CROSS SECTION MEASUREMENTS FOR THE PRODUCTION OF ACTIVITIES BY 14-MEV NEUTRONS

by

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INTRODUCTION

The cross sections for various neutron-induced reactions are important in the formulation of nuclear theories. If a reaction leads to the formation of an unstable isotope, the resulting radioactivity provides a possible means for determining the cross section. In particular if there are beta particles emitted from the product nucleus, they may be counted in order to determine the total number of active atoms present. The cross section for the formation of these active atoms can then be found from a knowledge of the neutron flux, sample weight, etc.

A program of cross section measurements was undertaken using 14-Mev neutrons from the D T reaction. This reaction provides monoenergetic neutrons whose flux can be accurately determined. The activities of the product nuclei were measured by beta-counting. In many cases no beta particles are emitted, either because the product nucleus is stable or because an unstable nucleus decays by K-capture or gamma ray emission. In this event beta-counting is not applicable and the methods which can be used are outside the scope of this investigation.
NEUTRON SOURCE

I. Description of the Accelerator

The neutrons used in this experiment were produced by the 250-kv Cockcroft-Walton accelerator at the Los Alamos Scientific Laboratory. The machine is of conventional design and is similar to the original model made by Cockcroft and Walton (4, pp. 619-630). This accelerator was constructed at the University of Illinois and a description of its earlier form has been published (11, pp. 587-597). The high potential is obtained from a transformer and a voltage quadrupler. An ion source and associated equipment are located at the high potential end of the accelerating tube for the purpose of supplying the deuterium ions to be used as bombarding particles. Power for this equipment is provided by a generator-set insulated from ground and driven by a long belt. Deuterons from the ion source are accelerated by the potential across the accelerating tube toward the target at ground potential. The deuteron beam is separated into its various mass components by an analyzing magnet which bends the desired beam through an angle to allow it to reach the target.

The general features of the machine can be seen in figures 1 and 2. Figure 1 shows the high voltage supply and vertical accelerating tube, and figure 2 shows the beam-
analyzing magnet and target assembly which are on the floor above the accelerating tube. The beam is well focussed so that it is only about 3 mm in diameter at the target and a limiting diaphragm confines its excursions to a region 7 mm in diameter on the target face.

The target consists of tritium absorbed in a thin layer of zirconium fused to a tungsten backing. The zirconium takes up tritium in the approximate ratio of one atom of tritium per atom of zirconium. This produces a relatively high concentration of tritons in a small volume. The method for preparation of these targets has been described in the literature (7, pp.579-582). The incident deuterons penetrate into the zirconium foil and interact with the absorbed tritons according to the following reaction:

\[
\text{H}^2 + \text{H}^3 \rightarrow \text{He}^4 + n + 17.6 \text{ Mev.}
\]

The high energy (~ 14 Mev) neutrons resulting from the reaction are then used as primary bombarding particles for various experiments. That is to say, the accelerator utilizes the D + T reaction to produce a strong source of monoenergetic neutrons. It is these neutrons, rather than the accelerated deuterons themselves, which are used for experimental purposes. The major portion of the neutron energy is, of course, obtained from the energy released by the reaction and not from the bombarding deuterons. A convenient method for determining the
number of neutrons is provided by the alpha particles from the reaction. Since there is one alpha particle for each neutron, one needs only to determine the number of alpha particles to obtain the neutron yield. High efficiency and excellent accuracy are easily achieved in alpha-counting.

II. Collision Mechanics for the Reaction

In order to find the neutron energy and flux, one must take into account the effects of the bombarding deuteron energy on the energy and angular distribution of the number of neutrons and alpha particles. The problem is one of an inelastic collision, inasmuch as kinetic energy of the fragments derives from the disintegration of the compound nucleus as well as from the kinetic energy of the bombarding deuteron. The additional energy supplied is the $Q$ of the reaction and is produced by a decrease in the total rest mass of the particles in the reaction. This mass change is small and may be neglected when making momentum calculations.

Momentum considerations show that the compound nucleus, consisting of the combined $H^2$ and $H^3$ nuclei, is in motion relative to the laboratory system of coordinates. The calculations are simplified if the reaction is first considered in the moving center-of-mass system of coordinates and then transformed into the stationary
laboratory coordinate system. In this way the momentum of a particle in the laboratory system is composed of two components. One of these is the momentum resulting from the velocity of the center-of-mass in the laboratory and the second is the momentum of the particle in the center-of-mass system itself.

The details of the solution to the problem have been published in the literature and only the results will be presented here. The reader is referred to a summary article by Hanson, Taschek, and Williams (9, pp.635-650) in which various reactions useful for the production of monoenergetic neutrons are considered. This article includes a discussion of the D + T reaction along with the general equations for reactions of this type.

Conservation of momentum and energy, including the reaction energy $Q$, lead to the following expression for the neutron energy as a function of the angle in the laboratory system:

$$E_3 = A_3^2 (\cos \theta_3 \pm \sqrt{r_3^2 - \sin^2 \theta_3})^2,$$

where

$$A_3 = \frac{\sqrt{m_1 m_3}}{(m_1 + m_2)} \sqrt{E_1}, \quad (2)$$

$$r_3 = \frac{B_3}{A_3}, \quad (3)$$

$$B_3 = \frac{m_2 m_4}{(m_1 + m_2)} \sqrt{E_1 - E_{th}}, \quad (4)$$
Equation (1) can be modified to give the energy of the alpha particles by substituting the proper subscripts.

Similarly, considerations of the differential solid angles in the center-of-mass system and the laboratory system lead to the following expression for the relation between the angular distributions of the neutrons in the two systems:

\[
\frac{I_{\text{cm}}}{I_{\text{lab}}} = \cos (\phi_3 - \theta_3) \frac{m_2 m_4}{(m_1 + m_2)} E_1 - E_{\text{th}} \frac{E_3}{E_1 - E_{\text{th}}},
\]

where

- \(I_{\text{cm}}\) = number of neutrons per unit solid angle in the center-of-mass system,
- \(I_{\text{lab}}\) = number of neutrons per unit solid angle in the laboratory system,
- \(\phi_3\) = angle in the center-of-mass system corresponding to the laboratory angle \(\theta_3\) described above.
The angle $\phi_3$ can be found from the equation,

$$\sin \phi_3 = \frac{E_3}{E_3'} \sin \theta_3.$$

(7)

The angular distribution for the alpha particles can be found by substituting the proper terms in equation (6). From these equations we can calculate the number of neutrons at one laboratory angle from the number of alpha particles counted at another angle, provided that the angular distributions of these particles in the center-of-mass system are known. It has been shown (1, pp. 500-502) that the product particles from the $\text{D} \rightarrow \text{T}$ reaction are isotropically distributed in the center-of-mass system for the low bombarding energies used in this machine. Thus the angular distributions of both the alpha particles and the neutrons can be readily calculated for any bombarding energy $E_1$.

III. Determination of the Neutron Yield

Equations (1) and (6) apply to the case of a thin target in which deuterons of only one energy are present. For thick targets such as those used in this accelerator the deuterons traverse their total range in the target material and as a result there are deuterons of every energy below the maximum bombarding energy in the target. The number of neutrons produced by the deuterons in each
energy interval will not be constant, since the cross section for the D + T reaction is not a constant as a function of energy. To find the number of particles at a particular angle in the laboratory system, an integration of equation (6) must be performed over all deuteron energies present in the target with an appropriate weighting factor for the number of reactions taking place at each energy. An analytic solution is not feasible because of the nature of the factors involved. However a numerical solution of sufficient accuracy can be obtained by dividing the energy spectrum into 10-kev intervals and making the calculations on the basis of the values of these factors in the middle of each interval. These results are then summed to find the desired integrals. The weighting factor for each interval can be expressed formally as follows:

\[ F(E) = N S(E) \sigma(E) \]  

(\text{8})

where

\[ N \] = number of target tritium nuclei per cm\(^3\),  
\[ S(E) \] = distance travelled by the deuteron in the energy interval involved,  
\[ \sigma(E) \] = average cross section in cm\(^2\) for the D + T reaction in the energy interval involved.

Both \( S \) and \( \sigma \) are functions of the deuteron energy and must be known from other measurements. The cross section \( \sigma(E) \) has been obtained from thick target yields on heavy
ice (D₂O) targets using tritons as bombarding particles (2, pp. 1154-1160). The function S(E) is not known for zirconium-tritium targets but is considered constant in the calculations. Consideration of the behavior of S(E) for other materials leads to the conclusion that this assumption does not introduce much error.

It is apparent that the neutrons at any particular angle in the laboratory are not monoenergetic but have a spread in energy corresponding to the continuous spectrum of deuteron energies in the target. This energy spread can be minimized by proper selection of the laboratory angle at which the neutrons are used. It can be shown that this angle is very nearly 90°. Hence the activations were made using as nearly as possible only those neutrons in a plane through the target and normal to the incident deuteron beam.

If the alpha particles in the reaction were left in an excited state the equations would be incorrect since some of the energy Q would not be available for kinetic energy of the two fragments. This would result in a group of neutrons of reduced energy. By measurement of the tracks of recoil protons in photographic emulsions, the neutron spectrum has been investigated (8) for evidence of such a group but none was found. The spectrum shows only a well-defined group at 14.3 Mev having a width at half maximum of 750 kev. This spread
in the measured energy is due almost entirely to resolution of the measurements and is greater than the calculated spread in neutron energy.

The schematic arrangement of the target and alpha-counter used to monitor the neutron flux is shown in figure 3. The alpha particles are counted by a proportional counter at 135° from the direction of the incident deuteron beam. The target is inclined at 45° to the incident beam so that the alpha particles reaching the monitor counter leave the target along the normal to its face. These alpha particles have an energy of about 3 Mev compared to the deuteron energy of only 125 kev so that even those alphas produced at the extreme range of the deuterons can easily leave the target. The energy lost in the counter window is approximately 2 Mev.

Pulses from the counter, after amplification, are counted by a scaling unit which is equipped with an adjustable discriminator for selecting the minimum pulse size to be recorded. In addition to pulses from the alpha particles entering the counter, some background pulses will be produced by neutron interactions with the counter materials. Most of these background pulses will be smaller than those from the alpha particles. Their number is easily determined by placing a shutter in front of the counter to stop the alpha particles. This
ARRANGEMENT OF TARGET AND ALPHA COUNTER

FIG. 3
Pulse Height Distribution in Alpha Monitor Counter

A - Background
B - Alpha Particles

FIG. 4
will not affect the neutron flux appreciably and the number of background counts can be found. The resulting spectrum of pulse heights in the counter is shown in figure 4. The effect of background pulses can now be compensated for by setting the discriminator on the recording scaler to count only pulses larger than some value \( V \). \( V \) is chosen so that the number of background pulses above \( V \) is roughly equal to the number of alpha pulses below \( V \). The error remaining in the alpha-count is negligible since less than 1% of the alpha pulses are below \( V \). Thus the alpha monitor setting is reproducible to better than 1%. Possible sources of error in the flux calculations are as follows: uncertainty in the shape of the curve representing \( \sigma(E) \), incorrect values of the rate of deuteron energy loss in the target, reduction of the deuteron energy by deposits on the target face, and non-uniform distribution of the tritium in the zirconium. These effects are believed to introduce less than 2% error in the flux measurement. Therefore, both the flux and neutron energy are well known.
BETA-COUNTING

I. Properties of Beta Particles

Beta particles going through matter suffer numerous collisions, both elastic and inelastic, which may cause large changes in their direction. The resulting path of the beta particle is tortuous and subject to large statistical variations. Furthermore the energy loss in a single inelastic collision may amount to nearly the total energy of the particle or may be relatively small.

Beta particles do not exhibit a well-defined range since the path length in traversing a given thickness of material will vary greatly, depending on the number of scattering events taking place. The effects of scattering and energy losses make the mathematical treatment of beta-ray absorption difficult if not impossible.

Experimentally it is found that the combination of scattering and energy loss produces a roughly exponential absorption curve for continuous beta-ray spectra. It should be emphasized that the measured curve is rarely straight on a semi-logarithmic plot and depends considerably on the particular geometry and equipment employed. The absorption curve deviates from the exponential law at larger absorber thicknesses and the observed net counting rate approaches zero. The value of the absorber at zero counting rate is called the range of the beta particles.
The range-energy relationship has been determined (6, pp.12-32) using beta-ray energies found from electron spectrometers and can be used to determine the energy of an unknown beta-ray by interpolation.

In the case of monoenergetic beta-rays the absorption curve is nearly a straight line when plotted using linear coordinates. The range in this case is found by extrapolating the absorption curve to zero counting rate.

II. Absolute Beta-Counting

The problems of absolute beta-counting, that is, the determination of total number of beta-decays per unit time in a sample, have been discussed in considerable detail by Zumwalt (14, pp.1-127) and others (3, pp.28-43). For clarity some of the more pertinent difficulties will be reviewed here. The types of counters to be considered are the end-window Geiger counter and the side-window proportional counter.

Zumwalt has given the expression for the beta counting rate from a radioactive sample as:

$$c/m = d/m f_c f_{w} f_{A} f_{H} f_{B} f_{S} G,$$  \(\text{(9)}\)

where:

- \(c/m\) = observed counting rate in counts per minute,
- \(d/m\) = disintegration rate of the sample in disintegrations per minute,
- \(f_c\) = counting loss factor,
- \(f_w\) = window and air absorption factor
\[ f_A = \text{effect of scattering in the air between the source and the counter window}, \]
\[ f_H = \text{effect of scattering from the walls of the counter shield or housing}, \]
\[ f_B = \text{backscattering factor}, \]
\[ f_S = \text{self-scattering and absorption factor}, \]
\[ G = \text{geometry factor}. \]

Each of these factors must be evaluated before the disintegration rate of the sample can be determined. It has been shown (14, pp.1-12) that when all factors are carefully evaluated the geometry factor \( G \) is independent of the beta-ray energy over a wide range of energies and that \( G \) closely approaches the value of the solid angle between source and detector.

The counting losses are caused by the occurrence of two events in the counter separated by less than the resolving time of the counter and counting circuit. In the case of the Geiger tube the counter itself is usually the limiting element in the circuit while for a proportional counter the associated electronic equipment may be responsible. In any event the extent of these losses will be a function of the counting rate and can be determined with sufficient accuracy by the multiple addition of small sources. In this method a number of sources of low activity are counted individually and then simultaneously. In general the number of counts per
minute when the sources are counted together will be less than the sum of the individual counting rates. The difference represents the counts lost by coincidences. Since such coincidences are statistical in nature, it is reasonable to assume the following relationship between the observed number of counts \( N_0 \) and the actual number of particles \( N_a \) entering the counter per unit time:

\[
f_c = \frac{N_0}{N_a} = e^{-N_aT},
\]

(10)

where \( T \) is the resolving time of the counter circuit. By taking several combinations of small sources the value of \( T \) can be found and a correction curve calculated. However, the resolving time, \( T \), is subject to some fluctuation and corrections of more than 10% should be avoided. With this limitation in mind, the value of \( f_c \) can be relied upon to considerably better than 1%.

The factor \( f_w \) for absorption of beta particles in the window may be determined by extrapolating an absorption curve to zero total absorber thickness. This can be done with good accuracy if the following conditions are met:

1. The absorbers used must be kept as close as possible to the window so that the scattering in the absorbers will approach as nearly as possible the scattering produced by the
window itself.

2. The absorber material should have as nearly as possible the same atomic number as the window. Aluminum is generally used even with mica windows although mica absorbers might be better.

3. The sensitive volume of the counter should be as close as possible to the counter window. Otherwise the effects of scattering in the window will give erroneous results when beta-rays of different energies are compared.

4. The window should be as thin as possible to avoid the necessity for long extrapolations of the absorption curve.

5. The window should have a conducting layer on it to avoid disturbances of the electric field in the counter when conducting absorbers such as aluminum are used.

With a thin window and moderately energetic beta particles ($E > 1$ Mev) the window absorption is only a few percent and hence $f_w$ is not subject to much error. With weaker beta rays the problem is more acute and very thin windows should be used. The absorption in the air between the sample and the window is usually included in $f_w$ by simply increasing the window thickness, expressed in $\text{mg/cm}^2$, by an amount corresponding to the mass per unit
area of the air involved. Since the mass absorption coefficient for beta-rays is relatively independent of the atomic number Z at low Z, this method is justified. However, this treatment is correct only for an absorber at the counter window and does not take into account the effect of scattering by the air near the source.

The effect of air-scattering, necessitating the factor $f_A$, may be treated as a separate effect which tends to increase the observed counts by scattering into the counter particles which would otherwise miss it. Those scattered out of the counter by the air are included in $f_w$ as mentioned above and may be considered as being absorbed. $f_A$ can be evaluated by the use of thin films of low Z material placed between the source and the counter. The effect of such a film can be found for various positions and the integrated effect found. A suitable density correction can then be applied and the effect of the air calculated. However, the effect is small and may be ignored for samples close to the window.

Likewise the effect of scattering by the housing giving rise to $f_H$ can be made negligibly small by placing the source close to the counter window. Since there are other reasons for counting in this position, $f_H$ need not be evaluated, but can be taken as equal to 1.00. If counting is to be done with the source far from the window, $f_H$ can be minimized by using a lining of low Z...
for the housing.

The backscattering factor $f_B$ is needed to correct for beta particles which start in the direction away from the counter but encounter the sample support and are scattered through approximately $180^\circ$ and enter the counter. The backscattering factor can be quite large for high $Z$ materials (i.e., $f_B = 1.3$ for Pt). Fortunately it is practically independent of the beta-ray energy over a wide range so that a determination of $f_B$ for a particular backing material at one beta-ray energy can be used for other beta-ray energies without introducing large errors.

The magnitude of this effect can be found by counting a sample first with a practically massless backing and then with a thick backing of some material. The ratio of these counting rates is then the backscattering factor $f_B$. The exact value of $f_B$ can only be found if the factor $f_w$ is evaluated for the backed and unbacked cases since the spectrum of backscattered beta-rays is degraded. Furthermore the value of $f_B$ will be strictly correct only if the source is too thin to exhibit self-scattering, otherwise the self-scattering will alter the number of particles entering the backing and a separate determination will have to be made for each source thickness. These difficulties can be avoided by using thin
Zapon films for sample supports in which case back-scattering is negligible and $f_B$ equals unity.

The self-scattering and absorption factor $f_s$ is a troublesome one whenever the beta-ray source has any appreciable thickness. Unlike the case for external absorbers, the absorbing material is intimately mixed with the active atoms. Beta particles starting near the front surface encounter very little material and a large fraction of them will leave the sample with few or no collisions. Those starting near the back will penetrate considerably more material and suffer more collisions. Some leaving the front surface in a direction opposite to the counter will be scattered through 180° and eventually reach the counter.

If the radiation from each differential layer is assumed to be absorbed exponentially by the material between it and the counter then the effective transmission of the sample can be found by integration over the sample thickness. This leads to the equation:

$$T = \frac{1 - e^{-\mu d}}{\mu d}, \quad (11)$$

where

$T = $ transmission,

$\mu = $ mass absorption coefficient $(\text{cm}^2/\text{mg})$,

$d = $ "thickness" of the sample $(\text{mg/cm}^2)$.

Presumably $\mu$ can be found by some other measurement such
as an absorption curve taken with absorbers between the source and the counter.

Unfortunately this equation is applicable only to very special cases usually not encountered in practice. The beta particles scattered in a flat sample do not emerge isotropically distributed in space but are in general concentrated along the normal to the sample surface. This has been demonstrated both by direct measurement (5, pp.282-290) and by self-scattering measurements to be discussed later. The effect is known as "self-focussing" and is produced by scattering action in the sample. Beta particles proceeding in the direction normal to the plane of the sample have a relatively high probability of leaving without scattering while those proceeding in the plane of the sample must traverse much more material before emerging and hence have a higher probability of being scattered. Of these latter some will be scattered into the direction normal to the sample.

Furthermore, the solid angle in the region of the plane of the sample is much larger than that for the region near the normal to the sample. The result of the path length effect and solid angle effect is to produce a concentration of beta particles in the direction normal to the sample surface and a corresponding reduction of the number of beta particles in the plane of the sample.
It is immediately apparent that the measured activity of such a sample is dependent on the solid angle subtended by the counter even after the geometry factor has been taken into consideration. That is to say, a counter on the normal to the sample will receive relatively more particles per unit solid angle if it has a small solid angle than if it has a large solid angle. The correct average number of particles per unit solid angle can be obtained either by counting over one or two complete hemispheres (2π or 4π steradians) or by making corrections for the asymmetry effect if some other counting geometry is used. If 2π (or 4π) counters are used, presumably equation (11) can be used for self-absorption corrections although there still remains the questionable assumption of exponential absorption in the sample.

For smaller solid angles such equations are not only quantitatively but qualitatively incorrect. This can be demonstrated experimentally in the following way. If a series of thin foils of equal areas but having different thicknesses are given equal irradiations, the resulting activity will be uniformly distributed throughout the material, that is, the number of active atoms per milligram of material will be a constant. These foils may then be counted in some fixed geometry to obtain a plot of the apparent specific activity \( \frac{c/m}{mG} \) as a
function of source thickness (mg/cm²). The limit of such a plot, as the source thickness approaches zero, should give the true value of the specific activity since both scattering and absorption will be zero. The counting rate will also be zero of course and the limit must be found by extrapolation. Experimentally it is found that for geometries less than $2\pi (G = 50\%)$ these curves show an increase in specific activity with increasing source thickness in the region of thin sources. This increase is attributed to the growth of the self-focussing effects mentioned above. As the source thickness is increased the scattering effects reach equilibrium and the curve turns downward as absorption becomes increasingly important. For thick sources the curve follows the equation (11) fairly closely.

Qualitatively it is reasonable that forescattering effects should reach equilibrium before absorption effects become large since the beta particles causing the increase in the normal direction are those which originally made oblique paths through the source and hence have a higher probability of being scattered than those leaving along the normal to the source. As the source is made thicker, multiple scattering becomes more important until the problem becomes one of diffusion after which no further change in angular distribution is to be expected. The process of inelastic collision will then produce the
approximately exponential absorption curve until the thickness approaches the beta-ray range. The magnitude of these self-focussing effects will be dependent on the solid angle, or geometry, of the counter as seen from the source position. For large solid angles approaching $2\pi$ steradians the effect will be zero while for low solid angles the effect will be quite pronounced.

The results of a series of such measurements in four different geometries are shown in figure 5. The activity used was that of Cu$^{62}$ produced by the (n,2n) reaction in Cu$^{63}$. The beta particles from Cu$^{62}$ have a maximum energy of about 2.9 Mev so that fairly large thicknesses can be used and still show the details of the early portion of the curve. Because of the short half-life of Cu$^{62}$ three separate activations were made and the proportional counter data were used to normalize the data from the three Geiger counter geometries. Additional curves were obtained in the region of thin sources for several elements and in every case the agreement obtained between the extrapolated values in the different geometries was within the experimental error of about 5%. In those cases where the half-lives were long, no normalization was necessary since the same activation was used to obtain all four curves. From these data it can be concluded that the extrapolations are essentially correct.
Self Scattering Curves $^{62}$Cu Betas in Copper Foils

1 - $G = 4.5\%$
2 - $G = 13\%$
3 - $G = 23\%$
4 - $G = 47\%$

FIG. 5
since the individual curves differ considerably in shape, yet extrapolate to the same value at zero thickness.

It is apparent that the value obtained by the application of equation (11) is quite erroneous, being high by a factor of more than 2.0 in the case of the 4.5\% geometry. Certainly in some combinations of source thickness and geometry it would be much better to make no self absorption correction at all. This effect is not confined to energetic beta particles, but has even been demonstrated (13, pp.1099) for the 155-kev beta-ray of Cl\textsubscript{4} in BaCo\textsubscript{3}. In this case equation (11) gives an extrapolated value of specific activity which is too high by a factor of approximately 1.4.

Since no analytical solution for the self-focussing effect exists to date, there are three possible methods for obtaining the true specific activity of a sample. First if specific activity is high enough it may be possible to use sufficiently thin sources to make the self-scattering and absorption negligible in which case \( f_s \) equals unity. Second, if a \( 2\pi \) or \( 4\pi \) counter is used the self-focussing will not affect the results and only absorption corrections need be made and equation (11) may be a sufficiently good approximation. Third, if a thick source is to be counted in a geometry less than \( 2\pi \), a curve similar to one of those in figure 5 can be
obtained experimentally and extrapolated to zero source thickness. In this case the difficulty is minimized by using as high a geometry factor as possible since the curve then approaches the axis almost horizontally making the extrapolated value less subject to error.

Thus all the factors involved in absolute beta-counting are subject to direct measurement under the proper circumstances except the geometry factor G. This must be determined either by calibration with some beta ray standard or can be calculated approximately from the spatial relationship between source and detector. It is perhaps best to make an experimental measurement of G and compare this to the calculated value. Any large disagreement may indicate a counter of low efficiency or poorly defined sensitive volume. The method used for this work is described in detail in the section on counter calibration.

III. Calibration of the Counters

The first step in absolute beta-counting is the calibration of the counters to be used. To do this one needs a standard source of beta particles of known disintegration rate. This standard is then counted in some reproducible location in the counting arrangement. From beta-absorption curves the effect of window absorption $f_w$
can be found by extrapolating these curves to zero absorber thickness.

The counting losses can be found by the multiple addition of small sources as previously mentioned. If the beta-ray standard is very thin and is mounted on a thin backing, no scattering corrections need be applied. Then from the equation (9) the geometry factor $G$ can be found:

$$G = \frac{c/m}{d/m \cdot f_w \cdot f_c},$$

assuming scattering from the air and the housing is negligible. If the beta-ray standard is mounted on a heavy backing and has appreciable self-thickness, then both the backscattering factor $f_B$ and the self-scattering factor $f_s$ will have to be evaluated in some way.

Two counters were used in this work. One was a Tracerlab end-window Geiger counter, type TGC-2, mounted in a vertical lead shield. The electronic equipment consisted of a high voltage supply, a discriminator adjusted to accept only pulses greater than 0.6 volts, and a scaler with a register for counting the pulses, all of which were combined on a single chassis. A six-foot coaxial cable connected the chassis to the counter tube. The samples to be counted were supported by a removable shelf which fit into several positions below
the counter window. The counter was of the argon-alcohol type and was filled to a pressure of about 50 cm of mercury. The end window was mica of 1.9 mg/cm² thickness and had a light coating of Aquadag to make it conducting. Measurements of the counting losses indicated resolving time of $6.9 \times 10^{-6}$ minutes with the six-foot coaxial cable attached. The counting losses were therefore 1% at an observed counting rate of 1420 c/m. These losses could be reduced by about a factor of two if desired by the use of shorter cables or by using a preamplifier at the counter.

The other counter, made by the author, was a brass side-window proportional counter lined with chromium. The filling gas was tank methane flowing through the chamber at atmospheric pressure. The window was rubber hydrochloride of 0.5 mg/cm² thickness and had graphite rubbed into it to make it conducting. The electronic equipment used with this counter consisted of four separate units; a regulated high voltage supply for the counter voltage, a preamplifier mounted as close as possible to the counter, an amplifier for the pulses from the preamplifier and finally a scaling unit having an adjustable discriminator so that only pulses greater than some chosen size would be recorded in the scaler and mechanical register. Counting loss measurements on this
unit showed losses of less than 1% at 50,000 c/m so no corrections were made to the observed rates which were always considerably less than 50,000 c/m.

IIIA. Properties of the Proportional Counter

Extensive tests were made in order to show that a proportional counter could be made to operate in a suitable way for absolute beta-counting. The requirements are that there should be a well-defined sensitive region in which all beta particles are counted with essentially 100% efficiency regardless of their energy. If this condition is not met, the geometry factor $G$ will not be independent of the energy of the beta particles and a calibration at one beta-energy will be insufficient.

In a Geiger counter this condition is readily obtained by using the proper filling gases at moderately high pressures. This insures high ionization density so that the probability of a beta particle traveling any appreciable distance without causing a count becomes extremely small. Since all counts cause pulses of nearly the same size in a Geiger counter and these pulses are very large, there is no difficulty in recording them without losses other than coincidence losses.

In a proportional counter, however, there is a complete spectrum of pulses corresponding to the spectrum of the beta particles being counted. The spectrum will
be modified by the counter geometry since some beta particles will not lose all their energy in the counter but will strike the walls. In any event there will be pulses produced ranging from some maximum size all the way down to zero in the case of low gas multiplication. If the gas multiplication is made sufficiently high, single electrons will be counted and the condition approaches that of the Geiger counter. Unfortunately Geiger counter action is an unstable condition so that spurious pulses or breakdowns may occur when the counter voltage is high enough to give large gas multiplication. There is also a lower limit to the pulse height that may be accepted by the discriminator. It is necessary to set the discriminator somewhat above the noise level in the circuits since the noise pulses are orders of magnitude more numerous than the desired pulses. Furthermore, there is a maximum pulse size that can be handled by the amplifier without serious overloading. If this amplitude is exceeded, the amplifier will be paralyzed for a considerable length of time following each pulse and the counting losses will become excessive. During recovery from such an overloaded condition there may be several transients which can cause spurious counts in the recording scaler.

The problem then is to find a combination of counter
voltage, amplifier gain, and discriminator setting which will separate the desired pulses from background noise without instability in the counter or overloading in the amplifier. To determine if this condition was attained, a pulse height distribution was obtained for RaE beta particles in the counter. This can be done by changing the discriminator on the scaler by small increments and observing the change in counting rate from a RaE standard. A histogram was obtained showing the number of pulses between any two discriminator settings. The discriminator settings were calibrated in terms of pulse height from the counter by use of a standard pulser connected to the counter wire. By extrapolating the distribution curve to zero pulse height, the number of counts below any particular bias setting can be estimated and compared to the total number of counts. The pulse height distribution curves obtained are shown in figures 6 and 7. The first of these was obtained with the amplifier gain reduced in order to show the shape of the whole spectrum while the second shows the lower end of the spectrum in detail. It was found that with the bias set to accept pulses greater than 0.5 millivolts (at the counter wire) less than 0.5% of the pulses were missed.

Amplifier overloading was reduced by using an input circuit to the amplifier with a very short time constant.
Pulse Height Distribution in Beta Proportional Counter with Ra E Beta Source

FIG. 6
Pulse Height Distribution in Beta Proportional Counter with Ra E Beta Source

FIG. 7
This shortens or "clips" the pulses so that large pulses do not block the amplifier for long periods. Such a short time constant differentiates the incoming pulses so that their amplitude is more nearly proportional to their initial slope than to the actual pulse height. Conditions in the counter are such that the spread in the initial slopes of the pulses is less than the spread in pulse heights. Furthermore, the amount of noise coming through the amplifier is less because the bandwidth is reduced. In this way the number of overloaded pulses is reduced, the effects of overloading are less serious and the discriminator can be set closer to zero. No recovery transients could be seen in an oscilloscope. The total duration of the pulses from the amplifier was 6 microseconds.

Under these conditions there was a counting plateau which changed only 1% between 3000 volts and 3500 volts on the counter wire. Tests using the 0.6 Mev beta-ray from Cs$^{137}$ showed that there was no appreciable reduction in the efficiency of the counter at this lower beta-energy.

It appears that the proportional counter can be made to duplicate the performance of a Geiger counter with the additional advantage of better resolving time and simplicity of construction. The electronic equipment
is somewhat more complex than for a Geiger counter but is equally reliable.

IIIB. Calibration Procedure

The beta particle standards used for calibration were obtained from the National Bureau of Standards. They consist of a deposit of RaDEF in PbO₂ mounted on a palladium-coated silver disk. The Bureau of Standards furnishes the following description of the preparation of these sources. The disintegration rate of the RaE is found by measuring the radon activity of a sample of ore containing radium in equilibrium with all its products. The RaD is then separated out of the ore quantitatively. The probable errors quoted for the disintegration rates are about 2% depending on the sample. The deposit is in the form of a circle one-half inch in diameter and has a thickness of about 1 mg/cm². The Ag-Pd backing is a one-inch diameter disk one-eighth inch thick. This heavy backing necessitates a back-scattering correction and the thickness of the deposit further complicates the problem by requiring a self-scattering correction. There are also alpha particles from the RaF and a weak beta-ray from the radium D. At least 5 mg/cm² of absorber must be used between source and counter in order to remove these unwanted radiations.
The absorber must be as close as possible to the window, otherwise foreshadowing effects will increase the observed counts causing errors in the calibration. The presence of these other radiations means that the absorption curve must be extrapolated over a greater range than would otherwise be necessary, resulting in larger errors in estimating the effects of window absorption $f_w$.

The backscattering factor can be found by making a similar RaE deposit on a thin (40μg/cm²) Zapon film. The ratio of the counting rates with and without an Ag-Pd blank behind the source is then the backscattering factor $f_B$. This ratio has been found to be 1.66 by Burtt (3, p.31) for Ag-Pd and 1.6 by Zumwalt (14, p.55) for silver. However, the backscattered radiation is degraded in energy and hence the slope of its absorption curve is different from that of unscattered radiation. In order to get the true value of the backscattering factor, absorption curves must be made for both the backed and unbacked source and extrapolated to zero total absorber thickness. The ratio of the extrapolated counting rates is then the true backscattering coefficient.

The source used for these measurements must also be very thin to avoid self-scattering, otherwise the number of backscattered particles will be disturbed by scattering in the source itself.
By using a series of RaE sources of various weights, a curve of the backscattering factor vs. source thickness was obtained and extrapolated to zero source thickness. This was done with 5 mg/cm$^2$ of aluminum absorber in front of the counter. Absorption curves were then run for the thinnest source with and without backing. From these two sets of data the backscattering factor at zero absorber and for a source of zero thickness was found. The value obtained was 1.79 ± 2% which does not agree with the values of 1.66 found by others. It should be mentioned, however, that the value of $f_B$ for 5 mg/cm$^2$ absorber was very close to 1.66. In any case the correct figure for a thin source is of little value since the Bureau of Standards RaE sources are thick enough to exhibit considerable self-scattering. Since the RaE used for the backscattering measurements is in the form of nitrate and is not mixed with PbO$_2$ it can not be used to determine the self-scattering factor for the RaE standards.

The only way that both $f_B$ and $f_s$ could be found would be to have a series of standards made with different known amounts of material in each and having thin backings. By making measurements on these, the effects of both backscattering and foreshadowing could be found as a function of source thickness. The correction factors for the standards supplied by the Bureau of Standards
could then be determined and applied. This procedure is impractical for the average laboratory and the information is not supplied with the beta-standards so that these standards are of little value for accurate work. However, Burtt (3, pp.40-41) found that by applying a self-scattering correction of 1.08 in addition to the value for backscattering of 1.66 he was able to get good agreement between the Bureau of Standards RaE sources and other beta-ray standards whose disintegration rates were determined by various means. It is interesting to note that the product of 1.08 and 1.66 is 1.79 which is the value of $f_B$ found by the author for a thin source. This seems to indicate that the effects of self-scattering very nearly compensate for the changes in backscattering for a source of 1 mg/cm² thickness.

RaE standards can be made in the laboratory by separating RaE from RaDEF. The growth of the daughter element RaF following the separation can be determined quantitatively by counting alpha particles. From the growth of RaF the quantity of RaE present at any time can be calculated from the decay constants of RaE and RaF. However, this requires the use of a calibrated alpha-counter and the standards are not permanent since the long-lived parent RaD is not present.

It was felt that the product of $f_B$ and $f_s$ of 1.79
used by Burtt could be used with good results since this produced agreement with other beta-ray standards. The values of both $f_B$ and $f_s$ are dependent on the geometry used since the distribution of scattered beta particles is not isotropic. Therefore the RaE standard was used to calibrate the end-window counter in the lowest shelves where $f_B$ and $f_s$ are constant over a wide range of values of $G$. The geometries for the highest shelf and for the proportional counter were obtained by using a thin source of Cs$^{137}$ to obtain ratios between the calibrated and uncalibrated positions. Absorption curves were made for every case in order to eliminate the effects of window absorption. The results of these measurements are shown in table I.

Table I

<table>
<thead>
<tr>
<th>Counter</th>
<th>Geometry factor $&quot;G&quot;$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
</tr>
<tr>
<td>End Window</td>
<td></td>
</tr>
<tr>
<td>Shelf No. 1</td>
<td>23.2%</td>
</tr>
<tr>
<td>Shelf No. 2</td>
<td>12.6%</td>
</tr>
<tr>
<td>Shelf No. 3</td>
<td>4.5%</td>
</tr>
<tr>
<td>Proportional (on window)</td>
<td>46.7%</td>
</tr>
</tbody>
</table>

These values of $G$ agree very well with values calculated from the solid angle between source and counter. In these calculations the sensitive volume was assumed to begin 3 mm behind the counter window for the end-window
counter. This distance corresponds closely to the location of the beginning of the counter wire. The calculated value of G for the proportional counter was made by assuming that the sensitive volume begins 1 mm behind the window. Actually there is probably no displacement near the center of the window but near the edges there are regions which are partially shielded by the counter walls so that the figure of 1 mm represents an average value for the displacement. If the displacement were zero the calculated value would be 50%. There is some variation of the counter sensitivity with time; therefore day-to-day checks on the values of G were made using the RaE standards.
I. Introduction

The measurement of activation cross sections by beta-counting is accomplished by the following procedure. A thin sample of some element is bombarded in a known neutron flux for a measured length of time. Where nuclei resulting from such processes as \((n,2n)\) \((n,p)\), \((n,a)\), are unstable and decay by emission of beta particles, the number of activated atoms may be determined by absolute beta-counting and the cross section calculated.

In order to do this, a knowledge of the decay scheme of the active isotope is required. These decay schemes are not easily determined without the use of special coincidence counting equipment. Therefore in this work only published decay schemes determined by other observers were used. The National Bureau of Standards has recently published a comprehensive summary (12, pp.1-309) of nuclear data giving complete references to the original work, and the decay schemes, etc., used in this investigation were obtained from this source. References for nuclear data presented herein will be given only if the data were obtained from sources not included in the above summary.
II. Identification of the Active Isotopes

The first step in measuring an activation cross section is to determine the identity of the various active nuclei produced by bombardment of the sample. The decay scheme necessary for evaluating the counting data can then usually be found from the literature. This also permits an assignment of the nuclear reaction responsible for the activity.

In general the decay of any radioactive substance follows the equation:
\[ \frac{dN}{dt} = -\lambda N, \]  \hspace{1cm} (13)

where

- \( N \) = number of radioactive atoms present at any time,
- \( \lambda \) = the decay constant, characteristic of the active isotope.

The solution to this differential equation is an exponential function of the form,
\[ N = N_0 e^{-\lambda t}, \]  \hspace{1cm} (14)

where \( N_0 \) is the number of active atoms present when the time \( t \) equals zero. If \( \frac{dN}{dt} \) is defined as the activity \( A \) of the sample, it follows that,
\[ A = A_0 e^{-\lambda t}. \]  \hspace{1cm} (15)

A semi-log plot of \( A \) as a function of \( t \) will produce a straight line of slope \( -\lambda \) and intercept \( A_0 \) at zero time.
A₀ is called the initial activity.

IIA. Half-Life

A more convenient term than the decay constant is the half-life T₁/₂ which is by definition the time required for the activity to decrease to one half of its initial value. T₁/₂ is related to the decay constant by the expression,

\[ T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda} \]  

(16)

The half-life of an observed activity serves as a convenient guide for identifying the radioactive isotope present in a sample. Although this does not provide conclusive evidence in all cases, there is usually additional information available which makes a definite assignment possible. The half-lives of many isotopes have been assigned with the aid of chemical identification of the element, and tables (10, pp.1-112) are available listing known isotopes by their half-lives. If an observed half-life does not agree with the value for some known isotope, additional investigation will be required to establish the identity of the isotope responsible for the activity.

Often, more than one activity will be observed from bombardment of a single isotope by 14-Mev neutrons. For example, in the case of the single isotope Al₂⁷, both
the \((n,p)\) and \((n,\alpha)\) reactions take place leading to the two resultant isotopes \(\text{Mg}^{27}\) and \(\text{Na}^{24}\) respectively. \(\text{Mg}^{27}\) decays by beta-emission, with a half-life of 9.6 minutes, to the stable isotope \(\text{Al}^{27}\). \(\text{Na}^{24}\) decays by beta-emission, with a half-life of 14.9 hours, to the stable isotope \(\text{Mg}^{24}\). The \((n,2n)\) reaction has a threshold above 14 Mev and hence the 6.3 second \(\text{Al}^{26}\) is not observed. The short-lived \(\text{Mg}^{27}\) is easily distinguished from the longer-lived \(\text{Na}^{24}\) by plotting the activity of the sample as a function of time.

The activity of the sample at any time will be the sum of two terms of the form,

\[
A_t = A_{01} e^{-\lambda_1 t} + A_{02} e^{-\lambda_2 t},
\]

where

- \(A_{01}\) = initial activity of type 1,
- \(\lambda_1\) = decay constant for type 1 atoms,
- \(A_{02}\) = initial activity of type 2,
- \(\lambda_2\) = decay constant for type 2 atoms.

Each of the terms would produce a straight line on semi-log plot, with a slope \(\lambda\) and intercept \(A_0\) at \(t = 0\). The sum of two such terms produces a curve which is asymptotic to the straight line representing the longer of the two activities. The curved line may be separated into its two components by simple graphical methods. The decay curve is plotted from zero time to some time which is
long compared to the half-life of the shorter-lived component. The tail of such a curve is very nearly straight since the shorter-lived activity is almost completely gone. Therefore, a straight line may be drawn through the tail of the decay curve and extrapolated back to zero time. The slope of this line is equal to the decay constant $\lambda_2$ of the longer-lived activity, and the intercept is the initial activity of this component. The numerical value of this activity at any time is then subtracted from the total activity. The difference is the value of the shorter-lived component at that time and the points lie on a straight line with slope $\lambda_1$, and an intercept $A_{01}$, at time zero. An example is shown for the Mg$^{27}$ and Na$^{24}$ activities in figure 3.

This method of separation can be used for a mixture of any number of components having decay constants $\lambda_1, \lambda_2, \ldots, \lambda_n$ provided that the decay constants are sufficiently different from each other. A difference of a factor of two between two decay constants is hardly sufficient unless the initial activities are very strong so that the decay curve may be followed through a number of half-lives. If the short activity is large compared to a longer one and if the half-lives are sufficiently different separation is somewhat easier since the ratio of the two continually improves in favor of the longer one.
Decay Curve for Mg\textsuperscript{27} and Na\textsuperscript{24} Produced in Aluminum by 14 Mev Neutrons

A - Total Activity
B - 15 hour Na\textsuperscript{24}
C - 9.6 minute Mg\textsuperscript{27}

TIME - MINUTES

FIG. 8
The procedure, then, is to activate a sample of the element to be investigated in a strong neutron flux and plot the resulting activity as a function of time. This decay curve is graphically resolved into its various components and the half-lives found for each. The isotope responsible for each half-life may be assigned from isotope tables (12, pp.1-309) by looking for those most likely to be produced by the bombardment of the sample element. The reactions, produced by 14-Mev neutrons, that have been identified in various elements by the author are \((n,n\gamma)\), \((n,2n)\), \((n,p)\) and \((n,\alpha)\).

**II.B. Beta Ray Energy**

In addition to checking half-lives, a particular radioactive isotope can be further identified by the energy of the emitted beta particles. An absorption curve provides a convenient method of determining the maximum energy of the beta particles, as described previously in the section on beta-counting. The determination of the maximum range by absorption curves is subject to errors of 5 to 10% because the net counting rate approaches zero and statistical fluctuations become large. It is usually simpler not to subtract the background due to gamma rays from the sample, but rather to try to estimate the point of intersection between the
beta-ray curve and the gamma ray background. This is illustrated in figure 9 which is a beta-absorption curve for the 12.8 hr. Cu$^{64}$ isotope. Cu$^{64}$ decays in three ways, first by K-capture with the emission of a 1.34 Mev gamma ray about 2% of the time, second by the emission of a 0.65 Mev positive beta particle, or third by the emission of a 0.57 Mev negative beta particle. The energies of the two beta particles are too nearly alike to be separated by absorption methods. From the curve it is seen that beta ray energies can be determined by absorption curves with sufficient accuracy to avoid ambiguity in most cases. If the gamma ray background is very large, care must be exercised in interpreting the absorption curve since the aluminum absorbers serve as excellent radiators of Compton electrons or electron pairs produced by the gamma rays. This effect will make the efficiency for counting gamma rays higher when absorbers are placed in front of the counters than when there are no absorbers and the gamma ray counting rate will sometimes be found to increase as the absorber thickness is increased. Whether this is observed or not depends on the energy of the gamma ray and on whether or not the beta rays present have sufficiently short ranges to permit observation of the increasing region of the
Absorption Curve for Cu$^{64}$ beta particles

Gamma Ray background

0.65 mev.

Counts per minute

Absorber thickness
Milligrams per square centimeter of aluminum

Fig. 9
absorption curve. An example of this effect is shown in figure 10 which is an absorption curve for Na\textsuperscript{24}. Na\textsuperscript{24} emits a 1.39 Mev ray, whose range is 625 mg/cm\textsuperscript{2} of aluminum, and both a 2.76 Mev gamma ray and a 1.38 Mev gamma ray in cascade. The gamma ray background is less than 2\% with no absorbers even though it reaches 3\% at an absorber thickness of 1000 mg/cm\textsuperscript{2} of aluminum.

With both the half-life and beta ray energy as guides, positive identification of a particular isotope is usually possible.

III. Cross Section Calculation

Having identified one or more radioactive products from nuclear reactions by the above methods, one may proceed with the determination of the cross sections for their production. In general the cross section for the production of a particular activity is the same as the cross section for the nuclear reaction by which it is produced. For example, in the case of the Al(n,p) reaction the number of Mg\textsuperscript{27} atoms created equals the number of (n,p) reactions which take place. Furthermore, as far as is known all of these Mg\textsuperscript{27} atoms decay with a half-life of 9.6 minutes. Therefore, a determination of the number of Mg\textsuperscript{27} atoms having this half-life is sufficient to determine the Al\textsuperscript{27} (n,p) cross section.
Absorption Curve for Na$^{24}$
beta particles

Gamma ray background

Counts per minute

Absorber thickness
Milligrams per square centimeter of aluminum

FIG. 10
However, there are isotopes which decay with more than one half-life. Nuclei of the same isotope but which exhibit different half-lives are called isomers. There may be isomers which decay with very short or very long half-lives so that they escape detection and care should be taken to distinguish between the cross section for production of a particular activity and the cross section for a nuclear process. If it is known that isomeric states exist in the product nucleus, the cross section for the production of one or more of the isomers may be found. The sum of all these cross sections will equal the cross section for the reaction. For example the $(n,2n)$ reaction in Ag$^{107}$ leads to the formation of Ag$^{106}$ which decays both by positron emission with a 24-minute half-life and by K-capture with an 8.6 day half-life. The cross sections for the production of both these activities must be added to obtain the cross section for the $(n,2n)$ process. One of the isomers resulting from a nuclear reaction may be stable in which case the cross section for the reaction cannot be found by activation methods. A typical example is the $(n,n\gamma)$ reaction in Au$^{197}$. This reaction produces both stable Au$^{197}$ and a 7-second isomer which decays to the stable ground state by gamma ray emission. Clearly the cross section for the reaction cannot be found by counting the resulting activity since only one of the isomers is radioactive.
III A. Growth of Activity During Bombardment

The number of activated atoms produced per minute in a thin sample during neutron bombardment can be expressed in the following equation,

\[
\frac{dN}{dt} = n v \sigma \nu,
\]

where

\( n v = \) the number of neutrons per \( \text{cm}^2 \) per minute incident on the foil,

\( \sigma = \) the cross section for activation in \( \text{cm}^2 \),

\( \nu = \) total number of target atoms in the sample.

The sample must be thin so that the neutron flux will not be appreciably attenuated in the sample since \( n v \) is to be considered a constant throughout the sample.

Let us now consider the case where \( n v \) is constant and independent of the time. The number of atoms activated per unit time will be a constant \( K \) but these atoms will decay with the rate \( \lambda N \) where \( N \) is the number of active atoms at any time \( t \). Then we have,

\[
\frac{dN}{dt} = K - \lambda N.
\]

This differential equation has a solution of the form,

\[
N = \frac{K}{\lambda} (1 - e^{-\lambda t}).
\]

The number of disintegrations per unit time is simply \( \lambda N \) so that the activity may be expressed as,

\[
A = K (1 - e^{-\lambda t}).
\]
If we now define the activity approached for large values of \( t \) as the saturated activity \( A_s \) we find that,

\[
A_s = K (1 - e^{-\infty}) = K = \text{nv} / 2
\]  
(22)

and

\[
A = A_s (1 - e^{-\lambda t}).
\]  
(23)

The cross section may now be expressed in terms of the flux, the number of atoms in the sample foil and the saturated activity.

\[
\sigma = \frac{A_s}{\text{nv} \nu}
\]  
(24)

IIIB. Determination of the Neutron Flux

The flux for the cross section calculations can be found by simple geometric considerations. If the neutron source and sample are sufficiently far apart to approximate a point source and a point sample then the average flux at the sample is simply,

\[
\text{nv} = \frac{Q}{4\pi r^2}
\]  
(25)

where \( Q \) is the source strength in neutrons per minute and \( r \) is the separation of source and sample. The value of \( Q \) is found by multiplying the counting rate in the alpha-monitor counter by a suitable factor as described in the section on the neutron source.
IIIC. Determination of the Number of Atoms in the Sample

The number of atoms in a foil can be found by weighing it. Then from Avogadro's number and the atomic weight of the element used,

$$\nu = \frac{\text{foil weight}}{\text{atomic weight}} = 6.02 \times 10^{23} \text{ atoms.} \quad (26)$$

IIID. Determination of the Saturated Activity

The saturated activity is obtained in the following way. The activity $A$ in equation (23) can be found by plotting the activity of a sample as a function of time after bombardment and extrapolating back to the time at end of bombardment. Since the bombarding time $t$ is known, $A_s$ can then be found. A mathematical solution for $A$ is also possible and is in general more accurate if the decay constant $\lambda$ is well known. The activity of a foil at the beginning of a counting period may be determined in terms of the total number of counts during that period and the counting time. The activity as a function of time after bombardment is,

$$A_t = \frac{dN}{dt} = A_0 e^{-\lambda t}, \quad (27)$$

or

$$dN = A_0 e^{-\lambda t} dt. \quad (28)$$
Integrating, we obtain the expression for the total number of disintegrations,

\[ n = \int_0^t A_0 e^{-\lambda t} \, dt = \frac{A_0}{\lambda} (1 - e^{-\lambda t}) \]  

(29)

From this we can find the initial activity \( A_0 \),

\[ A_0 = \frac{n}{1 - e^{-\lambda t}} \]  

(30)

Suppose now that a foil is bombarded for a time \( t_1 \), that a time \( t_2 \) elapses between the end of bombardment and the start of counting and that a number \( n \) disintegrations occur in a counting period of length \( t_3 \), then the expression for the saturated activity \( A_s \) is,

\[ A_s = \frac{n}{(1 - e^{-\lambda t_1}) e^{-\lambda t_2} (1 - e^{-\lambda t_3})} \]  

(31)

In deriving this expression for \( A_s \) it was assumed that \( n \) was constant throughout the bombardment. In practice this is not true and corrections must be made to take into account the variations of the flux with time. A numerical correction can be made by dividing the bombarding time into equal intervals short compared to the half-life of the desired activity. The average flux in each interval is then weighted according to the decay factor between this interval and the end of bombardment. The sum of these terms is a weighted average \( n^w \) for the flux which may then be used in the
calculations of the cross section together with $A_s$ as given in equation (31).

The number of disintegrating atoms is to be found by counting the emitted beta particles. In order to do this the various factors in equation (9) will have to be evaluated. It has been shown how the counting losses were determined. If the counting period is an appreciable part of a half-life, the counting rate will vary considerably and the counting loss corrections cannot be made by using the average counting rate for the period. Sufficient accuracy may be obtained by taking readings at intervals short compared to the half-life and correcting the number of counts in each interval by the appropriate counting loss factor.

The scattering factors $f_H$ and $f_A$ for the housing and for air are unity for samples close to the counters. In order to avoid complications with the backscattering factor $f_B$, all samples were mounted on thin Zapon films of less than $40\mu g/cm^2$ thickness for which $f_B$ is unity. The window and air absorption factor $f_w$ was obtained from the absorption curve.

To obtain the self-scattering factor, a curve showing the apparent specific activity of a series of uniformly activated foils as a function of sample thickness was extrapolated to zero thickness to obtain the true
specific activity as described earlier. In order to obtain data sufficiently close to zero thickness to permit an accurate extrapolation, it is necessary to use very thin foils, especially if the beta-energy is low or the foil material dense. In order to avoid large statistical fluctuations in counting, a high specific activity is required. Therefore, the activations for the self-scattering curves were made close to the target where the neutron flux is high but not very well known because of uncertainty in the location of the neutron source.

The foils used for all the measurements were in the form of disks one-half inch in diameter punched from sheets. Metallic foils were used where possible. For non-metallic substances foils were made of powders imbedded in polythene sheet. These were prepared by Group CMR-6 at Los Alamos. The purity of the samples is discussed in the section on errors. The foil size was chosen in order to duplicate the one-half inch RaE standards obtained from the Bureau of Standards and hence make the geometry for a sample foil identical with that of the standard at the same distance from the counter. This is important for high geometries since the solid angle varies considerably from the center to the edge of an extended source close to the counter.

Uniform activation of all the foils for a particular
curve was assured by stacking them in contact with one another and wrapping them in paper. This packet was then mounted on a motor shaft so that the foils were continuously rotated in the neutron flux during bombardment. After bombardment the foils were counted one at a time in each of the two counters previously described. Only the 23% geometry was used for the end-window Geiger counter and the 47% geometry for the proportional counter. Corrections were made for the decay of activity during counting. In the case of a short-lived activity being counted in the presence of a longer component, the longer activity was measured for each foil and subtracted from the data.

As was shown in figure 5 the self-scattering curve for the 23% geometry shows a positive slope near the axis while that for the 47% geometry does not. Apparently the 47% geometry is sufficiently close to 50% to prevent interference from self-focussing effects. This would be an ideal situation if it were not for the fact that the samples are in contact with the window so that there is no room for absorbers between source and detector. Thus beta-energies cannot be determined by absorption curves for this geometry. For this reason also the window absorption was found by adding one or two extra layers of the window material between the source and
the window. From these data a linear extrapolation on semi-log paper can be made to zero window thickness and \( f_w \) evaluated. The method is sufficiently accurate because the window is quite thin (0.5 mg/cm\(^2\)), making the extrapolation short. The window absorption was only about 1% in most cases so the extrapolation error is negligible.

The use of these two geometries has the advantage that the two self-scattering curves approach the axis in two quite different ways. This is of considerable help in determining the point of intersection with the axis since both curves must extrapolate to the same value. Unfortunately, the thin foils used to obtain the points nearest the axis are not always sufficiently flat to be considered as lying in a plane. The result is considerable fluctuation of the points in this region even when the counting statistics are good. The errors resulting from incorrect extrapolation are probably the greatest source of experimental error in the determination of the number of active atoms. If the beta-energy is high, fairly thick foils may be used to reduce these errors to 1 or 2% but for low energy beta rays the errors may be 5 or even 10%. These errors are always larger than the expected statistical fluctuations and hence must be estimated from the actual fluctuations in the
data. Because of the large fluctuations in the data, these curves must be determined several times, preferably with different sets of foils, before reasonable accuracy can be obtained.

It was first thought that several thin foils could be stacked for counting in order to obtain the equivalent of a thicker foil. However, this is fallacious unless the foils maintain good contact with each other especially at their edges. This is understandable since it is those beta particles originally traveling in the plane of the foils which provide the greatest amount of scattered radiation. If these are allowed to "leak out" through spaces between layers of foil the amount of scattering will be reduced and the situation is not the same as for a solid foil. The results of this effect are shown in figure 11 in which it can be seen that the stacked foils consistently give points below the curve obtained using single foils. It was also observed that stacked foils gave very erratic data as compared with single layers. In some cases the very thin foils were made from stacks of metallic leaf. These were prepared by wetting the layers with lacquer thinner so that surface tension would pull them tightly together. After drying, these layers would remain in good contact although they were not particularly flat. It should be pointed out that a warped foil gives too high a counting rate
Self Scattering Curve Cu$^{62}$ Beta Particles in Copper Foils

- Single layers of foil
- Multiple layers of foil

**FIG. 11**
in the 23% geometry since on the average it is farther from the supporting film and hence closer to the counter. In the 47% geometry the opposite is the case since the counter window is also the foil support, so that the foil is farther from the counter and the counting rate is reduced. From the self-scattering curve one can find the ratio of the apparent specific activity for any foil thickness to the true specific activity at zero foil thickness. This ratio is by definition the self-scattering factor $f_s$ for that foil. When all the necessary factors have been evaluated, $A_s$ can be found from equation (31).

From the weighted neutron flux $n\nu$, the number $\nu$ of atoms in the sample, and the saturated activity $A_s$, the cross section $\sigma$ can be calculated from equation (24).
RESULTS

I. Cross Sections Measured

The values of the cross sections found from the measurements are listed in Table II. The data from which these values were obtained are summarized in Tables III through XII.

Table II

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Half-life</th>
<th>Isotopic Cross Section</th>
<th>Estimated Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Al}^{27}(n,p)\text{Mg}^{27}$</td>
<td>9.6 min.</td>
<td>79.4 millibarns</td>
<td>± 7%</td>
</tr>
<tr>
<td>$\text{Al}^{27}(n,\alpha)\text{Na}^{24}$</td>
<td>14.0 hours</td>
<td>135</td>
<td>7%</td>
</tr>
<tr>
<td>$\text{P}^{31}(n,p)\text{Si}^{31}$</td>
<td>170. min.</td>
<td>90.6</td>
<td>10%</td>
</tr>
<tr>
<td>$\text{Fe}^{56}(n,p)\text{Mn}^{56}$</td>
<td>2.59 hours</td>
<td>123.5</td>
<td>10%</td>
</tr>
<tr>
<td>$\text{Cu}^{63}(n,2n)\text{Cu}^{62}$</td>
<td>9.9 min.</td>
<td>506</td>
<td>7%</td>
</tr>
<tr>
<td>$\text{Cu}^{65}(n,2n)\text{Cu}^{64}$</td>
<td>12.8 hours</td>
<td>967</td>
<td>8%</td>
</tr>
<tr>
<td>$\text{Cu}^{65}(n,p)\text{Ni}^{65}$</td>
<td>2.56 hours</td>
<td>13.3</td>
<td>20%</td>
</tr>
<tr>
<td>$\text{Ag}^{107}(n,2n)\text{Ag}^{106}$</td>
<td>24.5 min.</td>
<td>564%</td>
<td>10%</td>
</tr>
<tr>
<td>$\text{Ag}^{109}(n,2n)\text{Ag}^{108}$</td>
<td>2.3 min.</td>
<td>1007</td>
<td>10%</td>
</tr>
</tbody>
</table>

*Cross section for the production of the 24.5 minute isomer only.*
II. Data

Table III shows sample calculations of the geometry factors for the two counters. The calculations for the two upper shelf positions are based on measurements made on the Bureau of Standards RaE source No. 1047. The top shelves were also intercalibrated by using thin sources of RaE on Zapon films. The results show no significant difference from the values obtained from the Bureau of Standards beta-source. The second two calculations are for the intercalibration of the end-window counter with the proportional counter. This was done by counting a very thin source of Cs\textsuperscript{137} on both counters and applying the necessary corrections. The beta-absorption curves used to find the counting rates at zero absorber thickness are shown in figure 18.

Tables IV through XII summarize the measurements made for each cross section determination. The neutron yield was obtained by using a factor of 5.18 \times 10^{6} neutrons per alpha-count and the inverse square law was applied to find the neutron flux at the sample location. Tests have shown that the inverse square law holds to within 5 cm of the target with an accuracy of better than 1%. The conversion factor quoted was calculated for activations in the 90° plane and for the molecular deuterium beam at 250 kv accelerating potential. Since
the ions in the molecular beam consist of two deuterons with a single charge, the effective deuteron energy was only 125 kev.

The number of atoms in the sample was calculated as listed on the data sheets. The foil weights are not given but may be found by multiplying the thickness in mg/cm² by 1.27 cm² which was the area of all foils used.

The curves from which the self-scattering factor $f_s$ was obtained are included immediately after the data for each isotope.
### TABLE III

Counter Calibration Data

**A.** Bu. Stds. RaE source No. 1047 - 5870 d/m (1/12/51)

<table>
<thead>
<tr>
<th>Shelf 1</th>
<th>extrapolated counting rate</th>
<th>2430 c/m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f_S \times f_B = 1.79$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$G = \frac{2430(100%)}{5870(1.79)} = 23.2%$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shelf 2</th>
<th>extrapolated counting rate</th>
<th>1320 c/m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f_S \times f_B = 1.79$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$G = \frac{1320(100%)}{5870(1.79)} = 12.6%$</td>
<td></td>
</tr>
</tbody>
</table>

**B.** Cs$^{137}$ Source on Zapon (3/2/51)

<table>
<thead>
<tr>
<th>Shelf 2</th>
<th>extrapolated counting rate</th>
<th>5000 c/m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f_S \times f_B = 1.00$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$d/m = \frac{5000 \text{ c/m}}{G} = \frac{5000}{0.123} = 40,600 \text{ d/m}$</td>
<td></td>
</tr>
</tbody>
</table>

beta - proportional counter

<table>
<thead>
<tr>
<th>extrapolated counting rate</th>
<th>19,000 c/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_S \times f_B = 1.00$</td>
<td></td>
</tr>
<tr>
<td>$G = \frac{19,000}{40,600} \times 100% = 46.7%$</td>
<td></td>
</tr>
</tbody>
</table>

Sample absorption curves for determining the extrapolated counting rates are shown in figure 12.
Absorption Curves for Counter Calibration

1 $\text{Cs}^{137}$ - $G = 47\%$
2 $\text{Cs}^{137}$ - $G = 13\%$
3 $\text{RaE}$ - $G = 23\%$ Std $\# 1047$
4 $\text{RaE}$ - $G = 13\%$ Std $\# 1047$

FIG. 12
The value of the geometry factor $G$ as found at the time of the measurement is included and shows considerable daily variations. The number of counts for each measurement is listed in order to permit an estimate of the statistical fluctuations to be expected. It will be noted that the actual fluctuations in the results are greater than those calculated on a statistical basis.

The error quoted for the average value of the cross section for each reaction is the standard error of the mean calculated from the residuals. The overall estimated error is the r.m.s. value of the various errors quoted in the data.

If an element is composed of more than one stable isotope, the number of atoms in the sample needs to be corrected to include only those atoms of the particular isotope responsible for a nuclear reaction. This is conveniently done by dividing the cross section as found from the total number of atoms in the sample by the isotopic abundance of the reacting isotope. The result is called the isotopic cross section. Isotopic abundances and percent beta-decay are listed wherever these were not taken as 100%.

A representative decay curve is included for each element. The observed activity and the components into which it was resolved are shown.
In two instances the cross section for a particular reaction was found by comparing the saturated activity of the product isotope with the saturated activity of another isotope for which the cross section was measured. This method has the advantage that variations in the counter sensitivity cancel out and since both activities can be produced in the same foil and from the same bombardment, the flux need not be known for the comparison. It should be pointed out, however, that the variation of the flux with time must be known in order to make the necessary corrections when calculating the saturated activity from the bombardment time and the activity at the end of bombardment. The correction factors for two different activities will be different because the calculations depend on the decay constant of the activity under consideration.

This method was applied to find the ratio of the \((n,\alpha)\) cross section to the \((n,p)\) cross section for aluminum. As can be seen from the data presented in Table V, there is good agreement between the ratio of the two cross sections as found by comparing the saturated activities and as found from direct measurement of the two cross sections.

The cross section for the \(\text{Cu}^{65}(n,p)\ \text{Ni}^{65}\) reaction (see Table X) was found by comparing \(A_5\) for the 2.56 hour
Ni$^{65}$ activity to A$_s$ for the 12.3 hour Cu$^{64}$ activity. The cross section for the (n,p) reaction is relatively small so that it was necessary to follow special procedures in order to resolve the Ni$^{65}$ activity from the Cu$^{64}$ activity. First a foil of 120 mg/cm$^2$ thickness was used in order to attenuate the lower energy Cu$^{64}$ beta rays. Second, the bombardment was limited to two hours in order to avoid saturation of the longer-lived Cu$^{64}$. Third the activation was made in the high flux close to the target to improve the counting statistics. The counting was done in the 47% geometry to avoid complications in estimating the self-scattering factor for the Ni$^{65}$ beta rays. The estimate of f$_s$ was based on the measured value of f$_s$ for Mn$^{56}$ in iron. The decay scheme for Mn$^{56}$ is similar to that of Ni$^{65}$ and iron is very close in atomic number to copper. The value of f$_s$ found in the 47% geometry does not fluctuate greatly for the various elements, hence the error in the above estimate of f$_s$ is believed to be less than 15%. The window absorption was assumed to be equal for the two activities and no corrections were made. The self-scattering factor for the Cu$^{64}$ activity was determined experimentally for the particular foil used.

The short half-life of Ag$^{108}$ made it necessary to use separate activations for each foil thickness.
The activity from each foil was counted for a fixed period and the number of net disintegrations was normalized to a flux of $2.1 \times 10^9$ neutrons/(cm$^2$ minute) and a foil weight of one milligram. A curve was plotted showing the normalized number of disintegrations per milligram as a function of the sample thickness for each of the two counters. The extrapolated value of these curves at zero sample thickness was used to calculate the cross section for the reaction. The shape of the self-scattering curve is shown in figure 23. Each point is the average of several determinations.

The cross sections for all the other reactions were found by the methods described previously without special treatment of the data.
TABLE IV
Reaction: Al$^{27}$(n,p)Mg$^{27}$

\[ T_{1/2} = 9.6 \text{ minutes}; \lambda = 0.0722/\text{minute} \]
\[ f_w = 1.015 \text{ for } 23\% \text{ G} \]
\[ f_w = 1.002 \text{ for } 47\% \text{ G} \]

Atomic Weight 26.97

<table>
<thead>
<tr>
<th>Sample thickness</th>
<th>( n )</th>
<th>( f_s )</th>
<th>G</th>
<th>N</th>
<th>( A_s )</th>
<th>( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>neut. s/cm$^2$min.</td>
<td>mg/cm$^2$</td>
<td>atoms</td>
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<td></td>
<td></td>
<td></td>
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<td>1.73x10$^3$</td>
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<td>600x10$^{18}$</td>
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<td>0.216</td>
<td>6.39x10$^3$</td>
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<td>21.3</td>
<td>605</td>
<td>0.93</td>
<td>0.463</td>
<td>20.9</td>
<td>15.1</td>
</tr>
<tr>
<td>3.16</td>
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<td>605</td>
<td>0.93</td>
<td>0.463</td>
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<td>15.1</td>
</tr>
<tr>
<td>9.05</td>
<td>21.2</td>
<td>605</td>
<td>1.14</td>
<td>0.216</td>
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<td>39.3</td>
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<tr>
<td>7.95</td>
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<td>605</td>
<td>0.93</td>
<td>0.463</td>
<td>53.4</td>
<td>38.9</td>
</tr>
</tbody>
</table>

Estimated Error:
2% 1%

Isotopic Cross Section for Al$^{27} = 79.4$ millibarns

Estimated Overall Error ± 7%
Self Scattering Curve $^{27}$Mg Beta Particles in Aluminum Foils

A - 23% Geometry
B - 47% Geometry

FIG. 13
TABLE V

Reaction: Al^{27}(n,\alpha)Na^{24}

\( T_{1/2} = 15 \text{ hours; } \lambda = 7.7 \times 10^{-4}/\text{minute} \)

\[
\begin{align*}
\text{fw} & = 1.03 \text{ for } 23\% \text{ G} \\
& = 1.015 \text{ for } 41\% \text{ G}
\end{align*}
\]

Time Schedule for eqn. (31)

- \( t_1 = 3 \text{ hours} \)
- \( t_2 = 5 \text{ hours} \)
- \( t_3 = 5 \text{ hours} \)

Atomic Weight 26.97

| Sample | T
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>neut. s</td>
<td>mg/cm²</td>
</tr>
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<td>-------</td>
<td>--------</td>
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<tr>
<td>4.5x10⁸</td>
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Estimated Error:

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2%</td>
<td>1%</td>
<td>2%</td>
</tr>
</tbody>
</table>

Isotopic Cross Section \( \text{Al}^{27} = 135 \text{ Millibarns} \)

Estimated Overall Error ± 7%

From a separate determination (see text)

Ratio of \( \frac{\sigma(n,\alpha)}{\sigma(n,p)} = 1.70; \sigma(n,\alpha) = 1.70 \times 79.4 \text{ Mb} = 135 \text{ Mb}. \)
Self Scattering Curve Na$^{24}$ Beta Particles in Aluminum Foils

A - 23% Geometry
B - 47% Geometry

FIG. 14
TABLE VI

Reaction: $^{31}\text{P}(n,p)^{31}\text{Si}$

$T = 157 \text{ minutes; } \lambda = 4.41 \times 10^{-3}/\text{minute}$

$T = 157 \text{ minutes; } \lambda = 4.41 \times 10^{-3}/\text{minute}$

Time Schedule for eqn. (31)

- $t_1 = 75 \text{ minutes}$
- $t_2 = 15 \text{ minutes}$
- $t_3 = 300 \text{ minutes}$

Atomic Weight 30.98

Plastic Composition
49.6% Phosphorous
by weight

<table>
<thead>
<tr>
<th>Sample thickness</th>
<th>$f_s$</th>
<th>$G$</th>
<th>N</th>
<th>$A_s$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutrons cm$^2$ min.</td>
<td>m$_0$/cm$^2$</td>
<td>atoms</td>
<td>counts</td>
<td>d/min.</td>
<td>millibarns</td>
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<tr>
<td>1.97</td>
<td>32.0</td>
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<td>0.216</td>
<td>75x10$^3$</td>
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<td>28.2</td>
<td>345</td>
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<td>25.2</td>
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<td>92.6</td>
<td>0.94</td>
<td>0.467</td>
<td>40.9</td>
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</tbody>
</table>

Estimated Error:

2% 1% 5% 6% 1%

Average $90.6 \pm 4%$

Isotopic Cross Section 90.6 millibarns
Overall Estimated Error $\pm 10%$
Self Scattering Curve $^{31}$Sil Beta Particles in Phosphorous plus Polythene Foils

A - 23% Geometry
B - 47% Geometry

FIG. 15
Activities in Phosphorous Induced by 14 Mev Neutrons

$T_\frac{1}{2} = 2.3$ min.

$T_\frac{1}{2} = 157$ min.

COUNTS PER MINUTE

TIME - MINUTES

FIG. 16
TABLE VII

Reaction: Fe$^{56}(n,p)$Mn$^{56}$

$T_{1/2} = 2.56$ hours: $\lambda = 4.51 \times 10^{-3}$/minute

Time Schedule for eqn. (31)

$t_1 = 60$ minutes
$t_2 = 30$ minutes
$t_3 = 90$ minutes

Atomic Weight 55.85

<table>
<thead>
<tr>
<th>Sample</th>
<th>neut.s/cm$^2$/min.</th>
<th>mg/cm$^2$</th>
<th>thickness</th>
<th>$f_s$</th>
<th>G</th>
<th>N</th>
<th>$A_s$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.99x10$^3$</td>
<td>30.0</td>
<td>410x10$^{18}$</td>
<td>1.15</td>
<td>0.231</td>
<td>122.3x10$^3$</td>
<td>27.5x10$^3$</td>
<td>112</td>
<td></td>
</tr>
<tr>
<td>5.99</td>
<td>30.0</td>
<td>410</td>
<td>0.86</td>
<td>0.469</td>
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<td>5.7</td>
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<td>1.15</td>
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<td>0.86</td>
<td>0.47</td>
<td>72.2</td>
<td>26.2</td>
<td>112</td>
<td></td>
</tr>
</tbody>
</table>

Estimated Error:

$2\%$ $1\%$ $7\%$ $6\%$ $1\%$

Average $113 \pm 1\%$

Isotopic Abundance of Fe$^{56} = 91.5\%$

Isotopic Cross Section for Fe$^{56} = 123.5$ millibarns

Estimated Overall Error = $\pm 10\%$
Self Scattering Curve Mn\textsuperscript{56} Beta Particles in Iron Foils

A - 23\% Geometry
B - 47\% Geometry

Fig. 17
Activities in Iron Induced by 14 Mev Neutrons

FIG. 18

$T_{1/2} = 5 \text{ min.}$

$T_{1/2} = 2.55 \text{ hrs.}$

TIME - MINUTES

COUNTS PER MINUTE
TABLE VIII

Reaction: Cu$^{63}$ (n,2n) Cu$^{62}$

$T_{1/2} = 9.9$ minutes: $\lambda = 0.070$/minute

$f_w = 1.01$ for 23\% G
$f_w = 1.016$ for 47\% G

Atomic Weight 63.54

<table>
<thead>
<tr>
<th>Sample thickness (mg/cm$^2$)</th>
<th>$n$</th>
<th>$v$</th>
<th>$f_s$</th>
<th>G</th>
<th>N</th>
<th>$A_s$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutrons/cm$^2$/min.</td>
<td>mg/cm$^2$</td>
<td>atoms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.81x10$^3$</td>
<td>49.4</td>
<td>594x10$^{18}$</td>
<td>0.90</td>
<td>0.460</td>
<td>43.7x10$^3$</td>
<td>43.8x10$^3$</td>
<td>354</td>
</tr>
<tr>
<td>1.81</td>
<td>15.6</td>
<td>187</td>
<td>1.08</td>
<td>0.230</td>
<td>8.65</td>
<td>11.2</td>
<td>332</td>
</tr>
<tr>
<td>4.60</td>
<td>32.1</td>
<td>386</td>
<td>1.13</td>
<td>0.222</td>
<td>50.4</td>
<td>64.7</td>
<td>364</td>
</tr>
<tr>
<td>4.60</td>
<td>24.1</td>
<td>291</td>
<td>0.96</td>
<td>0.460</td>
<td>64.0</td>
<td>46.9</td>
<td>355</td>
</tr>
<tr>
<td>2.77</td>
<td>42.8</td>
<td>562</td>
<td>1.15</td>
<td>0.221</td>
<td>38.4</td>
<td>52.2</td>
<td>335</td>
</tr>
<tr>
<td>2.77</td>
<td>33.1</td>
<td>393</td>
<td>0.94</td>
<td>0.460</td>
<td>48.0</td>
<td>38.5</td>
<td>349</td>
</tr>
<tr>
<td>2.19</td>
<td>28.4</td>
<td>342</td>
<td>1.12</td>
<td>0.220</td>
<td>21.3</td>
<td>27.9</td>
<td>372</td>
</tr>
<tr>
<td>2.19</td>
<td>22.0</td>
<td>264</td>
<td>0.97</td>
<td>0.460</td>
<td>26.7</td>
<td>19.4</td>
<td>335</td>
</tr>
</tbody>
</table>

Estimated Error: 2\% 1\%

Average 350 ± 1.5\%

Isotopic Abundance of Cu$^{63}$ = 69.09\%

Isotopic Cross Section for Cu$^{63}$ = 350/0.6909 = 506 millibarns

Overall Estimated Error + 7\%
Self Scattering Curve Cu$^{62}$ Beta Particles in Copper Foils

A - 23% Geometry
B - 47% Geometry
TABLE IX

Reaction: Cu$^{65}$(n,2n)Cu$^{64}$

$T_{1/2} = 12.8$ minutes; $\lambda = 9.02 \times 10^{-4}$/minute

$T_1 = 1.09$ for 23% $G$
$T_2 = 1.02$ for 47% $G$

Beta radiation = 54% of total disintegrations
Atomic Weight = 63.54

<table>
<thead>
<tr>
<th>$nV$</th>
<th>Sample thickness</th>
<th>$f_s$</th>
<th>$G$</th>
<th>$N$</th>
<th>$A_s$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>neut.s</td>
<td>cm$^2$/min.</td>
<td>mg/cm$^2$</td>
<td>atoms</td>
<td>counts</td>
<td>d/min.</td>
<td>millibarns</td>
</tr>
<tr>
<td>5.42</td>
<td>6.65</td>
<td>80.0</td>
<td>1.26</td>
<td>0.216</td>
<td>38.4</td>
<td>7.46</td>
</tr>
<tr>
<td>5.42</td>
<td>7.17</td>
<td>86.0</td>
<td>0.90</td>
<td>0.463</td>
<td>62.7</td>
<td>7.36</td>
</tr>
<tr>
<td>14.10</td>
<td>7.32</td>
<td>88.1</td>
<td>1.26</td>
<td>0.224</td>
<td>334.9</td>
<td>20.1</td>
</tr>
<tr>
<td>14.10</td>
<td>7.32</td>
<td>88.1</td>
<td>0.89</td>
<td>0.467</td>
<td>499.0</td>
<td>19.1</td>
</tr>
</tbody>
</table>

Estimated Error:

- 2% $\pm 3$
- 1% $\pm 6$

Isotopic Abundance of Cu$^{65}$ = 30.91% Average $299 \pm 2.5$

Isotopic Cross Section for Cu$^{65}$ = 967 millibarns

Estimated Overall Error $\pm 8%$
TABLE X

Reaction $^{65}$Cu$^{65}(n,p)^{65}$Ni $^{65}$

Foil Thickness = 120 mg/cm$^2$

$t_1/T_{1/2} = 0.781$, $T_{1/2} = 2.56$ hours

$(1-e^{-\lambda t}) = 0.420$
$A_0 = 4300$ c/m
$f_s = 0.65 \pm 15\%$

beta - decay = 100\%

$A_s = \frac{4300 \text{ c/m}}{(0.65)(0.420)} = 1.76 \times 10^4$ c/m

(relative $\overline{\text{M}}V = 1.15$)

$(n,p) = 1.76 \times 10^4 (1.03) = 1.94 \times 10^{-2}$

$(n,2n) = \frac{1.76 \times 10^4}{8.51 \times 10^5 (1.15)}$

$(n,p) = 1.94 \times 10^{-2} \text{ (967 m.b.)} = 18.8$ millibarns

Overall Estimated Error $\pm 20\%$
Activities in Copper Induced by 14 Mev Neutrons

FIG. 21

COUNTS PER MINUTE

TIME - HOURS

$T_{1/2} = 10$ min.

$T_{1/2} = 12.8$ hrs.

$T_{1/2} = 2.6$ hrs.
TABLE XI

Reaction: Ag$^{107}$(n,$\alpha$)Ag$^{106}$

$T_{1/2} = 24.5$ minutes, $\lambda = 0.0233$/minute

Time Schedule for eqn. (31)

- $t_1 = 30$ minutes
- $t_2 = 30$ minutes
- $t_3 = 30$ minutes

<table>
<thead>
<tr>
<th>Sample thickness</th>
<th>$\nu$</th>
<th>$f_s$</th>
<th>$G$</th>
<th>$N$</th>
<th>$A_s$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{neut. s}$</td>
<td>$\text{mg/cm}^2$</td>
<td>atoms</td>
<td>counts</td>
<td>d/min.</td>
<td>millibarns</td>
<td></td>
</tr>
<tr>
<td>6.48</td>
<td>10.16</td>
<td>72.0x$10^{18}$</td>
<td>1.15</td>
<td>0.233</td>
<td>13.6x$10^3$</td>
<td>13.8x$10^3$</td>
</tr>
<tr>
<td>6.48</td>
<td>10.16</td>
<td>72.0</td>
<td>0.93</td>
<td>0.467</td>
<td>27.3</td>
<td>12.4</td>
</tr>
<tr>
<td>23.8</td>
<td>9.61</td>
<td>68.0</td>
<td>1.14</td>
<td>0.231</td>
<td>64.4</td>
<td>49.1</td>
</tr>
<tr>
<td>23.8</td>
<td>9.53</td>
<td>68.5</td>
<td>0.94</td>
<td>0.470</td>
<td>99.1</td>
<td>45.5</td>
</tr>
</tbody>
</table>

Estimated Error:

- 2% 5% 6% 1%

Average

- 290 ± 7%

Isotopic Abundance of Ag$^{107} = 51.35\%$

Isotopic Cross Section for Ag$^{107} = 564$ millibarns

Estimated Overall Error ± 10%
Self Scattering Curve Ag\textsuperscript{106} Beta
Particles in Silver Foils

A - 23\% Geometry
B - 47\% Geometry
TABLE XII

Reaction; Ag\textsuperscript{109} (n,2n) Ag\textsuperscript{108}

\[ T_{1/2} = 2.3 \text{ minutes; } \lambda = 0.297/\text{minute} \]

Time Schedule for eqn. (31)

\[ f_w = 1.01 \text{ for } 23\% G \]
\[ f_w = 1.01 \text{ for } 47\% G \]
\[ t_1 = 2 \text{ min.} \]
\[ t_2 = 2 \text{ min.} \]
\[ t_3 = 5 \text{ min.} \]

The number of disintegrations \( N \) is normalized to a flux of \( 2.1 \times 10^9 \text{ neutrons/(cm}^2\text{minute)} \) and a foil weight of one milligram.

<table>
<thead>
<tr>
<th>Sample Thickness mg/cm(^2)</th>
<th>( N ) Disintegrations G=23%</th>
<th>( N ) Disintegrations G=47%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.9</td>
<td>3975</td>
</tr>
<tr>
<td></td>
<td>4.3</td>
<td>3850</td>
</tr>
<tr>
<td></td>
<td>6.1</td>
<td>4024</td>
</tr>
<tr>
<td></td>
<td>9.6</td>
<td>3970</td>
</tr>
<tr>
<td></td>
<td>12.0</td>
<td>4108</td>
</tr>
<tr>
<td></td>
<td>27.0</td>
<td>4145</td>
</tr>
<tr>
<td></td>
<td>54</td>
<td>3308</td>
</tr>
<tr>
<td></td>
<td>85</td>
<td>3448</td>
</tr>
<tr>
<td></td>
<td>131</td>
<td>2926</td>
</tr>
<tr>
<td></td>
<td>261</td>
<td>1735</td>
</tr>
</tbody>
</table>

Extrapolated disintegrations = 3700 ± 5%

\[
A_s = \frac{3700 (0.297)}{(0.449) (0.551) (0.774)} = 5.74 \times 10^3 \text{ (d/m)/mg.}
\]

\[
2 = \frac{10^{-3}}{107.9} \times 6.02 \times 10^{23} = 5.58 \times 10^{13} \text{ atoms/mg.}
\]

\[
\sigma = \frac{5.74 \times 10^3}{(2.1 \times 10^9) (5.58 \times 10^{13})} = 4.9 \times 10^{-25} \text{ cm}^2
\]

Isotopic abundance of Ag\textsuperscript{108} = 48.65%

Isotopic cross section = \( \frac{490 \text{ mb}}{0.4865} = 1007 \) millibarns

Estimated overall accuracy ± 10%
Self Scattering Curve Ag\textsuperscript{108} Beta Particles in Silver Foils

A - 23\% Geometry
B - 47\% Geometry

FIG. 23
Activities in Silver Induced by 14 Mev Neutrons

COUNTS PER MINUTE

TIME - DAYS

FIG. 24
Activities in Silver Induced by 14 Mev Neutrons

T₁/₂ = 2.4 min.
T₂/₅ = 24.5 min.

COUNTS PER MINUTES

TIME - MINUTES

FIG. 25
III. Additional Activities Observed

In addition to the reactions listed in Table II, for which cross sections were measured, a number of other activities induced by neutron bombardment were observed. The element bombarded, the observed half-lives of the resulting activities, the probable reaction and the published half-lives are listed in Table XIII. There are cases in which an observed activity could be produced in an impurity in the sample by one of the more common types of nuclear reaction. These ambiguities were resolved by activating a sample of the element suspected as the impurity. From the counting rate in this sample it can be decided whether or not a few percent of the impurity could be responsible for the observed activity. Several weak activities which might have resulted from \((n,2\alpha)\) processes were attributed to impurities in the samples on this basis.
<table>
<thead>
<tr>
<th>ELEMENT BOMBARDED</th>
<th>OBSERVED HALF-LIFE</th>
<th>PROBABLE REACTION</th>
<th>PUBLISHED HALF-LIFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorine</td>
<td>27 sec. 112 min.</td>
<td>F${}^{19}$($n,p$)O${}^{19}$ $F${}^{19}$(n,2n)F${}^{18}$</td>
<td>29 sec. 112 min.</td>
</tr>
<tr>
<td>Silicon</td>
<td>2.35 min.</td>
<td>Si${}^{28}$($n,p$)Al${}^{28}$</td>
<td>2.4 min.</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>~2.4 min.</td>
<td>P${}^{31}$($n,2n$)P${}^{30}$ or P${}^{31}$($n,\alpha$)Al${}^{28}$</td>
<td>2.6 min.</td>
</tr>
<tr>
<td>Vanadium</td>
<td>5.5 min. 45 hour</td>
<td>V${}^{51}$($n,p$)T${}^{51}$ or V${}^{51}$($n,\alpha$)Sc${}^{43}$</td>
<td>6 min. 44 hour</td>
</tr>
<tr>
<td>Manganese</td>
<td>1.6 hour 3.7 min.</td>
<td>Mn${}^{55}$($n,p$)Cr${}^{55}$ Mn${}^{55}$($n,\alpha$)V${}^{52}$</td>
<td>1.6 hour 3.8 min.</td>
</tr>
<tr>
<td>Iron</td>
<td>~5 min.</td>
<td>Fe${}^{54}$($n,2n$)Fe${}^{53}$</td>
<td>9 min.</td>
</tr>
<tr>
<td>Cobalt</td>
<td>72 days 2.6 hour</td>
<td>Co${}^{59}$($n,2n$)Co${}^{58}$ Co${}^{59}$($n,\alpha$)Mn${}^{56}$</td>
<td>72 days 2.6 hour</td>
</tr>
<tr>
<td>Columbium</td>
<td>~20 hour ~60 hour</td>
<td>Cb${}^{93}$($n,2n$)Cb${}^{92}$ Cb${}^{93}$($n,\alpha$)Y${}^{90}$</td>
<td>21.6 hour 62 hour</td>
</tr>
<tr>
<td>~10 day ~42 day</td>
<td></td>
<td>Cb${}^{93}$($n,2n$)Cb${}^{92}$ Cb${}^{93}$($n,\alpha$)Cb${}^{93}$</td>
<td>10.1 day 42 day</td>
</tr>
<tr>
<td>Tantalum</td>
<td>3.15 hour</td>
<td>Ta${}^{181}$($n,2n$)Ta${}^{180}$</td>
<td>8.2 hour</td>
</tr>
<tr>
<td>Gold</td>
<td>7.7 sec. 13 hour</td>
<td>Au${}^{197}$($n,n\gamma$)Au${}^{197}$* Au${}^{197}$($n,2n$)Au${}^{196}$* Au${}^{197}$($n,2n$)Au${}^{196}$</td>
<td>7.5 sec. 13 sec.</td>
</tr>
<tr>
<td>~3 hour</td>
<td></td>
<td>Bi${}^{209}$($n,p$)Pb${}^{209}$</td>
<td>3.3 hour</td>
</tr>
</tbody>
</table>

**TABLE XIII**
DISCUSSION OF ERRORS

The largest errors for many cases are in the calibration of the counters with the RaE beta-standards. The disintegration rate of these standards is known with a probable error of 2%. An additional error of 2 to 3% is introduced by the necessity of making long extrapolations of the absorption curves. The probable error in the product of the backscattering factor and the self-scattering factor is not known but is believed to be about 5% on the basis of the results obtained by Burtt (3, p. 40). The estimated error in the counter calibration is therefore 6%. This could be reduced to 1 or 2% if thin beta ray standards free of alpha-radiation and mounted on thin backings were available.

Determination of the true specific activity from the self-scattering curves is another source of large errors. For elements of low atomic number such as aluminum for which very thin foils are readily obtained, the self-scattering curve can be extrapolated with about 2% uncertainty. In such cases as Cu\(^{65}\) where the beta-energy is low or as Ag where the atomic number is high, the use of very thin foils is required in order to determine the shape of the initial portion of the curve. Wrinkles in the foils or variations in the thickness become more prominent in this region and the accuracy of
the measurements is reduced. The greatest fluctuations in the self-scattering curves were obtained with the foils made of phosphorous imbedded in polythene plastic. These foils had small air bubbles scattered through them, hence the apparent thickness in mg/cm² is subject to some error. Additional errors may be introduced by non-uniformity of the mixture but these are believed to be small.

The errors quoted for the neutron flux are based on the sensitivity of the calculations to variations in the different parameters involved. At the low bombarding energies used, the corrections for the asymmetry in the angular distribution of the particles in the laboratory is not very large and hence the calculations are not very sensitive to changes in the bombarding energy, etc. Errors introduced by migration of the deuteron beam over the target face will cancel out if several runs are averaged together.

The effect of using an incorrect value of the decay constant will depend considerably on the time intervals used for bombarding, waiting, and counting. If these intervals are short compared to the half-life, the error in each factor in equation (31) will be roughly linear with the error in the half-life. The time schedule and half-life used in the calculations are included in
order to permit corrections to the data if a better value of the half-life is found. The time intervals were not always identical for every measurement of a particular activity so average values are given. The half-lives used are fairly accurately known so that any corrections will be small.

The purity of all samples used was known to be at least 99%, hence the number of atoms is subject to errors of less than 1% from this source. Any possibility of one of the activities being due to an impurity is ruled out by the magnitude of the cross section measured since these would have to be multiplied by a factor of at least 100 if they were due to impurities. The resulting cross sections would usually exceed by a considerable amount the known values for the total neutron cross sections which are very nearly equal to the geometric cross sections for 14 Mev neutrons.

Errors in the sample weights and statistical errors were less than 1% in most cases.

The relative values of the cross sections should be more accurate than the absolute values since the calibration error does not enter into the measurements. There will be 1 or 2% error remaining due to the fluctuations in the counter sensitivities even though these were checked periodically.


