others are double. The double thickness wheels proved to be more practical to fabricate than wheels cut from one-eighth inch stock. After cutting by hand, the disc edges were machined at high speed to insure true circles for dynamic balance.

In Fig. 1, the neutron beam passes parallel to the horizontal white masking tape fastened to the axle of the apparatus, and approximately one foot above the tape. The small circle near the upper edge of the disc marks the center of the beam, which passes perpendicularly through the disc. The diameter of the beam at this point is about

3.3 inches; the circle is about 2 inches in diameter. The circle has cross lines on it not visible in the picture, and is used primarily in positioning the apparatus accurately in the beam by sighting with a telescope previously oriented with respect to the beam.

The cross arm pivoted on the trunnions of the apparatus supports four heavy lead shields (of which two, marked "7" and "3" in chalk, can be seen in Fig. 1) each of which contains a Tracerlab TCG-1 end-window Geiger-Muller counter. The shields provide two inches of lead on all sides of the counters except over the windows, which are set back one-half inch from the faces of the shields which are adjacent to the polyethylene disc. The face-plate of each shield has a hole the size of the counter window, with a 45 degree outward flare the outermost quarter of an inch (See Fig. 3). This construction provides a partial telescope for the beta particles that can enter each counter, and was chosen by trial and error for the purpose of equalizing counting geometry as much as possible for betas of varying maximum energies. The circle marked on the polyethylene disc in Fig. 1 and mentioned above is a rough indication of the effective area that can be "seen" by a counter at any given time.

The counters are mounted in two pairs 180 degrees apart and facing one another, with the pairs of lead face plates one-half inch apart. The disc rotates midway between each pair of face plates. Rotation at certain speeds causes flutter of the disc, but due to the set-back of the counters from the face plates, the error caused in counting rates by flutter or even non-central position of the disc between

face plates is small. This was tested by counting with the disc held flat against one face plate; the counts of the opposing tubes differed less than seven percent.

Each end-window Geiger tube feeds pulses to its own counter and register, as shown. The cross arm may be rotated to any position through 360 degrees. However, only 10 positions 22.5 degrees apart are used for each counter, since the counters cannot be brought any closer to the neutron beam, without inducing enough activity in the counters and shields to make measurements inaccurate, than counter 7 stands in Fig. 1. Since the counter pairs are 180 degrees apart, this prevents the use of a quadrant at the top and at the bottom when the beam is on.

Speed of disc rotation is controlled by the rheostat shown, and is monitored by a stroboscope (not shown) used to view the rotating disc during operation.

B. Collimation of Neutron Beam

High counter background during beam-on operation required good collimation of the neutron beam. Various combinations of collimators were tried both at 30 feet from the beam origin and at 50 feet (disc is 53 feet from beryllium target). The final choice was a two-inch diameter collimator six feet long, surrounded by lead and concrete of a minimum thickness of six feet, placed 30 feet from the beryllium target, with no further collimation along the beam except the 15 feet of wall and the bricks shown in Fig. 1, which were placed to shield the counters from stray scatters (See Fig. 4). Attempts to improve col-

limation by placing liners the size of the beam in the neutron port actually increased counter background by 50 percent in counter positions nearest the beam.

A telescope sighted on the beryllium target (80-inch radius) was used to position the collimator, and subsequently, the disc apparatus.

C. Theory of Rotating Disc Method

Detailed theoretical consideration of the beta activity counting rates to be expected was required to test the feasibility of using the rotating disc method to separate and measure the activities whose presence was known or suspected.

It is, therefore, necessary to derive the expression for expected counting rate of an activity of sufficiently short half-life to reach equilibrium in a minute or less, and to modify this expression to encompass longer-lived activities not expected to reach equilibrium.

At the risk of oversimplification, the operation of the rotating disc may be described as follows: as the circle shown near the rim of the disc (Fig. 1) rotates through the beam, it receives a burst of neutrons creating a given beta activity. As the disc moves on around, this beta activity decays exponentially with its proper half-life. A counter stationed at a fixed angular position could measure this activity. Since the disc rim is continuous, new areas are continuously bombarded to create beta activity which the counter measures at a steady count rate at a given angular position. This situation persists until the disc has made one revolution. If the speed of revolution is

sufficiently great with respect to the half-life in question, there remains an appreciable activity when the same areas of disc are bombarded again. Therefore, the counter indicates a greater count rate during the second revolution than during the first. This process continues until the number of active nuclei made at each passage through the beam is just balanced by the number decaying during the remainder of a revolution of the disc. When this equilibrium is reached, the counter measures the same count rate from that time onward for this particular beta activity at any given angular position.

The derivation of a useful but not too cumbersome expression for the counting rate at a given angular position requires some simplifying approximations. Fig. 5 shows the area (shaded) of the disc instantaneously "visible" to the beam, and the portion of this area that can be later scanned by one of the end-window counters.

The approximate version of this latter portion is shown in Fig. 5 as the cross-hatched area A subtending the angle α . Likewise, the shaded region B subtending the angle β (Fig. 6) is the approximate version of the area that can be instantaneously scanned by one of the counters.

The angle θ represents the angular position of a given point of the disc with respect to the beam position, (which is designated as $\theta = 0$) and the angle θ_0 represents the angular position of the counter with respect to the beam position. The finite sizes of the beam and counter windows introduce approximations into the use of these angles,

but the error involved is small for a disc radius large relative to "a" (the radial extent of the scanned area) except at values of θ_0 near the beam position.

Proceeding to the derivation: the number of active nuclei built up in an area subtending angle $\Delta\theta$ during passage through the bombarded zone subtending angle α is obtained from the following differential equation

$$\frac{d}{dt} (\Delta n) = JN\sigma haR (\Delta\theta) - \lambda \Delta n \quad (1)$$

where Δn represents the number of radioactive nuclei present

J represents the beam flux

N represents the target carbon atoms per cubic centimeter of disc

σ represents the cross section for formation of the active nuclei considered

λ represents the disintegration constant of the active nuclei considered

h and a are identified in Fig. 6.

Then the increment of radioactive nuclei, expressed as a function of time, is found by integration of Equation (1) to be

$$\Delta n(t) = \frac{haR (\Delta\theta) JN\sigma}{\lambda} (1 - e^{-\lambda t}) \quad (2)$$

and for passage of $\Delta\theta$ through the region of bombardment, $t = \frac{\alpha}{\omega}$.

When the area subtending $\Delta\theta$ leaves the bombarded zone, it is logical to express further decay in terms of θ .

$$\Delta n(\theta) = \frac{haR (\Delta\theta) JN\sigma}{\lambda} (1 - e^{-\frac{\lambda\alpha}{\omega}}) e^{-\frac{\lambda\theta}{\omega}}$$

or, for simplicity

$$\Delta n(\theta) = K (1 - e^{-\frac{\lambda\alpha}{\omega}}) e^{-\frac{\lambda\theta}{\omega}}, \quad (3)$$

$$\text{where } K = \frac{haR (\Delta\theta) JN\sigma}{\lambda}$$

This expression is valid only during the first revolution of the disc. When the area subtending $\Delta\theta$ has again passed through the bombarded zone, the expression becomes

$$\Delta n_2(\theta) = Ke^{-\frac{\lambda\theta}{\omega}} \left[(1 - e^{-\frac{\lambda\alpha}{\omega}}) + (1 - e^{-\frac{\lambda\alpha}{\omega}}) (e^{-\frac{2\pi\lambda}{\omega}}) \right]$$

which simplifies to

$$\Delta n_2(\theta) = Ke^{-\frac{\lambda\theta}{\omega}} \left[(1 - e^{-\frac{\lambda\alpha}{\omega}}) (1 + e^{-\frac{2\pi\lambda}{\omega}}) \right]$$

Likewise, during the third revolution,

$$\Delta n_3(\theta) = Ke^{-\frac{\lambda\theta}{\omega}} \left[(1 - e^{-\frac{\lambda\alpha}{\omega}}) (1 + e^{-\frac{2\pi\lambda}{\omega}} + e^{-\frac{4\pi\lambda}{\omega}}) \right]$$

Continuing this process, one finds that during the r^{th} revolution,

$$\Delta n_r(\theta) = Ke^{-\frac{\lambda\theta}{\omega}} \left[(1 - e^{-\frac{\lambda\alpha}{\omega}}) \left(\sum_{r=0}^{\infty} e^{-\frac{2\pi r\lambda}{\omega}} \right) \right]$$

Now the series $\sum_{r=0}^{\infty} e^{rx}$ equals $\frac{1}{1 - e^x}$, where r is an integer, so after a great number of revolutions

$$\Delta n(\theta) \rightarrow Ke^{-\frac{\lambda\theta}{\omega}} (1 - e^{-\frac{\lambda\alpha}{\omega}}) \left(\frac{1}{1 - e^{-\frac{2\pi\lambda}{\omega}}} \right). \quad (4)$$

This expression may be used as an equality for activities whose value of λ is sufficiently large with respect to ω to make the expression $e^{-\frac{2\pi r\lambda}{\omega}}$ vanishingly small in a reasonably small number of revolutions: i.e., the expression holds for activities that reach equilibrium within the "warm-up" time before counting is started.

For an activity of longer half-life, (i.e., C^{11}), equation (4) must be modified as follows:

The series $\sum_{r=0}^{\infty} e^{-\frac{2\pi r\lambda}{\omega}}$ is replaced by the integral $\int_0^Q e^{-\frac{2\pi r\lambda}{\omega}} dr = \frac{\omega}{2\pi\lambda} (1 - e^{-\frac{2\pi Q\lambda}{\omega}})$, where Q is a large but finite number of revolutions.

Now $\frac{2\pi Q\lambda}{\omega} = t$, the elapsed time for revolving the disc in the beam, so one may write for a long-lived activity the expression

$$\Delta n(\theta) = Ke^{-\frac{\lambda\theta}{\omega}} (1 - e^{-\frac{\lambda\alpha}{\omega}}) \frac{\omega}{2\pi\lambda} (1 - e^{-\lambda t}). \quad (4a)$$

Continuing the derivation from Equation (4), (short-lived activity), the disintegration rate at angular position θ is:

$$\lambda \Delta n(\theta) = \lambda K e^{-\frac{\lambda \theta}{\omega}} (1 - e^{-\frac{\lambda \alpha}{\omega}}) \left(\frac{1}{1 - e^{-\frac{\lambda \beta}{\omega}}} \right)$$

The counting rate at position θ_0 of the counter is $C_{(\theta_0)} \approx \sum_{\theta_0}^{\theta_0+\beta} \epsilon_{(\theta)} \lambda \Delta n(\theta)$ where $\epsilon_{(\theta)}$ is the counting efficiency of the counter for the activity in question (including solid angle corrections).

This may be written in the limit after resubstituting the value of K , as

$$C_{(\theta_0)} = \frac{h a R J N \sigma}{(1 - e^{-\frac{\lambda \beta}{\omega}})} (1 - e^{-\frac{\lambda \alpha}{\omega}}) \int_{\theta_0}^{\theta_0+\beta} \epsilon(\theta) e^{-\frac{\lambda \theta}{\omega}} d\theta$$

Making the approximation that $\epsilon(\theta)$ is constant rather than a function of θ , one may integrate to obtain:

$$C_{(\theta_0)} \text{ short-lived} = \frac{h a R J N \sigma \epsilon}{(1 - e^{-\frac{\lambda \beta}{\omega}})} (1 - e^{-\frac{\lambda \alpha}{\omega}}) (1 - e^{-\frac{\lambda \beta}{\omega}}) \left(\frac{\omega}{\lambda} \right) e^{-\frac{\lambda \theta_0}{\omega}} \quad (5)$$

In the case of a long-lived activity, the analogous equation to (5) is

$$C_{(\theta_0)} \text{ long-lived} = h a R J N \sigma \epsilon (1 - e^{-\lambda t}) \left(\frac{\omega^2}{2 \pi \lambda^2} \right) (1 - e^{-\frac{\lambda \alpha}{\omega}}) (1 - e^{-\frac{\lambda \beta}{\omega}}) e^{-\frac{\lambda \theta_0}{\omega}} \quad (6)$$

In this case, however, the values of $\frac{\lambda \alpha}{\omega}$ and $\frac{\lambda \beta}{\omega}$ are so small for any disc speed of 60 revolutions per minute or more, that it is possible to simplify equation (6) by use of the approximation $1 - e^{-x} \approx x$ with no appreciable error; this yields

$$C_{(\theta_0)} \text{ long-lived} = \frac{h a R J N \sigma \epsilon}{2 \pi} (1 - e^{-\lambda t}) e^{-\frac{\lambda \theta_0}{\omega}} \quad (7)$$

Furthermore, the value of $e^{-\frac{\lambda \theta_0}{\omega}}$ was so close to unity for all angular positions when the disc rotated at 60 rpm or more, that it was

called unity, giving the final expression

$$C_{\text{long-lived}} = \frac{h a R J N \sigma \epsilon}{2 \pi} (1 - e^{-\lambda t}) \propto \beta. \quad (8)$$

Taking the specific cases of B¹² and C¹¹ as short and long-lived activities respectively, and taking the ratio of equations (5) and (8),

$$\frac{C(\theta_0) B^{12}}{C_{C11}} = \frac{\sigma B^{12} \epsilon B^{12}}{\sigma_{C^{11}} \epsilon_{C^{11}}} \left(\frac{\omega \alpha \beta}{2 \pi \lambda B^{12}} \right) \left(\frac{1 - e^{-\lambda_{C^{11}} t}}{1 - e^{-\frac{2 \pi \lambda B^{12}}{\omega}}} \right) \left(1 - e^{-\frac{\lambda B^{12}}{\omega}} \right) \quad (9)$$

$$\left(1 - e^{-\frac{\lambda B^{12} \beta}{\omega}} \right) e^{-\frac{\lambda B^{12} \theta_0}{\omega}}$$

It is to be noted that the beam flux, number of target atoms, and a group of geometrical quantities cancel out. The time "t" in Equation (9) means time elapsed from beginning of bombardment of the rotating disc until the (instantaneous) counting rate C_{C11} is measured.

The quantities α , β , $\epsilon_{B^{12}}$ and ϵ_{C11} appearing in Equation (9) merit discussion. The quantity α may be determined two ways. One method consists of computing directly from the known beam collimation the instantaneously bombarded area of the disc which is "seen" by the counter, and then comparing this area to the annular area it sweeps out during one revolution of the disc. This purely geometrical method yielded $\alpha = 1/18.2$ revolution. Another method consists of counting C¹¹ activity first with the disc rotating and then with the disc stationary (moving bombarded area to counter after turning beam off). The stationary count should be α times the rotating count. This method yielded $\alpha = 1/16.0$ revolution. The latter value was accepted. The difference between the two values, about 12 percent, represents a measure of the amount by which the true effective area "seen" by the counter exceeded the estimated effective area "seen" by the counter for C¹¹ activity.

An experimental determination of this ratio (using concentric rings of polyethylene irradiated simultaneously and counted one at a time) yielded a value of 1.07; i.e., seven percent difference. This would seem to indicate that the experimental determination of the value of α is correct to $\pm$ five percent. The value of β was also determined by the concentric ring counting experiment, and was found to be 1/38 revolution.

For short-lived activities, and disc rotation speeds of 600 rpm and over, the values of α and β are not at all critical; this may be seen as follows: under these conditions, Equation (5) may be simplified in the same manner that Equation (6) was simplified to give Equation (7); the result is:

$$\underset{\text{short-lived}}{C(\theta_0)} \approx \frac{h\alpha R J N \sigma \epsilon}{(1 - e^{-\frac{2\pi\lambda}{\omega}})} \frac{\lambda}{\omega} \alpha \beta e^{-\frac{\lambda \theta_0}{\omega}} \quad (10)$$

Then equation (9) becomes (writing $B^{12} \rightarrow B$, $C^{11} \rightarrow C$)

$$\frac{C(\theta_0)}{C} \approx \frac{\beta \epsilon_B}{\epsilon_C} \left(\frac{\lambda B}{2\pi\omega} \right) \left(\frac{1 - e^{-\lambda_c t}}{1 - e^{-\frac{2\pi\lambda B}{\omega}}} \right) e^{-\frac{\lambda B \theta_0}{\omega}} \quad (11)$$

which is independent of α and β .

This fact was further checked as follows: plots were made of Equation (5) (exact short-lived formula) for speeds from 6,000 rpm down to 60 rpm (see Figs. 7 and 8), to an arbitrary ordinate scale, for half-lives as long as 0.88 second. These plots were repeated to the same scale for Equation (10). The difference between the two sets of plots was undetectable above 500 rpm, and was at most five percent at 60 rpm for $T_{\frac{1}{2}} = 0.88$ second. The values of α and β mentioned ($\alpha = 1/16$, $\beta = 1/38$ revolution) were accepted without further ado.

The quantities $\epsilon_{B^{12}}$ and $\epsilon_{C^{11}}$ were never determined absolutely, but this was not considered necessary since only the ratio $\epsilon_{B^{12}}/\epsilon_{C^{11}}$ occurs in Equation (9). The only plausible difference between $\epsilon_{B^{12}}$ and $\epsilon_{C^{11}}$ occurs because of the difference in beta energies of the two activities; the Boron 12 beta spectrum has a maximum energy of 13.4 Mev, while the Carbon 11 beta spectrum has a maximum energy of 0.98 Mev. Aside from the differing self-absorption (in the polyethylene) factors involved, this presented the problem of making a counter geometry that would be not too dissimilar for high and low energy betas. Trial and error produced the design of Fig. 3. The object of this counter-and-shield design was to present either a clear air path to any incident betas, or else a path filled with enough lead to stop all betas up to 14 Mev, with a minimum transition between the two conditions. Experiments with the absorber insertion device pictured in Fig. 3 showed that 80 mils of lead was sufficient to stop all the betas. 250 mils of lead was used to form the channel through which betas had to come to enter the counter. Therefore, only self-absorption, air-path absorption, and counter-window absorption were taken into account for computing the ratio $\epsilon_{B^{12}}/\epsilon_{C^{11}}$ and other efficiency ratios, as $\epsilon_{L^{13}}/\epsilon_{C^{11}}$, etc. Determination of the self-absorption factors was the basis of several side-experiments to be described later; air and window absorption factors were computed from the literature.

Equation (11) now stood ready for use in determining the cross sections of short-lived beta activities generated in carbon by comparison with known cross section for formation of C^{11} except for one quantity -

the value of $C(\theta_0)$ (short-life). If only one short-lived activity had been present, there would have been no difficulty here, but possible production of six or more activities posed the problem of their separation.

Search of the literature produced a list of the possible activities that might be generated as given in Table I. These activities broke down roughly into half-life groups (as shown by horizontal double lines in the table).

The logical plan of attack was the physical separation of these groups by variation of disc speed and delayed counting. Figure 7 shows a plot to an arbitrary scale of B^{12} activity for various speeds, and Fig. 8 shows the same plot for Li^8 and/or He^6 activity.

At 60 rpm, B^{12} activity decreases vanishingly beyond angular counting position 45° , while the Li^8 and/or He^6 activities remain fairly high. Figure 9 shows what counting rate might be expected from a mixture of these activities (5 millibarns of B^{12} plus 3 millibarns of Li^8 and/or He^6) at various speeds. Changes in slope and height of the plotted counting rate curves (for equilibrium condition) with disc speed indicated a possible way to separate some of the activities present and give at least estimates of the amounts present of others.

D. Details of Operations and Measurements

Numerous runs were made with the disc rotating at various speeds, with single and double thickness discs, with stationary discs, with and without absorbers in front of the counters. The general procedure for each run was as follows:

1. Bring disc up to monitored operating speed.
2. Turn on neutron beam, time recorder, and neutron beam intensity monitor.
3. Wait one minute for equilibrium condition.
4. Take three-minute counts at each of ten angular positions with the four counters, using one-minute to re-position counters and scalers.
5. Repeat counts with absorbers when desired.
6. Switch one or more counters to Brush Recorder input, just as beam is turned off.
7. Wait one minute for short-lived activities to die out, then start remaining counters on a ten-minute C^{11} count.
8. Stop disc, turn on neutron beam for a fixed time (usually 20.5 minutes). Meanwhile, count beam-on background at various angular positions. This background includes much built-up C^{11} activity, so a special absorber must be used for compensation.
9. Turn beam off, move bombarded zone to a counting position, wait one minute, and then take a ten-minute C^{11} count with one pair of counters, while the other pair counts beam-off- C^{11} built up background.

The choice of counting intervals, waiting periods and order of operations was dictated by many factors, and usually involved compromises. For example, ten-minute or longer counts would apparently have been better than three-minute counts in step 4 of the procedure. But this would

have meant almost two hours for step 4, instead of about 30 minutes, and in particular, 30 minutes for the first three positions. Now the positions first counted are those nearest the end of a revolution (i.e., where short-lived activity is the lowest), in order to do so while the C^{11} activity built up is still at a low level. Using ten-minute counts would allow C^{11} activity to build up to the point where C^{11} counts would exceed short-lived activity counts and thus increase the error therein greatly. The counting intervals, and, in general, all operations, were run on a rigid time-schedule in order to make simpler computations possible in correcting for C^{11} activity build-up; if two runs were timed identically it was often possible to use the corrections computed for each counting interval of one run for the other run after a single ratio-adjustment of all the counts.

Beam intensity variation caused computation difficulties also. A Zeus monitor recorded the relative beam intensity on a moving plot, and showed that the intensity invariably started high and decreased about seven percent during the course of each disc run. This required normalization of counts taken at the start and end of a disc run to the mean beam intensity level, since the C^{11} activity was cumulative while short-lived activities were not.

The scheme of operation and computation required to produce values of cross sections for the various activities is shown as a flow chart in Figure 10. A typical illustration is found in the calculation of the B^{12} cross section. This calculation requires all the runs shown on the chart plus additional runs with discs of other thicknesses (to

determine the self-absorption factor of B^{12} betas). The scheme starts at the extreme right (longest half-lives) and progresses to the left and downward. Each activity counting rate is used to correct the counting rate to its left, in the same general manner that a plot of a mixture of activities is broken down into its component activities. In this case, however, the actual counting rate of a given short-lived activity determined in a run at one speed must be converted to the rate this activity would have had at a second speed before being used to correct a run made at the second speed. The curves of Fig. 8 illustrate this point.

In the case of the B^{12} cross section calculation, a short-cut was possible. Since it was found that the Be^7 and C^{10} activities were low, and that B^8 and Li^9 activities could not be detected, and since He^6 and Li^8 have practically identical half-lives, it was possible to take a 60 rpm run to stress Li^8 and He^6 activities, pretend that these two were one activity, correct for speed up to 600 rpm, and, presuming identical timing for the two runs under identical beam intensity conditions, simply subtract the speed-corrected 60 rpm run counts from the 600 rpm counts to get the B^{12} activity curve directly, with further correction necessary only for the seven percent slope in beam intensity with time. The cross section was then computed by use of Equation (9) and the Cl^{11} activity count.

Figure 11 shows a typical 600 rpm run, plotted on a semi-logarithmic scale. The top curve is the raw data, reduced to counts per minute, taken at each angular position. The second curve of Fig. 11

has been corrected by subtracting beam-on background and C^{11} build up, which are shown separately in Fig. 12. The C^{11} curve in Fig. 12 is broken because this particular set of data was taken with two counters that started the run in a position 135 degrees from the neutron beam, since the two other counters started at the 315 degree position. The third curve down has been corrected for $(Li^8 + He^6 + C^{10})$ activity as described above. This is the B^{12} beta-activity curve. Beam intensity corrections were made to all the data in advance in order to eliminate the beam-variation distortion from each of the curves shown.

Fig. 13 shows similar curves for a 60 rpm run.

The C^{11} activity count was relatively easy to obtain. One minute after the neutron beam was turned off, all the activities except C^{11} had become negligible. A ten-minute count was taken, and then a second ten-minute count was taken to verify the fact that no other activity was detectable. Background runs taken with no beam and a fresh disc were used to subtract out normal cosmic-ray effect. After background correction, the second count matched the first to within statistical error upon being corrected for the decay of C^{11} between the two counts.

The C^{10} activity was counted by connecting a Brush Recorder to the register input of one or two counters just as the beam was turned off. Within three seconds, the B^{12} , Li^8 , and He^6 activities were essentially gone, and only C^{10} and C^{11} activities were left. (Be^7 activity was quite low since this is a gamma-activity, and was practically constant because of its long half-life.) The count rate for the first

minute was compared with the rate for the second minute, after correcting the former for $\text{Li}^8 + \text{He}^6$ and the latter for C^{11} decay in 1 minute. Subtraction yielded the apparent C^{10} activity.

The Be^7 activity was measured in a separate experiment. A small piece of polyethylene was placed against the cyclotron tank window for about ten hours of neutron bombardment. This piece of polyethylene was counted for C^{11} beta activity at a known time after end of bombardment, and was then aged until the C^{11} rate was negligible. Daily and then weekly counts were made on this piece, with and without lead converters. The sample was placed in direct contact with the counter tube window for all counts. The gamma counting efficiency of the counter tube was determined by a side experiment for use in computing the cross section for Be^7 production.

The separation of Li^8 and He^6 activities required absorption technique. The two activities have practically identical half-lives, but do differ in their beta spectra (See Table I). It was calculated that 262 mils of aluminum should just stop all the He^6 betas (3.7 Mev maximum), while leaving a fraction of the Li^8 betas (12.8 Mev maximum). A series of absorbers was used to attenuate the count rate at the 135-degree position of a 60 rpm run.

This was repeated at the 45 degree position of a 60 rpm run to check the effect of the same absorbers on B^{12} (13.43 Mev maximum) betas. This involved some computation, since the 45 degree position counter saw all three activities - He^6 , Li^8 , and B^{12} .

The actual computation of every cross section required the value of the self-absorption factor for the activity in question for the disc thickness used. These self-absorption factors were measured. The C^{11} beta self-absorption factor is of prime importance, both because the C^{11} activity is used as a monitor, and because the beta energy is low, making self-absorption great. To measure the C^{11} self-absorption factor, polyethylene foils of thicknesses varying from 2 mils to one-eighth inch were cut to the same size (3.0 by 3.0 inches), weighed accurately to determine the weight per unit area, and then irradiated simultaneously in a fairly uniform scattered proton beam of large size. The proton beam was used because it was readily available and also because the cross section for C^{11} production is higher with protons than with neutrons. The foils were then counted carefully one at a time, after a delay of some minutes, and the activities were all corrected back to the same initial time. A plot was made of count rate divided by weight per unit area against weight per unit area (Fig. 14).

If there had been no self-absorption, the resulting curve would have been a horizontal line. Extrapolation of the curve back to zero thickness was made horizontally from the nearest point to correct for the effects of self-backscattering, which operates to raise the apparent counting rate of very thin samples²⁰. The ratio of the ordinates at a given thickness and at zero thickness is the self-absorption factor for the given thickness of disc. The self-absorption factor is defined as the fraction of betas, born in a disc, that can reach the surface of the disc.

The self-absorption factor of B^{12} was determined in a less satisfactory manner. Very thin discs could not be rotated because of their physical limitations, so only three disc thicknesses were used for the B^{12} self-absorption determination. However, the change in self-absorption factor was only five percent between a one-sixteenth and a one-eighth inch disc, so that the final value of 0.97 for a sixteenth-inch disc is probably not in error more than two percent because of the high beta energy endpoint. The Li^8 self-absorption factor was assumed to be very close to that of B^{12} , since the beta spectra are quite similar⁽¹⁷⁾. The values for He^6 and C^{10} factors were computed by interpolation and checked by data in the literature, since direct measurement was not considered practical. It is estimated from range and stopping power considerations that the loss of He^6 from a 1/8 inch disc by recoil did not exceed five percent, and that the loss of Li^8 was even lower.

E. Data and Calculation of Results

Typical data obtained during runs of the rotating disc are shown in Tables IV and V. The plots of Figs. 11, 12, and 13 summarize these data and some of their results.

In each run, the data taken with each counter was usually kept separate throughout the entire calculation, and only final cross sections were averaged, or at the most, the data taken by a pair of counters (on the same cross arm and hence, at the same angular position at all times) were combined before calculation. About twenty-five individual disc runs were made. The first few runs were rejected for poor beam collimation, which caused high beam-on backgrounds.

Some sample calculations will now be presented. Equation (9) was usually modified before actual use in a calculation because the B^{12} and C^{11} counting rates were usually employed as follows: The B^{12} rate was taken as the intercept of the best-fitting theoretical activity curve of B^{12} (which required only a knowledge of the half-life) on the zero angular position ordinate. This used all the B^{12} points plotted during a single run for one or two counters (reducing statistical variation), and also eliminated the need for the B^{12} decay factor in Equation (9). Also, since the instantaneous C^{11} counting rate was not a meaningful experimental quantity because C^{11} equilibrium had not been achieved, Equation (9) was modified to accept the background-corrected C^{11} 10-minute count taken 1 minute after the beam was turned off.

These changes converted Equation (9) into

$$\frac{\text{count rate/min } B^{12} \text{ at zero position}}{\text{Total 10 min } C^{11} \text{ count 1 min after beam off}} = \frac{\sigma_{B^{12}} \epsilon_{B^{12}}}{\sigma_{C^{11}} \epsilon_{C^{11}}} \frac{(T_{1/2} B^{12})}{(T_{1/2} C^{11})} \frac{\omega}{\alpha \beta} \frac{(1 - e^{-\frac{\lambda_B \alpha}{\omega}})(1 - e^{-\frac{\lambda_{B\beta}}{\omega}})}{(1 - e^{-\lambda_C t_1})(1 - e^{-\lambda_C t_2})(1 - e^{-\lambda_C t_3})(1 - e^{-\lambda_C t_4})} \quad (9a)$$

where:

$$\frac{\epsilon_{B^{12}}}{\epsilon_{C^{11}}} = \frac{(\text{self absorption factor of } B^{12})(\text{air transmission of } B^{12})}{(\text{self absorption factor of } C^{11})(\text{air transmission of } C^{11})} \frac{(\text{window transmission of } B^{12})}{(\text{window transmission of } C^{11})}$$

$T_{1/2} B^{12}$ is expressed in seconds

$T_{1/2} C^{11}$ is expressed in minutes

α, β are expressed in revolutions

ω is expressed in revolutions per second

t_1 = total beam-on time for run

t_2 = time elapsed from beam off to C^{11} count start

t_3 = time of C^{11} count

λ_B = disintegration constant of B^{12} (per second)

λ_c = disintegration constant of C^{11} (per minute)

Similar expressions hold for other short-lived activities. Equation (9a) is henceforth referred to as the "basic yield equation".

Calculation of B^{12} Cross Section

Using the data of Table IV and Figure 13, it was now possible to compute the cross section of B^{12} production. The following data were inserted into the basic yield equation (9a) for a 600 rpm run (double thickness disc).

Count rate per minute of B^{12} (activity)	3500
Count rate in ten minutes of C^{11} (activity)	5565
Self absorption factor of B^{12} , double disc (287 mg/cm ²)	0.92
Self absorption factor of C^{11} , double disc (287 mg/cm ²)	0.159
Air transmission of B^{12}	0.999
Air transmission of C^{11}	0.951
Counter window transmission of B^{12}	0.995
Counter window transmission of C^{11}	0.955
$T_{\frac{1}{2}} B^{12}$ (best value from Fig. 13) in seconds	0.0225
$T_{\frac{1}{2}} C^{11}$ in minutes	20.5
Disc revolutions per second (ω)	10

α in revolutions	1/16
β in revolutions	1/38
t_1 in minutes	1.00
t_2 in minutes	39.50
t_3 in minutes	10.00

Finally, using $\sigma_{C^{11}} = 22$ millibarns, (temporarily ignoring the error therein, ± 4 millibarns) the equation yields $\sigma_{B^{12}} = 4.89$ millibarns.

The combined result of eight disc runs, at speeds of 2280, 1200, and 600 rpm yielded a value of $\sigma_{B^{12}} = 4.93 \pm 0.46$ millibarns (relative to $\sigma_{C^{11}} = 22$ millibarns). Upon introducing the error in the absolute value of the C^{11} cross section, the value becomes $\sigma_{B^{12}} = 4.9 \pm 1.0$ millibarns. The primary contributing factors to the error are (1) the error in the C^{11} cross section, (2) error in the half-life of B^{12} , (3) statistics involved in subtracting a two large numbers (raw data minus beam-on background) and (4) determination of self-absorption factors. However, the statistical error and half-life determination error are essentially the same error, and are not additive. The 2280 rpm runs yielded good statistics, but precluded half-life determination because of the flatness of the activity curves.

Calculation of C^{10} Cross Section

The calculation of other cross sections proceeded in a like manner, but was complicated by factors such as the almost identical half-lives of Li^8 and B^{12} .

The C^{10} cross section, however, lent itself to straightforward computation, since the C^{10} activity could be separated from others by

the Brush Recorder run. The activity count immediately after beam off was compared to the residual C^{11} activity at a later time. After correcting the former for residual Li^8 and He^6 activity, and the latter for decay of C^{11} activity since the time of the first count, it was possible to determine the amount of C^{10} decaying in the first minute after beam off by subtraction. Numerous runs were required to obtain a positive result since the non-equilibrium condition that results as soon as the beam is turned off lowers all activity count rates (except C^{11}) quickly. The final accepted value of the number of C^{10} counts in the first minute after beam off was 20 ± 10 . The fraction of the existing activity that manifested itself in that minute was $1 - e^{-\lambda t}$ (where $\lambda = 0.693/19.1$ and $t = 60$ seconds), or 0.887. Therefore, the count rate that must have persisted at equilibrium, just before the beam was turned off, was about

$$\left(\frac{20}{0.887}\right) \left(\frac{0.693}{19.1}\right) (60) = 49 \text{ counts per minute}$$

It was not proper to do this last computation in terms of atoms of C^{10} present, since the absolute number of atoms could only be stated if the geometrical efficiency of the counter were known. The determination of this efficiency has been carefully avoided by the expressing of the basic yield equation in such a form that the geometrical efficiency factor appears both in numerator and denominator. As has been stated before, the purely geometrical efficiency of the counting set-up used was found to be effectively independent of the activity being counted.

The C^{10} count rate was now inserted into the basic yield equation (9a). The pertinent new data required not already given under in the B^{12} calculation are to be found in Table VI, which lists self-absorption, window transmission, and air transmission factors. The result was $\sigma_{C^{10}} = 0.67 \pm 0.38$ millibarns. It is not surprising that this yield should be low, since the reaction involved is $C^{12}(n;3n)C^{10}$, which could not be expected to compete favorably with other possibilities.

Improvement of the error in this value was considered, but the problem was a difficult one. Obviously, the equilibrium (beam on) technique could give the 49 count per minute rate, but only under heavy masking by shorter activities at a speed of 60 rpm or more. Even if speed of rotation had been reduced to three revolutions a minute to inhibit the shorter-lived activities, the C^{10} activity would have been hardly visible against the necessarily high beam-on background, and it is doubtful that the accuracy of the determination would have been improved. Long equilibrium counts would have permitted build-up of C^{11} activity even more, with no corresponding increase in C^{10} activity, thus giving no gain in statistics.

Separation of Li^8 and He^6 Activities

The separation of Li^8 and He^6 activities posed a special problem, since these two activities have practically identical half-lives (within the probable errors thereof). This was done by placing absorbers in the counter telescope system, as shown in Fig. 3, during a 60 rpm run. Data were taken with and without absorbers at various angular positions. Data taken at angular positions 90 degrees and greater

tested the absorption of Li^8 and He^6 activity (see Figs. 9 and 13), while angular position 45 degrees yielded data on the absorption of B^{12} activity (after subtracting out the extrapolated Li^8 and He^6 values), which was used as a monitor.

After making the usual beam background and C^{11} build up corrections, (C^{10} correction was negligible), it was found that the Li^8 plus He^6 activity was reduced to 0.17 ± 0.02 of its no-absorber value by 262 mils of aluminum, which is the thickness calculated to stop all the He^6 betas of energy 3.7 Mev maximum(16). The B^{12} activity was reduced to 0.59 ± 0.05 of its no-absorber value. Since the beta energy end points of B^{12} and Li^8 are quite close, and since their beta spectra are remarkably similar in all respects(17), it was considered reasonable to make the approximation that $0.17/0.59$ of the Li^8 plus He^6 activity (mixture) was due to Li^8 . This yielded the fraction of Li^8 activity as 0.29 ± 0.07 .

Examination of the 60 rpm data in Table VI and the plot thereof in Fig. 13 permits direct reading of the Li^8 activity counting rate. The partly dotted line represents an activity of $T_{\frac{1}{2}} = 0.88$ seconds. (No independent determination of a half-life was feasible here, because of the mixture of activities present.) The ordinate at zero angular position of the extrapolated curve (ignoring the first two B^{12} -admixture points) represents the mixture of Li^8 , He^6 , and C^{10} activities. The C^{10} activity correction was not subtracted in drawing Fig. 13, in order to avoid making the figure confusing, since the C^{10} correction is less than the standard deviations indicated. The subtraction of C^{10} activity

tips the curve clockwise slightly and makes a slightly shorter half-life (0.86 seconds) produce a better fit to the data. The net result is about the same as without subtraction, since the whole curve is lower but has more (negative) slope; the ordinate at zero angular position for Li^8 plus He^6 activity is still about 1000 counts per minute. Therefore, the Li^8 counting activity rate at zero degrees was called 290 ± 100 counts per minute.

The He^6 rate was then found, by subtracting the Li^8 rate and Cl^{10} rate (42 counts per minute at 60 rpm), to be 670 ± 100 counts per minute at zero degrees angular position.

Calculation of Li^8 and He^6 Cross Sections

The calculation of Li^8 and He^6 cross sections was now done by application of the basic yield equation (9a); the only difference in the right-hand terms occurred in the efficiency factors (see Table VI).

The results were

$$\sigma_{\text{Li}^8} = 0.82 \pm 0.27 \text{ millibarns}$$

$$\sigma_{\text{He}^6} = 2.54 \pm 0.38 \text{ millibarns}$$

$$\text{relative to } \sigma_{\text{Cl}^{11}} = 22.0 \text{ millibarns.}$$

$$\text{Relative to } \sigma_{\text{Cl}^{11}} = 22 \pm 4 \text{ millibarns, the values are:}$$

$$\sigma_{\text{Li}^8} = 0.82 \pm 0.42 \text{ millibarns}$$

$$\sigma_{\text{He}^6} = 2.54 \pm 0.96 \text{ millibarns}$$

Calculations of Be^7 Cross Section

The counting of Be^7 activity was difficult because the activity is gamma rather than beta, and occurs only in the ratio of 1 gamma per 0.107 disintegrations. Determination was needed of the efficiency for

gamma counting of the counter tube. The work of Bradt et al⁽¹⁸⁾ gives tables and curves of gamma counting efficiencies for Geiger tubes constructed with lead windows one mil thick, for gamma energies 0.1 Mev to 3 Mev. Since the gamma counting rate of a small circle of polyethylene bombarded for about ten hours close to the cyclotron tank was quite low, a lead converter was required. Therefore, a one-mil lead foil was placed over the 2.0 mg/cm² mica window of an end-window counter for counting. Counts of several hours duration were taken first daily and then weekly. For normalization, the polyethylene disc was counted soon after exposure, without the lead foil, to obtain the C¹¹ beta activity.

Before the values of gamma counting efficiency from the Tables⁽¹⁸⁾ could be used, it was necessary to check their validity for the particular counter tube employed. This was done as follows: A radium source whose weight of radium was known (10.07 mg) was counted with 72 inches distance (with and without a collimator) between the source and counter window. The number of gammas per alpha disintegration, and their energies and relative quantity are known⁽¹⁹⁾. The gamma counting efficiency varies with gamma energy, so it was necessary to compute the theoretical average counting efficiency by taking the weighted product of the fraction emitted of each energy gamma times the counting efficiency thereof. This yielded the following value:

10.07 mg Ra $\rightarrow$ $2.29 \times 10.07 \times 3.7 \times 10^7$ gammas/sec of average counting efficiency 0.84×10^{-3} .

The radium source count described above yielded 0.91×10^{-3} efficiency without collimation and 0.87×10^{-3} with collimation (which cut down scattering from the thicker lead around the counter sides). This agreement with the theoretical value of 0.84×10^{-3} computed from the tables of Bradt et al seemed to warrant the use of their tables for the Be^7 gamma efficiency, since their efficiency curves are fairly flat in the region 0.4 to 0.8 Mev. (The weighted average energy of the Ra gammas is 0.78 Mev.) The value used for Be^7 gamma counting efficiency was $7.1 \pm 0.2 \times 10^{-3}$. It is of interest to note that quoted values of about two percent gamma counting efficiency are actually for counter tubes with walls thicker than one mil of lead. A test made with the addition of eight mils of lead between window and Be^7 source raised the count rate by about a factor of three, thus giving an apparent 2.1 percent counting efficiency.

The calculation of a cross section for Be^7 was made directly by computing (1) the production rate of C^{11} in the sample and (2) the production rate of Be^7 . Both C^{11} and Be^7 counts were taken with essentially 50 percent geometry. The C^{11} production rate was computed by extrapolating the C^{11} beta activity (corrected for self-absorption and window loss) back to end of bombardment, and then, determining the required production rate from the recorded decay and bombardment times. Less than one percent error was admitted by ignoring C^{11} activity imparted more than 2.5 hours before end of bombardment. For simplicity, the Be^7 production rate was computed with no decay corrections (before end of bombardment), since the error involved was negligible in 13 hours

intermittent bombardment. Using the C^{11} beta transmission data from Table VI for a single thickness disc, the number of C^{11} atoms present at end of bombardment was computed to be 3.49×10^7 ; the production rate was then computed to be 1.52×10^6 per minute.

For Be^7 gamma activity, it was computed that the counter would give one count per minute for every 3.31×10^8 nuclei of Be^7 present at end of bombardment. For a run time of 532 minutes, this meant one count per minute represented 6.23×10^5 Be^7 nuclei produced per minute; or 9.0 millibarns of Be^7 cross section. The Be^7 gamma count rate per minute at end of bombardment, which was determined to be 0.98 ± 0.35 , yielded $\sigma_{Be^7} = 8.8 \pm 3.2$ millibarns relative to $\sigma_{C^{11}} = 22$ millibarns. Adding the absolute C^{11} cross section error yielded $\sigma_{Be^7} = 8.8 \pm 4.6$ millibarns.

Discussion of Other Cross Sections

The remaining unmentioned possible products are B^8 , Li^9 , and Be^{10} . The B^8 and Li^9 cross sections could not have exceeded one millibarn each, judging from the manner in which the 60 rpm activity mixture curves agreed with the theoretical mixture curve of Fig. 8. There was no evidence of any shorter half-life present than that of B^{12} . Be^{10} has too long a half-life (2.5×10^6 yrs) to be detected by this method without unduly long bombardment.

Summary of Cross Sections

Activity	Gross Section Relative to	Gross Section Relative to
	Cl^{11} 22 millibarns (in 10^{-27} cm^2)	Cl^{11} 22 = 4 millibarns (in 10^{-27} cm^2)
B ¹²	4.93 ± 0.46	4.93 ± 1.0
He ⁶	2.54 ± 0.38	2.54 ± 0.96
Li ⁸	0.82 ± 0.27	0.82 ± 0.42
C ¹⁰	0.67 ± 0.38	0.67 ± 0.50
B ⁸	< 0.8	< 1.0
Li ⁹	< 0.8	< 1.0
Be ⁷	8.8 ± 3.2	8.8 ± 4.6

IV. DETAILS OF APPARATUS AND METHOD - CLOUD CHAMBER METHOD

A. Details of Apparatus

The cloud chamber used was of the rubber diaphragm type, with a diameter of 22 inches, and a depth of four inches. The chamber was placed horizontally in a vertical magnetic field of 21,700 gauss produced by a peak current of 4,000 amperes pulsed through ~~a pair of Helmholtz coils~~. The field strength decreased a maximum of four percent from the central maximum at a radial distance of six inches from the center of the chamber. The collimated neutron beam entered and left the cloud chamber through two windows of five mil aluminum foil which were vertically centered in the chamber walls and diametrically opposite one another. Figure 15 shows a general view of the complete cloud chamber apparatus.

Events occurring in the chamber were recorded on Eastman Super XX strip film 1.81 inches wide, using a stereoscopic camera having a pair of 127 mm focal length lenses set at f8. The lenses were 4.5 inches apart and about 52 inches directly above the bottom of the chamber. The plane containing the lens axes was normal to the neutron beam direction. Since the camera had no shutter, the length of the exposure was determined by the 100 micro-second light flash obtained by the discharge at 1,700 volts of a pair of condenser banks of 256 microfarads each through a pair of General Electric FT 422 flash tubes. These flash tubes were mounted on opposite sides of the cloud chamber in the space between the Helmholtz coils. The light from each was directed into the chamber by a pair of cylindrical lucite lenses in horizontal beams normal to the neutron beam direction.

The cloud chamber cycle of operation was automatic and occupied a period about one minute. The pulsed current for the magnetic field was supplied by a mine-sweeper generator energized by a 150 hp motor. The field was constant at its peak value for about 0.15 second. The fast expansion of the chamber occurred during this interval, and the cyclotron was pulsed near the end of the chamber sensitive time. A 400-volt clearing field across the chamber was turned off just before the expansion in order to permit sharp tracks. Turbulence in the chamber was minimized by maintaining the chamber at a constant temperature of about 20°C by means of a temperature controlled, circulating water system.

During the course of operation, frequent tests were made of the lighting system, expansion ratio, and total gas pressure. The peak coil current was monitored every few expansions, and was kept adjusted within the range 4000 ± 20 amperes. Short sections of film were developed during the run to test adequacy of f-setting, lateral collimation, expansion ratio setting, track density, and beam intensity.

B. Collimation of the Neutron Beam

The neutron beam used was produced in the same manner as in the case of the rotating disc method except that a beam of somewhat less than maximum intensity was used.

The neutron beam was collimated in the igloo as shown for the rotating disc method, but with a 2.5 to 4.0 inch diameter tapered collimator instead of with a straight-walled 2-inch diameter collimator. The beam was further collimated at the neutron port to a size of 0.5 inch high by 2.5 inches wide by means of three-foot long brass blocks,

and was then "skimmed" by copper blocks four feet long to eliminate as far as possible particles scattered by previous collimation. The cloud chamber was about 65 feet from the beam source, and received a neutron beam of cross section slightly under 0.75 inch by 3.5 inches.

Choice of beam intensity was made by operating the cloud chamber at increasing intensities until the desired average number of events per expansion was obtained.

C. Gas Mixture

Acetylene and methane were considered the most desirable gasses to use in the chamber on the basis of proper carbon to hydrogen ratio for adequate statistics in normalization of cross sections. Acetylene, however, attacks copper and brass. Methane was found acceptable, but required the admixture of hydrogen gas to obtain a reasonably low expansion ratio (about 32 percent). Alcohol was not added to the saturated water vapor required to operate the chamber because of its action on lucite. The final mixture used was a compromise dictated by the following factors:

1. Maximum possible carbon to hydrogen ratio
2. Expansion ratio of about 32 percent
3. Maximum possible carbon to oxygen ratio
4. Stopping power not to be excessive

The composition of this mixture in terms of the expanded partial pressures at 19.5°C was as follows:

Methane (99% CH ₄ , 1% C ₂ H ₆)	47.45 cm Hg.
Hydrogen	34.85 cm Hg.
Water Vapor	1.75 cm Hg.

The stopping power of this mixture was calculated to be 0.645 relative to standard air. Comparisons of $H\rho$ and range for tracks of several particles identified by other means verified this figure to within about $\pm$ five percent.

D. Stereoscopic Projector

The actual measurements of direction, radius of curvature, range and density of the star tracks were made with the aid of a special stereoscopic double projector⁽⁹⁾. The optical system of the projector was identical with that of the camera setup except for the addition of an aluminized mirror placed at 45 degrees to make operation convenient, and a piece of plate glass introduced to correct for distortions introduced by the top glass of the cloud chamber. Western Union Type 100 arc lamps furnished the necessary illumination to project the track images on a specially coated glass (Eastman Recordak Green Translucent Screen Type 75551) which was mounted on a pedestal permitting vertical movement and also rotation about horizontal and vertical axes.

Before measurements were made, the film was adjusted to the same position relative to the optical system that it had when the picture was taken. For this purpose, five crosses had been inked on the top glass of the cloud chamber as reference marks. The line of centers of the crosses paralleled the neutron beam axis to within one-half percent; the crosses were spaced three inches apart. The green screen was placed horizontal at the optical position occupied by the upper surface of the top glass of the cloud chamber during its operation. The two images of the set of crosses projected thereon were then brought into proper focus, aligned, and made the same correct size.

The origin of a reprojected track was located in space by moving the screen vertically and horizontally until the two images of the track origin coincided at the vertical rotation axis of the screen. Then the screen was rotated and tilted until the two track images coincided for their entire length. The length and slant radius of curvature of the track was then measured by matching it to one of a series of concentric arcs ruled on Lucite Templates. The dip angle α and the beam angle β could be measured. The dip angle α is the angle between the initial track direction and the horizontal, measured in a vertical plane; the beam angle β is the angle between the beam direction and the horizontal projection of the initial track direction. The equivalent horizontal radius of curvature can be computed from the slant radius of curvature by the relation $\rho \approx \rho_{\text{slant}} \cos \alpha$.

E. Stereoscopic Viewer

A stereoscopic viewer was also used to examine the cloud chamber pictures. This viewer was habitually used first in preliminary study of each pair of pictures to determine the number of stars, the number of prongs, number of proton recoils, approximate locations of events, approximate tracks densities, and general direction of prongs. The film was then transferred to the projector for measurements of radii of curvature, angles, and ranges where applicable.

F. Fragment and Star Identification

The pieces of information that may be available or useful for identifying a given star or star fragment are⁽¹⁴⁾:

1. Direction and energy distribution of the incident neutron beam.

2. Nuclei present as targets (for charge and mass balance)
3. Orientation and intensity of the cloud chamber magnetic field
4. Stopping power of the gas mixture in the chamber
5. Number and relative density of prongs
6. Individual track characteristics
  - a. Absolute density
  - b. Initial direction
  - c. Initial radius of curvature
  - d. Rate of change of radius of curvature with range
  - e. Range

Only in rare cases are all the pieces of information listed under (6) available for a single track; in general only some are available.

The systematic application of the data available is greatly facilitated by the use of the tables, which constitute UCRL-1445, "Energy and Ionization of Light Particles as a Function of $H\rho$ " (by Donald Johnson, August, 1951). An additional variable, range, is readily supplied from range-energies curves⁽¹⁵⁾. The range-energy relationships for the deuteron and triton are derived from the proton data; and for He^3 , from He^4 data, by means of the equation $R_1 \left(\frac{M_1}{M_2} E \right) = \frac{Z_2^2}{Z_1^2} \frac{M_1}{M_2} R_2 (E)$ where $R_2 (E)$ signifies range of particle 2 at energy E , and $R_1 \left(\frac{M_1}{M_2} E \right)$ signifies range of particle 1 at energy $\frac{M_1}{M_2} E$.¹⁵ All ranges must be computed for the actual gas mixture used in the cloud chamber, since the values shown in or computed from range-energy and curves are

normally given for air at standard conditions. This involves calculation of the stopping power relative to air of the gas mixture used, as shown in Table II.

A further aid to fragment identification and, at the same time, a check on the accuracy of the stopping power and range calculations, is the graphic construction of fragment-ending curves for all possible fragments up to and including He^4 . This was done from the computed range tabulated as function of $H\rho$ for each fragment. The constructed curves were checked by matching against actual track endings found in cloud chamber pictures and identified otherwise.

The curves were found to match known fragment endings well, and could then be used to identify other unknown endings quickly provided the latter were reasonably horizontal and sufficiently long. It was found preferable to trace actual track endings (already identified) for precise matching, since it was possible to obtain tracings for both edges of a track, while the constructed endings were designed for an idealized track of no finite width.

The tables and ending curves could be used to identify all but the shortest fragment tracks (three centimeters or less). Heavier fragments, however, do not lend themselves to extrapolation of their ranges and specific ionizations in the manner that He^3 values can be obtained from He^4 data. Therefore, practically all identifications above He^4 were made by conservation of charge. Mass balance is a rather uncertain criterion, and was used only with reservations, for the following reasons:

1. One or more neutrons may be and usually are given off in each reaction at the energy used⁽¹⁴⁾.

2. Approximately 36 oxygen stars should have been seen among the thousand-odd stars studied; only 14 were identified with any certainty, leaving 22 ± 6 probable oxygen stars unaccounted for.

3. About 11 of the stars seen must be presumed to have been initiated from C^{13} instead of C^{12} nuclei.

Energy and momentum balances could likewise be used as identification criteria only with reservations, since the incident neutrons had an energy spectrum, and any secondary neutrons had unknown direction, momentum and energy. The objectives of this work and the number of stars studied to obtain reasonable statistics precluded the application of energy and momentum criteria in all but a few cases of special interest.

The actual steps followed in reasoning out a given disintegration reaction varied with the data available and the accuracy with which that data could be obtained. In general, determination of track density was the most inaccurate required operation, especially for very dense tracks. Efforts were made to minimize the error involved by using a "more than" or "less than" comparison system rather than a relative comparison, as follows: In most pictures, it was easy to find known proton recoil tracks of various densities. Certain identification of the particle involved (single-prong "stars" of more than three centimeters length and any appreciable curvature were almost invariably protons) permitted use of the H_p -specific ionization table to determine

the specific ionization (i.e., track density) by measuring the radius of curvature. This gave a number of check values of track density (specifically, the specific ionization in units of "times minimum ionization", henceforth called density) for use as go, no-go gauges (monitor-densities) to bracket the track densities of star fragments.

The major difficulties found in applying this system were:

1. Proton recoils of desired monitor-densities were not always available in the region of observation.
2. Variation of illumination, film, photography and developing made monitor-densities non-transferable from picture to picture or even to different regions of the same picture without approximation.
3. Few high monitor - densities (300 x minimum ionization and over) were available, and their comparison was difficult.

For lightly-ionizing tracks of large radius of curvature, this system worked quite well; high energy singly-charged particles could almost always be identified with very little chance of error.

It is to be noted that identification of a fragment by any means other than charge and mass balance automatically determines the kinetic energy of the fragment. Energies were recorded for all particles of energy over a few Mev.

G. Details of Measurement

The general plan of operation in reading the cloud chamber pictures was as follows:

1. Examine pictures on stereoscopic viewer
  - a. Determine if picture is to be used, on basis of illumination, background, and events shown.

b. Count proton recoils present in area four inches wide by 12 inches long. Note dubious recoils under three centimeters long, caused by neutrons under 40 Mev, not originating in beam.

c. Count and record stars present in same area. Count and record prongs. Estimate and record track densities.

2. Examine picture on stereoscopic projector

a. Measure slant radii of curvature and dip angles

b. Measure ranges and beam angles where applicable

c. Resolve dubious recoils

d. Check recoils and stars for origin within the chosen counting volume (four inches by 12 inches by 1.5 inches)

e. Make identification by track-ending curve comparisons where applicable.

3. Make identifications from the data available as described in Section IV-E

4. Repeat parts of 1. and 2. as required to resolve inconsistencies. Consider rejection of entire picture for remaining inconsistencies.

5. Record data.

Rejection was always done by whole pictures rather than by individual stars, since it was felt that selective rejection of individual stars would bias the results in favor of two-prong stars because these would be rejected less often on the basis of inconsistencies.

Reasons for rejection were:

1. No beam pulse

2. Over-illumination and over-exposure

3. Too many short star prongs

4. Too many prongs at steep angles with horizontal. This was not believed to introduce selective error, since prong distributions assumed, on the average, to be circularly symmetric about the beam axis.

5. Two or more stars in accidental spatial coincidence.

Except for the reasons named, pictures were taken consecutively as they came on the film roll, since it was felt that "shopping around" for interesting events would introduce observer bias.

H. Normalization of Data

Normalization of the cross sections determined for various events, products, and reactions was made by use of the neutron-proton scattering cross section. The value 77 ± 1.5 millibarns was adopted for this cross section after careful comparison of the results obtained by Hadley et al.⁽⁶⁾, Breuckner et al.⁽⁹⁾, and others.

The ideal normalization scheme would have been one of counting all proton recoils produced by the beam in a given area of each picture (actually, a given volume in the cloud chamber), counting all other events produced on the same region, and saying

$$\frac{\text{proton recoils per hydrogen nucleus present}}{\text{desired events per carbon nucleus present}} = \frac{77 \text{ millibarns}}{X \text{ millibarns}} \quad (12)$$

to obtain X, the cross section for the event in question.

Short proton recoils are difficult to identify. Therefore, an arbitrary cut off was made at three centimeters, which is the range of a one Mev proton elastically scattered at 84 degrees (laboratory

system) by a 90 Mev incident neutron. This method (used by Breuckner et al.⁽⁹⁾) requires the determination of the fraction of proton recoils lost thereby.

This determination was made both analytically and graphically.

For the analytical determination, the n-p cross section curve of Hadley et al.⁽⁷⁾ was numerically integrated by approximation from 84 to 90 degrees (laboratory angle) and then over the whole curve; this yielded the fraction lost as follows:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{lab}} = 4 \left(\frac{d\sigma}{d\Omega}\right)_{\text{c.m.}} \cos \theta_{\text{lab.}}$$

$$\text{proton yield}_{84^\circ \text{ to } 90^\circ (\text{lab})} = 2\pi \int_{84^\circ}^{90^\circ} 4 \left(\frac{d\sigma}{d\Omega}\right)_{\text{c.m.}} \cos \theta \sin \theta d\theta.$$

Approximating $\frac{d\sigma}{d\Omega}$ as a constant,

$$\text{proton yield}_{84^\circ \text{ to } 90^\circ} \approx -4\pi \left(\frac{d\sigma}{d\Omega}\right)_{\text{c.m.}} \left[\cos^2 \theta\right]_{84^\circ}^{90^\circ} \approx 4\pi \left(\frac{d\sigma}{d\Omega}\right)_{\text{c.m.}} \left(\frac{1}{90}\right)$$

$$\text{Total yield} \approx -4\pi \left(\frac{d\sigma}{d\Omega}\right)_{\text{c.m.}} \left[\cos^2 \theta\right]_0^{90^\circ} \approx 4\pi \left(\frac{d\sigma}{d\Omega}\right)_{\text{c.m.}} \quad (\text{where the average value is used as approximation.})$$

Now $\left(\frac{d\sigma}{d\Omega}\right)_{\text{c.m.}}$ in the region 178 to 180° is about 13 millibarns per steradian, while the average value 0° to 180° is about 8 millibarns per steradian. Using these approximate values, one obtains for the fraction of protons lost $\left(\frac{1}{90}\right)\left(\frac{13}{8}\right) = 0.0163$ or about 1.6 percent.

For the higher and lower energy neutrons in the spectrum, this result is slightly different (2.6 percent for 60 Mev neutrons, 1.35 percent for 120 Mev neutrons), but it is reasonable to assume on the basis of this approximate calculation that the fraction of protons lost for the 90 Mev neutron spectrum is about 1.6 ± 0.7 percent.

The other determination was made by performing the same integration graphically. Using the curve of Hadley et al.⁽⁷⁾ in the center of mass system, multiplying this curve by $\sin \theta_{cm}$ (after extrapolating the curve to 180° for proton yield by symmetry), yielded the fraction of protons lost as 2.0 percent. Using the same technique on the tabular laboratory angle data of Hadley et al.⁽⁷⁾ yielded 1.3 percent. The data presented by Brueckner et al.⁽⁹⁾, which is only in bar graph form, but does extend the data further in angle, yielded 1.2 percent as the fraction lost.

The final value chosen for fraction of recoil protons (under 1 Mev) not counted was 1.5 ± 0.5 percent. This means that in Equation (12), the value 77 ± 1.5 millibarns was replaced by (0.985 ± 0.005) times (77 ± 1.5) or 76 ± 2 millibarns.

A final step needed for normalization was the determination of the relative numbers of nuclei of carbon and hydrogen present in the cloud chamber gas. This was done as follows: Taking the partial gas pressures shown in Table II, one computed the relative numbers of carbon, hydrogen and oxygen nuclei present (remembering that the methane used contained one percent of ethane):

Carbon: 47.925

Hydrogen: 263.95

Oxygen 1.75

The oxygen necessarily present is a source of error. This error was decreased somewhat by discarding all stars identified as oxygen stars. These numbered fourteen. On the basis of the above

relative numbers of nuclei, and approximating the oxygen star formation cross section as equal to that of carbon, one should find about 36 oxygen stars among 1000 stars. Therefore, the relative number for oxygen (1.75) was reduced to $(36 - 14)/36 \times 1.75$, or 1.07 and then lumped with the carbon number to yield

Carbon 48.995 and hydrogen 263.95, or a hydrogen-to-carbon target-nucleus ratio of 5.387.

It is believed that the error admitted by lumping the undiscovered oxygen stars with carbon stars is actually less than the apparent 2.2 percent given by 1.07 parts in 48.995 because oxygen nuclei probably behave very much in the same manner as do carbon nuclei for knock-out processes at 90 Mev, and it is among these two-prong stars that most of the undiscovered oxygen stars are apt to be, since multiprong oxygen stars were more easily discovered. Therefore, the oxygen-inclusion error was called $\pm$ one percent.

Equation (12) could now be modified to read, for a given reaction X in carbon,

$$\frac{\sigma_X(\text{millibarns})}{76 \text{ millibarns}} = \frac{\text{number of proton recoils counted}}{(\text{number of events } \gamma \text{ counted})(5.387)} \quad (13)$$

The error introduced thus far by the "apparent" n-p cross section of 76 millibarns and by the ratio 5.387 was estimated as $\pm$ 3.5 percent (taking into account the probable error of the best n-p cross section value, oxygen error, and gas pressure determination error). Naturally, this error increased for any actual cross section computed by Equation (13) because of statistical variations and errors in counting proton recoils and carbon events.

I. Results of Cloud Chamber Method

The cloud chamber method yielded a number of cross sections which are shown in the summary of Table VII. In presenting the cloud chamber data, the following conventional symbols have been used:

P = proton

d = deuteron

t = triton

α = helium, mass number not determined experimentally

Li = lithium, mass number not determined experimentally

Be = beryllium, mass number not determined experimentally

B = boron, mass number not determined experimentally

Neutrons leaving the target nucleus are not indicated in this system, since their number is usually undetermined. For example, the notation (p, d, Be) indicates a cloud chamber star consisting of three visible prongs — one proton, one deuteron, one beryllium residual nucleus of undetermined isotopic number, and an undetermined number of neutrons.

Comparison with other data

The cross section for star formation was calculated to be 232 ± 17 millibarns. Adding on the 22 ± 4 millibarns of C^{11} production (not detected in star analysis), one obtained 254 ± 21 millibarns. De Juren and Knable⁽²⁾ obtained a value of 224 ± 40 millibarns at 95 Mev, which would presumably have become about 237 ± 40 millibarns at 90 Mev. These two results agree within their errors.

A second comparison was made with the data of Hadley and York⁽⁶⁾, as follows:

Product	Protons over 20 Mev	Deuterons over 27 Mev	Tritons over 33 Mev
Gross Section (millibarns) (author)	85.3 ± 9.2	26.1 ± 3.4	3.9 ± 0.93
Gross Section (millibarns) (Hadley-York)	90 ± 20	26 ± 6	3 ± 0.8

A third comparison made was of the yield of protons over 35 Mev, estimated by Hadley and York to be about 52 millibarns. The value obtained in the present work was 57.5 ± 5 millibarns. This agreement seems to indicate that no appreciable number of protons was lost through mistaking two-prong stars for proton recoils.

An attempt was made to determine the elastic cross section by counting all the short single-prong tracks, and then subtracting the 22 millibarns of C^{11} reaction and the 1 millibarn of "lost" proton recoils. This was not too satisfactory a process, since extremely short tracks were hard to differentiate from the film background. The elastic cross section thus determined was 250 ± 60 millibarns, which is in fair agreement with the value computed from the work of De Juren and Knable⁽²⁾, namely 285 ± 25 millibarns, but agrees only because of the rather large error that must be assigned to the measured value. Adding the elastic and inelastic cross sections thus determined yields a value for the total cross section, as follows:

Star formation	232 ± 17 millibarns
$C^{12}(n,2n)C^{11}$	22 ± 4
Elastic collision	250 ± 60
	504 ± 80

which agrees with the value of 520 ± 15 millibarns extrapolated to 90 Mev from the work of De Juren and Knable⁽²⁾.

Analysis of Results

Some deductions can be made to remedy the lack of experimental determinations of the isotopic (mass) numbers of heavy fragments in the cloud chamber method. This involves mass balancing and a number of assumptions, as follows:

1. Only the unstarred fragments shown in Table III are assumed possible.
2. The 1.1 percent of C^{13} present in the target is assumed to undergo reactions in the same manner as C^{12} , and hence not to favor any particular type of reaction. For 90 Mev incident neutrons, this does not seem an unreasonable assumption.
3. The 2.2 percent of O^{16} lumped with C^{12} (as mentioned before) is also assumed to favor no particular reaction.
4. It is estimated that no free neutron (including the incident neutron) leaves the target nucleus, in about ten percent of all reactions in which at least one charged particle is knocked out.

This estimate is arrived at as follows:

- a. The 5 millibarn yield for $C^{12}(n;p)B^{12}$ found by the rotating disc method, compared to the 95 millibarn yield for (p,B) stars found by the cloud chamber method indicates that about five percent of the incident neutrons which knock out single protons remain trapped in the residual boron nucleus.
- b. In the case of (d,B) stars, a plot of the energy distribution of the high-energy deuterons (over 27 Mev) shows a distinct peak at

about 70 Mev, and a lower broad maximum at about 30 to 40 Mev. The higher peak is assumed to be due to deuteron pick-up with no free neutron leaving the nucleus, while the lower maximum is assumed to be due to a spallation with neutron emission. A rough resolution into these two classes (limited by the presence of only sixty-six pertinent events in over a thousand stars) would seem to indicate that about one-third of the high-energy (over 27 Mev) deuterons are emitted by pick-up, and therefore about 20 percent of all (d,B) stars were accompanied by no emitted neutrons (i.e., about 5 millibarns worth). See Fig. 17.

c. In the case of deuterons emitted in stars of type other than (d,B), the low deuteron energies found as a rule seem to indicate very few pick-up processes (presumably followed by spallation) if any; it is doubtful that the subsequent spallations required in such cases (to produce the fragments seen) would not result in neutron emission.

d. In the case of (t,B) stars, the triton energy distribution seems to indicate that about half of these occurred by pick-up with no neutron emission (i.e., 1.8 millibarns worth).

e. If Be^8 is assumed to be the intermediate step for production of alpha pairs, then the 1.8 ± 0.6 millibarns of (d, t, 2α) stars occur with no neutron emission.

f. The two unambiguous reactions $\text{C}^{12}(\text{n}; \text{t}, \alpha)\text{Li}^6$ and $\text{C}^{12}(\text{n}, 2\text{d}, \text{t})\text{Li}^6$ give 1.8 ± 0.7 millibarns of no neutron emission.

The above reactions, especially the pick-up and n-p processes, are the more likely ones to give no neutron emission, and yield about 15 millibarns of no neutron emission out of 250 millibarns worth of

inelastic events, i.e. about six percent. Allowing an increment for undetected no-neutron emissions among the other reactions in accordance with b and c. raises the estimate to about ten percent.

It is now possible to make some deductions regarding yields of specific heavy isotopes:

1. The 4.1 ± 1.0 millibarn cross section for (d, t, Be) stars is the minimum possible cross section for Be^7 production. (Assumptions 1, 2, and 3 or 4)

2. If all four assumptions are used, the greatest part of the following cross sections may be added to give a new and higher estimate of Be^7 cross section:

(d, d, Be) stars - 5.7 ± 1.3 mb

(p, t, Be) stars - 2.9 ± 0.9 mb

(α , Be) stars - 2.5 ± 1.1 mb

The final result of 14.5 ± 4.3 millibarns for the Be^7 production cross section which is to be compared with the rotating disc method value of 8.8 ± 4.6 millibarns.

3. The maximum Be^{10} cross section is 16.1 ± 3.5 millibarns if assumption 4 is not used, but drops to 6.8 ± 1.6 millibarns if assumption 4 is used; this latter value is the most probable cross section.

4. Using all four assumptions, Be^9 is assigned a maximum yield of 15 ± 3.5 millibarns.

5. The yield of Be^8 (as an intermediate nucleus in the process of making two alphas) is assigned a maximum value of 26 ± 4 millibarns.

6. Using all four assumptions, Li^8 is assigned a maximum yield of 3.4 ± 1.4 millibarns. This includes a maximum possible yield of 0.2 ± 0.2 millibarns of Li^9 . The value for Li^8 is higher than the experimental result of 0.8 ± 0.4 millibarns found by the rotating disc method, but does not necessarily contradict it, since the deduced result is a maximum. The deduced Li^9 yield agrees with that deduced by the rotating disc method (< 1 millibarn).

7. The respective yields of Li^7 and Li^6 cannot be deduced from the evidence at hand. The sum of Li^7 and Li^6 yields is about 40 millibarns.

8. In the case of boron isotopes, the rotating disc method furnished 4.93 ± 1.0 millibarns for B^{12} and < 1 millibarn for B^8 yield, but the present analysis discloses no breakdown of the 115 millibarns of B^{11} plus B^{10} yield.

9. No deductions can be made from the cloud chamber results concerning He^6 yield; the rotating disc method result was 2.54 ± 0.96 millibarns.

See Tables VIII and IX for a summary of the deductions made in this section.

V. CONCLUSIONS

The cross sections determined by the two methods cover the possible reactions (within the definition of the word "reaction" as given in Section I) induced in carbon by 90 Mev neutrons. In the case of the cloud chamber method, only limited and approximate identifications of heavy fragments could be made as regards their mass numbers. The rotating disc method, however, filled in this data in the case of several radioactive products, with the notable exception of Be^{10} .

The mechanisms by which high and low energy singly charged particles (protons, deuterons, and tritons) are produced may be compared by means of the data in Table VII. Of the high energy singly charged particles, 74 percent of the protons, 57 percent of the deuterons and 50 percent of the tritons were produced from two-prong stars (by knock-on or pick-up); the remainder came from multi-fragment stars of spallation.

It is, therefore, noteworthy how well the yields for p,B stars (95 ± 9 millibarns) d,B stars (24 ± 4) and t,B stars (3.6 ± 1) agree numerically with the yields for high energy protons (95 ± 9), deuterons (26 ± 3) and tritons (3 ± 1) from all reactions.

The total proton, deuteron and triton yields, of all energies and from all reactions, were 172.5 ± 15 , 89.5 ± 10 , and 21.5 ± 6 millibarns respectively, showing a greater preponderance of deuterons and tritons relative to protons than was the case in the yields of high energy singly charged particles.

It can be stated with some assurance that Li^8 is present as a residual nucleus, that the splitting of carbon into three alpha particles does occur with 90 Mev neutrons; and that carbon does split into two heavy fragments (Li , Li or α , Be).

He^6 was not identified in the cloud chamber experiment except in one questionable case of a $p, p, \text{He}^3, (\text{He}^4 \text{ or } \text{He}^6)$ four-prong star. However, a number of the particles designated by " α " in the cloud chamber results are undoubtedly He^6 or He^3 , particularly among the four prong stars.

The cross sections measured by Hadley and York have been verified and extended to encompass lower energy singly charged particles.

It is believed that the main objectives of this work have been reached. The cloud chamber method yielded a great deal more data of better quality than did the rotating disc method, but the latter could give some data not obtainable with the former. The only final limitations to the cloud chamber method are the skill and patience of the operator, while the rotating disc method has definite limitations as follows:

1. The high beam-on background. This could be reduced by arranging to count only between beam pulses.
2. The present errors in the short half-lives involved.
3. Cumulative errors involved in subtracting successive beta activity count rates.
4. Only reaction products with suitable lifetimes can be identified.

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TABLE I

POSSIBLE RADIOACTIVE PRODUCTS OF CARBON

Isotope	Activity	Half-Life	Maximum Beta Energy (Mev)	Remarks	Reference
B ¹²	β^-	0.022 $\pm$ 0.002 s 0.025 s 0.027 $\pm$ 0.002 s	13.46 $\pm$ 0.06		Becker and Gaerttner, Phys. Rev. <u>56</u> , 855 (1939) Hornyak and Lauritsen, Phys. Rev. <u>77</u> , 160 (1950) Jelly and Paul, Proc. Cam. Phil. Soc. <u>44</u> , 133 (1948)
Li ⁹	β^-	0.168 $\pm$ 0.004 s	$\sim$ 11		Knable, Phys. Rev. <u>83</u> , 1054 (1951)
B ⁸	β^+	0.65 s	13.7 $\pm$ 0.3		Alvarez, Phys. Rev. <u>80</u> , 519 (1951)
He ⁶	β^-	0.87 $\pm$ 0.06 s	3.7	no γ	Latham, Nature <u>159</u> , 367 (1947)
Li ⁸	β^-	0.89 $\pm$ 0.02 s	12.7	no γ	Hornyak and Lauritsen, Phys. Rev. <u>77</u> , 160 (1950)
C ¹⁰	β^+	19.1 $\pm$ 0.8 s	2.2 $\pm$ 0.1	γ 0.96 Mev	Sherr, Muether and White, Phys. Rev. <u>75</u> , 282 (1949)
C ¹¹	β^+	20.5 m	0.98	no γ	Solomon, Phys. Rev. <u>60</u> , 279 (1941) Townsend, Proc. Roy. Soc. A. <u>177</u> , 357 (1941)
Be ⁷	χ -cap	52.93 $\pm$ 0.22 d	0.48 (γ)	one γ per 10.7 disintegrations	Segrè and Wiegand, Phys. Rev. <u>75</u> , 39 (1949)
Be ¹⁰	β^-	2.5 x 10 ⁶ yr	0.56 $\pm$ 0.01	no γ	McMillan, Phys. Rev. <u>72</u> , 591 (1947)

TABLE II
CLOUD CHAMBER GAS STOPPING POWER

Gas	Partial Pressure in cms Hg	Molecular Stopping Power Relative to Air at STP	Partial Stopping Power
Methane	47.45	0.86	$47.45/76 \times 0.86 = 0.536$
Hydrogen	34.85	0.20	$34.85/76 \times 0.20 = 0.091$
Water Vapor	1.75	0.74	$1.75/76 \times 0.74 = 0.017$

total
pressure = 84.05

total
stopping power = 0.645

TABLE III
ASSUMED POSSIBLE FRAGMENTS OF CARBON STARS

Atomic Number	Isotopes
0	n^1
1	H^1 H^2 H^3
2	He^3 He^4 He^6
3	Li^6 Li^7 Li^8 Li^9
4	Be^7 Be^{8*} Be^9 Be^{10} Be^{11*}
5	B^8 B^{9*} B^{10} B^{11} B^{12}
6	C^{10} C^{11} C^{12} C^{13}

* Heavy-particle unstable

TABLE IV

600 rpm run data in counts per 3 minutes, corrected for beam intensity variation

θ_0 degrees	(1) Raw count	(2) Background, beam on	(3) ^{60}Co buildup count (calculated)	(4) $\text{Li}^8 - \text{He}^6 - \text{C}^{10}$ (speed converted)	(5) B^{12} activity (1-(2 - 3- 4))
45°	16102	5866	1178	1860	7198
67.5	12156	3343	964	1859	5810
90	10042	2648	710	1858	4826
112.5	8788	2421	460	1857	4048
135	7538	2149	144	1855	3390
225	7404	2080	1978	1845	1501
247.5	7415	2426	1880	1844	1269
270	7318	2690	1746	1842	1052
292.5	8059	3650	1616	1841	953
315	10658	6691	1309	1840	818

^{60}Co count: 5565 counts (background subtracted) in 10 minutes, taken 1 minute after beam off.
Beam was on 39.50 minutes.

TABLE V

60 rpm data in counts per 3 minutes, corrected for beam intensity variation

θ_0 degrees	(1) Raw count	(2) Background, beam on	(3) $\text{Cl}1$ buildup count (calculated)	(4) Remaining activities (1-(2 - 3))
45	11288	5866	1155	4267
67.5	7390	3343	950	3097
90	5972	2648	700	2624
112.5	5255	2421	450	2284
135	4580	2149	161	2271
225	5964	2080	1950	1934
247.5	5947	2426	1850	1671
270	6020	2690	1700	1630
292.5	6186	3650	1540	1547
315	9442	6691	1290	1461

$\text{Cl}1$ count: 5593 counts (background subtracted) in 10 minutes, taken 1 minute after beam off.
Beam was on 42.50 minutes.

TABLE VI

Absorption and Transmission Data

Activity	Max. Energy	Self-Absorption Factor		Counter Window Transmission Factor	Air Transmission Factor
		Single disc (143.5 mg/cm ²)	Double disc (287 mg/cm ²)		
B ¹²	13.43 Mev	0.97 ± 0.02	0.92 ± 0.02	0.995	0.999
Li ⁸	12.8 Mev	0.965 ± 0.02	0.915 ± 0.02	0.995	0.999
He ⁶	3.7 Mev	0.87 ± 0.03	0.69 ± 0.03	0.99	0.99
C ¹⁰	2.2 Mev	0.67 ± 0.03	0.485 ± 0.03	0.98	0.98
C ¹¹	0.98 Mev	0.328 ± 0.01	0.159 ± 0.01	0.955	0.951

TABLE VII

Results of Cloud Chamber Method. Cross sections expressed in millibarns (10⁻²⁷ cm²), normalized to the n-p cross section

Star	Number Found	Cross Section	No. of protons of energy over 20 Mev.	No. of deuterons of energy over 27 Mev.	No. of tritons of energy over 33 Mev.
Two prong:	557	125 ± 10	278	66	7
p B	422	95 ± 9	278		
d B	104	24 ± 4		66	
t B	16	3.6 ± 1.0			7
α Be	11 ± 2	2.5 ± 1.1			
Li Li	4 ± 2	0.9 ± 0.6			
(Unidentified Two Prong)	4)				
Three Prong:	318	71 ± 9	68	25	3
α α α	43	9.8 ± 2.0			
He ³ α α	5	1.1 ± 0.4			
p α Li	78	17.7 ± 2.5	30		
p He ³ Li	7	1.6 ± 0.6	1		
d α Li	46	10.5 ± 2.0		10	
d He ³ Li	2	0.4 ± 0.2			

Star	Number Found	Cross Section	No. of protons of energy over 20 Mev.	No. of deuterons of energy over 27 Mev.	No. of tritons of energy over 33 Mev.
t α Li	6	1.4 ± 0.5			
t He ³ Li	4	0.9 ± 0.4			
p p Be	28	6.3 ± 1.5	19		
p d Be	43	9.8 ± 2.0	12	11	
p t Be	13	2.9 ± 0.9	6		1
d d Be	25	5.7 ± 1.3		3	
d t Be	18	4.1 ± 1.0		1	2
Four Prong	151	34 ± 7	32	17	3
p p $\alpha\alpha$	29	6.6 ± 1.5	11		
p p He ³ α	2	0.4 ± 0.02			
p d $\alpha\alpha$	41	9.3 ± 2.0	10		
p d He ³ α	1	0.2 ± 0.2	1		
d d $\alpha\alpha$	25	5.7 ± 1.3		11	
d t $\alpha\alpha$	8	1.8 ± 0.6		2	1
d t He ³ α	5	1.1 ± 0.4		1	
p t $\alpha\alpha$	15	3.4 ± 1.0	4		1

Star	Number Found	Cross Section	No. of protons of energy over 20 Mev.	No. of deuterons of energy over 27 Mev.	No. of tritons of energy over 33 Mev.
p t He ³ α	2 2	0.4 ± 0.2	1		
p p p Li	1	0.2 ± 0.2	2		
p p d Li	7	1.6 ± 0.6	2		
p d d Li	5	1.1 ± 0.4		2	
d d d Li	1	0.2 ± 0.2			
p d t Li	7	1.6 ± 0.6	1	1	1
d d t Li	2	0.4 ± 0.2			
Five Prong	7	1.6 ± 0.6			
p p p d α	2	0.4 ± 0.2			
p p d d α	1	0.2 ± 0.2			
p d d d α	1	0.2 ± 0.2			
p d d t α	3	0.7 ± 0.3			
Total Stars	1033	232 ± 17	378	115	13
Heavy Fragments:					
B	542	120 ± 12			
Be	304 ± 4	79 ± 9	(This includes presumed Be ⁸ $\rightarrow$ 2 α)		

Star	Number Found	Cross Section	No. of protons of energy over 20 Mev.	No. of deuterons of energy over 27 Mev.	No. of tritons of energy over 33 Mev.
Li	170 ± 4	44 ± 7			
Singly Charged Particles:					
p	769	173 ± 15	378		
d	400	90 ± 10		115	
t	96	22 ± 6			13

TABLE VIII

SUMMARY OF REACTIONS

1. Production of Carbon Isotopes

<u>Reaction</u>	<u>Cross Section</u>	<u>Method</u>
$^{12}\text{C}(n;n)^{12}\text{C}$ (elastic scatt)	$275 \pm 50 \text{ mb.}^{(2)}$	Ref. (2)
$^{12}\text{C}(n;2n)^{11}\text{C}$	$22 \pm 4 \text{ mb.}^{(5)}$	Ref. (5)
$^{12}\text{C}(n;3n)^{10}\text{C}$	$0.67 \pm 0.50 \text{ mb.}$	Rot. Disc.

2. Production of Boron Isotopes (Two-Prong Stars)

	<u>Cloud Chamber Method</u>	<u>Rotating Disc Method</u>
$^{12}\text{C}(n;p)^{12}\text{B}$ $(n;p,n)^{11}\text{B}$ $(n;p,2n)^{10}\text{B}$ $(n;p,4n)^8\text{B}$	$95 \pm 9 \text{ mb.}$	$4.93 \pm 1.0 \text{ mb.}$
$^{12}\text{C}(n;d)^{11}\text{B}$ $(n;d,n)^{10}\text{B}$ $(n;d,3n)^8\text{B}$	$24 \pm 4 \text{ mb.}$	$< 1.0 \text{ mb.}$
$^{12}\text{C}(n;t)^{10}\text{B}$ $(n;t,2n)^8\text{B}$	$3.6 \pm 1 \text{ mb.}$	

3. Production of Be Isotopes (2 and 3 - prong Stars)

$^{12}\text{C}(n;2p,n)^{10}\text{Be}$ $(n;2p,2n)^9\text{Be}$ $(n;2p,4n)^7\text{Be}$	$6.3 \pm 1.5 \text{ mb.}$	
$^{12}\text{C}(n;d,p)^{10}\text{Be}$ $(n;d,p,n)^9\text{Be}$ $(n;d,p,3n)^7\text{Be}$	$9.8 \pm 2 \text{ mb.}$	$8.8 \pm 4.6 \text{ mb.}$
$(n;2d)^9\text{Be}$ $(n;2d,2n)^7\text{Be}$	$5.7 \pm 1.3 \text{ mb.}$	
$^{12}\text{C}(n;t,p)^9\text{Be}$ $(n;t,p,2n)^7\text{Be}$	$2.9 \pm 0.9 \text{ mb.}$	
$*^{12}\text{C}(n;t,d,n)^7\text{Be}$	$4.1 \pm 1.0 \text{ mb.}$	
$^{12}\text{C}(n;\alpha)^9\text{Be}$ $(n;\alpha,2n)^7\text{Be}$	$2.5 \pm 1.1 \text{ mb.}$	

4. Production of $\text{Be}^{8*} \rightarrow 2\alpha$

$^{*}\text{Cl}^{12}(\text{n};\alpha,\text{n})2\alpha$	$9.8 \pm 2.0 \text{ mb.}$
$^{*}\text{Cl}^{12}(\text{n};\text{He}^3,2\text{n})2\alpha$	$1.1 \pm 0.4 \text{ mb.}$
$^{*}\text{Cl}^{12}(\text{n};2\text{p},3\text{n})2\alpha$	$6.6 \pm 1.5 \text{ mb.}$
$^{*}\text{Cl}^{12}(\text{n};\text{p},\text{d},2\text{n})2\alpha$	$9.3 \pm 2.0 \text{ mb.}$
$^{*}\text{Cl}^{12}(\text{np}2\text{d},\text{n})2\alpha$	$5.7 \pm 1.3 \text{ mb.}$
$^{*}\text{Cl}^{12}(\text{n};\text{p},\text{t},\text{n})2\alpha$	$3.4 \pm 1.5 \text{ mb.}$
$^{*}\text{Cl}^{12}(\text{n};\text{d},\text{t})2\alpha$	$1.8 \pm 0.6 \text{ mb.}$

5. Production of Lithium Isotopes

$\left. \begin{array}{l} \text{Cl}^{12}(\text{n};3\text{p},\text{n})\text{Li}^9 \\ \text{Cl}^{12}(\text{n};3\text{p},2\text{n})\text{Li}^8 \\ \text{Cl}^{12}(\text{n};3\text{p},3\text{n})\text{Li}^7 \\ \text{Cl}^{12}(\text{n};3\text{p},4\text{n})\text{Li}^6 \end{array} \right\}$	$0.2 \pm 0.2 \text{ mb.}$	$< 1.0 \text{ mb.}$
$\left. \begin{array}{l} \text{Cl}^{12}(\text{n};\text{p},\text{He}^3)\text{Li}^9 \\ \text{Cl}^{12}(\text{n};\text{p},\text{He}^3,\text{n})\text{Li}^8 \\ \text{Cl}^{12}(\text{n};\text{p},\text{He}^3,2\text{n})\text{Li}^7 \\ \text{Cl}^{12}(\text{n};\text{p},\text{He}^3,3\text{n})\text{Li}^6 \end{array} \right\}$	$1.6 \pm 0.6 \text{ mb.}$	
$\left. \begin{array}{l} \text{Cl}^{12}(\text{n};\text{p},\alpha)\text{Li}^8 \\ \text{Cl}^{12}(\text{n};\text{p},\alpha,\text{n})\text{Li}^7 \\ \text{Cl}^{12}(\text{n};\text{p},\alpha,2\text{n})\text{Li}^6 \end{array} \right\}$	$17.7 \pm 2.5 \text{ mb.}$	$0.82 \pm 0.42 \text{ mb.}$
$\left. \begin{array}{l} \text{Cl}^{12}(\text{n};\text{d},\text{He}^3)\text{Li}^8 \\ \text{Cl}^{12}(\text{n};\text{d},\text{He}^3,\text{n})\text{Li}^7 \\ \text{Cl}^{12}(\text{n};\text{d},\text{He}^3,2\text{n})\text{Li}^6 \end{array} \right\}$	$0.4 \pm 0.2 \text{ mb.}$	
$\left. \begin{array}{l} \text{Cl}^{12}(\text{n};2\text{p},\text{d})\text{Li}^9 \\ \text{Cl}^{12}(\text{n};2\text{p},\text{d},\text{n})\text{Li}^8 \\ \text{Cl}^{12}(\text{n};2\text{p},\text{d},2\text{n})\text{Li}^7 \\ \text{Cl}^{12}(\text{n};2\text{p},\text{d},3\text{n})\text{Li}^6 \end{array} \right\}$	$1.6 \pm 0.6 \text{ mb.}$	
$\left. \begin{array}{l} \text{Cl}^{12}(\text{n};\text{p},2\text{d})\text{Li}^8 \\ \text{Cl}^{12}(\text{n};\text{p},2\text{d},\text{n})\text{Li}^7 \\ \text{Cl}^{12}(\text{n};\text{p},2\text{d},2\text{n})\text{Li}^6 \end{array} \right\}$	1.1 ± 0.4	
$\left. \begin{array}{l} \text{Cl}^{12}(\text{n};\text{d},\alpha)\text{Li}^7 \\ \text{Cl}^{12}(\text{n};\text{d},\alpha,\text{n})\text{Li}^6 \end{array} \right\}$	$10.5 \pm 2.0 \text{ mb.}$	
$\left. \begin{array}{l} \text{Cl}^{12}(\text{n};\text{t},\text{He}^3)\text{Li}^7 \\ \text{Cl}^{12}(\text{n};\text{t},\text{He}^3,\text{n})\text{Li}^6 \end{array} \right\}$	$0.9 \pm 0.4 \text{ mb.}$	
$\left. \begin{array}{l} \text{Cl}^{12}(\text{n};3\text{d})\text{Li}^7 \\ \text{Cl}^{12}(\text{n};3\text{d},\text{n})\text{Li}^6 \end{array} \right\}$	$0.2 \pm 0.2 \text{ mb.}$	
$\left. \begin{array}{l} \text{Cl}^{12}(\text{n};\text{p},\text{d},\text{t})\text{Li}^7 \\ \text{Cl}^{12}(\text{n};\text{p},\text{d},\text{t},\text{n})\text{Li}^6 \end{array} \right\}$	$1.6 \pm 0.6 \text{ mb.}$	

$\text{Cl}^{35}(\text{n}; \text{Li}^6) \text{Li}^7$
 $\text{Cl}^{35}(\text{n}; \text{Li}^6, \text{n}) \text{Li}^6$

$0.9 \pm 0.6 \text{ mb.}$

$^*\text{Cl}^{35}(\text{n}; \text{t}, \alpha) \text{Li}^6$
 $^*\text{Cl}^{35}(\text{n}; 2\text{d}, \text{t}) \text{Li}^6$

$1.4 \pm 0.5 \text{ mb.}$

$0.4 \pm 0.2 \text{ mb.}$

*Denotes unambiguous reactions.

TABLE IX

YIELD OF HEAVY FRAGMENTS

Fragment	Cross Section, Rotating Disc Method	Cross Section, Cloud Chamber Method
C ¹⁰	0.67 ± 0.50 mb.	---
B ¹²	4.93 ± 1.0 mb.	---
B ¹¹	---	} 118 ± 13 mb.
B ¹⁰	---	
B ⁸	<1.0 mb.	
Be ¹⁰		6.8 ± 1.6 mb.
Be ⁹	---	15 ± 3.5 mb.
Be ^{8*} ($\rightarrow 2\alpha$)	---	26 ± 4 mb.
Be ⁷	8.8 ± 4.6 mb.	14.5 ± 4.3 mb.
Li ⁹	<1.0 mb.	0.2 ± 0.2 mb.
Li ⁸	0.82 ± 0.42 mb.	3.4 ± 1.4 mb.
Li ⁷	---	} 40 ± 7 mb.
Li ⁶	---	
He ⁶	2.54 ± 0.96 mb.	---

Fig. 1
Rotating disc apparatus, right view.

ZN381

Fig. 2

Rotating disc apparatus, left view.

Fig. 3

Exploded view of counting tube and shield.

MU3960

Fig. 4

General setup of rotating disc experiment.

SHADED AREA REPRESENTS INSTANTANEOUS EFFECTIVE BOMBARDED REGION
 INNER CIRCLE REPRESENTS INSTANTANEOUS EFFECTIVE COUNTED REGION
 OUTER CIRCLE REPRESENTS BEAM SIZE AT ROTATING DISC

MU3955

Fig. 5

Bombarded area diagram.

MU3956

Fig. 6
Idealized rotating disc diagram.

Fig. 7
Theoretical B^{12} activity at various disc speeds.

Fig. 8

Theoretical $\text{Li}^8 + \text{He}^6$ activity at various disc speeds.

Fig. 9
Theoretical $B^{12} + Li^8 + He^6$ activity at various disc speeds.

MU3966

Fig. 10

Data and calculation flow chart.

Fig. 11

Typical 600 rpm run data.

MU3963

Fig. 12

Typical background data.

Fig. 13

Typical 60 rpm run data.

Fig. 14
Cl¹¹ self-absorption curve.

ZN 246

Fig. 15

General view of cloud chamber apparatus.

MU3965

Fig. 16

Graphic integration of n-p cross section curve.

MU3953

Fig. 17

Energy distribution of high energy deuterons.