Methods for Measuring Fast Neutron Cross Sections*

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I. INTRODUCTION

IN a previous report[1] methods for measuring fast neutron flux were described, and it was pointed out that the principal application of such flux determinations is to the measurement of cross sections. The present paper is concerned with a description of methods for measuring cross sections assuming a knowledge of neutron flux.

As emphasized in (1) significant cross-section measurements require the use of monoergic neutrons, and the present discussion will be concerned mostly with this case. The methods to be described have been used primarily for medium fast neutrons, i.e., in the energy range from a few kev to about 20 Mev. Techniques used for measurements on slow neutrons differ markedly from those applied at higher energies. While the distinction between slow and fast neutrons is an arbitrary one, the change in techniques occurs at a few kev energy, and is caused by a change in method of producing monoergic neutrons. To study the properties of slow neutrons, neutrons of a given energy are usually selected from a continuous energy distribution on the basis of their time of flight by suitable timing devices, or on the basis of their wavelength by diffraction methods. Monoergic fast neutrons, on the other hand, may be produced directly by reactions in the target of a charged particle accelerator[2] or by monoergic gamma-rays producing photoneutrons in D or Be.[3] It will be assumed here that measurements are to be carried out with such sources.

The following symbols will be used:

E_0 = energy of primary neutrons;
E = energy of scattered neutrons;
σ_t = total cross section;
σ_e = total elastic scattering cross section;
σ_i = total inelastic scattering cross section;
φ = scattering angle of neutron in the laboratory system of reference;
θ = scattering angle of neutron in the center-of-mass system of reference;
$\sigma_e(\varphi)$ = differential cross section for elastic scattering through an angle φ, per unit solid angle in the laboratory system;

$$\sigma_e=\int_0^\pi \sigma_e(\varphi)2\pi \sin\varphi d\varphi=\int_0^\pi \sigma_e(\theta)2\pi \sin\theta d\theta;$$

$\sigma_i(E)dE$ = cross section for inelastic scattering into the energy interval between E and $E+dE$;
σ_a = cross section for absorption, i.e., for all processes other than scattering.

II. TOTAL CROSS SECTIONS

Of all neutron cross sections the total interaction cross section can be determined most easily and precisely. The measurement consists of a simple transmission experiment in good geometry in which a sample is introduced between the source of neutrons and a detector. If I denotes the counting rate of the detector in the presence of the sample and I_0 the counting rate without the sample, the total cross section is given by

$$\sigma_t=(1/N)\ln(I_0/I), \tag{1}$$

where N is the number of nuclei per cm² in the sample.

Sample

The minimum diameter of a sample is determined by the fact that it must shadow the detector completely. On the other hand, it is desirable that the sample not be larger in diameter than necessary for this purpose in order to minimize the corrections which have to be applied to the measurements for neutrons which are scattered by the sample into the detector. Scattering of neutrons into the detector is an effect which is particularly important at high neutron energies at which the elastic scattering is almost entirely shadow scattering with a strong maximum in the forward direction.

The following considerations affect the thickness of the sample. If the sample is thin compared to a mean free path, very good statistical accuracy in the determination of the transmission through the sample is required for an accurate measurement of the cross section. On the other hand, if the sample has a thickness of a mean free path or more, any background count of the detector will affect the measurement of the cross section strongly. In addition, the thicker the sample the more important will be the effect of multiple scattering in the sample. Another difficulty which is introduced by

* Report sponsored by the Subcommittee on Neutron Measurements and Standards of the Committee on Nuclear Science of the National Research Council.
† Operated under AEC contract.
[1] Barschall, Rosen, Taschek, and Williams, Revs. Modern Phys. 24, 1 (1952).
[2] Hanson, Taschek, and Williams, Revs. Modern Phys. 21, 635 (1949).
[3] A. Wattenberg, Preliminary Report No. 6, Nuclear Science Series, National Research Council.

the choice of a thick sample becomes important when the cross section varies rapidly with neutron energy. In this case the neutrons of energies for which the cross section is highest will be absorbed or scattered out very rapidly and the transmission through the sample will no longer follow an exponential absorption law. As a result, measurements of cross sections in the neighborhood of a peak in the cross section near a resonance will tend to give too low values. As a compromise between the disadvantages of both too thin and too thick samples, many total cross-section measurements have been carried out with transmissions of the order of 60 percent. If the cross section varies strongly with energy, samples of different thicknesses have to be used in order to keep the transmission reasonably constant.

Some care must also be taken in the choice of the compound out of which the sample is to be formed. Whenever available, the sample should be made out of the element in solid form. There is considerable danger that powders adsorb water vapor, CO_2, or other gases. In some cases absorbed gases may be driven off by heating the sample and then sealing it in a gas-tight container. If the element is not readily available in elemental form, it may be necessary to use compounds. Compounds which are labeled "chemically pure" frequently contain water, a component which would greatly affect the measurements. Great care must be taken when the cross section of one element is subtracted from the cross section of the compound, since all nuclides heavier than hydrogen exhibit resonances in their cross sections and the observed variation of cross section with energy in the neighborhood of a resonance depends on the experimental energy resolution which is used. It is best to attempt to perform the subtraction experimentally. This can be done in the following way: If it is desired, for example, to measure the cross section of oxygen, one may compare the transmission through a sample of BeO with that through a sample of Be which contains the same number of Be atoms as the BeO sample. In this way the effect of resonances in Be may be eliminated.

For the measurement of the cross section of gases one may use the liquefied gas in a Dewar. Bubble formation in the liquid frequently disturbs the measurements. For this reason, such measurements have been carried out by using the gas under very high pressure in appropriate containers.[4] Since the equation of state of the gas is usually not accurately known at high pressures, the number of atoms contained in the sample should be determined by weighing the sample rather than by measuring the gas pressure.

Detector

Almost any detector which is sensitive to neutrons may be used for measuring total cross sections. It is necessary to ascertain, however, that the detector will not detect gamma-rays which are always present in the neighborhood of a neutron source. The sensitivity of the detector to gamma-rays should be checked at frequent intervals by means of a source of high energy gamma-rays. As a detector for neutrons of energy above one Mev and up to energies of the order of 20 Mev, hydrogen recoil detectors either in the form of counters or organic scintillators[5] are most frequently used. They have the advantage of discriminating against low energy background neutrons and of a high detecting efficiency. At neutron energies below one Mev, recoil protons are frequently difficult to distinguish from electrons produced by energetic gamma-rays. As a consequence, it becomes preferable to detect the neutrons through exoergic reactions. In particular, the $B^{10}(n,\alpha)$ reaction is convenient to use because of the availability of $B^{10}F_3$ Since such a counter has a high efficiency for neutrons of low energies, it becomes necessary to shield the counter against slow neutrons in order to avoid excessive backgrounds. Suitable high efficiency BF_3 counters have been described.[6]

It is desirable to construct the detector with as small diameter as is compatible with the desired efficiency. Since the energy of neutrons emitted from accelerated particle sources depends on the angle of emission of the neutrons, a counter of small diameter will receive neutrons of relatively small energy spread. In addition, the smaller the diameter of the detector the smaller the size of the sample sufficient to shadow the detector. As a consequence, the effect of neutrons scattered into the detector may be reduced.

Neutron Source

Sources of monoergic neutrons have been discussed in an article by Hanson, Taschek, and Williams.[2] The $Li(p,n)$ reaction is usually used as a source of neutrons of low energy. As was pointed out,[2] the center-of-mass motion produces two neutron groups with different energies in the forward direction at the lowest neutron energies. In order to avoid this second energy group, the observations should be carried out at angles larger than 90° with respect to the incident protons for neutron energies below 120 kev. In addition the excited state of Be^7 introduces a second group of neutrons at energies above about 600 kev. Above this energy the $T(p,n)$ reaction is the most convenient source. At energies above those accessible with the $T(p,n)$ reaction, the $D(D,n)$ reaction may be used and at higher energies the $T(D,n)$ reaction.

The target assembly should be as light as possible in order to avoid scattering of neutrons in it.

If one wishes to observe details of the variation of neutron cross sections with energy, the energy spread of the neutrons should be as small as possible. This

[4] Bashkin, Mooring, and Petree, Phys. Rev. **82**, 378 (1951).

[5] R. Ricamo and W. Zünti, Helv. Phys. Acta **24**, 419 (1951).

[6] L. W. Seagondollar and H. H. Barschall, Phys. Rev. **72**, 439 (1947); Peterson, Barschall, and Bockelman, Phys. Rev. **79**, 593 (1950).

energy spread depends on three factors: (1) The spread in energy of the charged particles incident upon the target; (2) the energy loss of the charged particles in the target; (3) the angle subtended by the detector at the source, since the energy of the neutrons depends on their direction of emission with respect to the incident charged particles. All three factors may in principle be made as small as one wishes: The first by passing the charged particle beam through an electrostatic or magnetic analyzer, the second by using a very thin target, the third by using a small counter or a large distance from the source. A limitation to the energy resolution is the Doppler effect produced by the thermal motion of the target atoms in the source. This amounts at room temperature to several hundred ev for fast neutrons produced by bombarding light nuclei with charged particles. A Doppler effect of the same order of magnitude occurs in the interaction of fast neutrons with light nuclei. While it might be possible to cool the targets in order to reduce the Doppler effect, this has not been done. A reason is that in most vacuum systems the deposition of impurities on a cooled target would result in a thickening of the target. Actually it is usually impractical to use energy spreads of less than about one kev partly for reasons of intensity, partly because of the large number of energies at which measurements have to be taken in order to cover an appreciable energy range.

Corrections

In general, two corrections have to be applied to the observed transmission before the cross section can be calculated. The first is the effect of neutrons scattered by the sample into the detector. As has already been mentioned, one wishes to keep this correction as small as possible by an appropriate choice of the geometry of the experiment, since it is rarely possible to calculate the correction with any degree of accuracy. While some experimental information regarding the angular distribution of scattered neutrons is available, it usually does not cover the range of small angle scattering in which one is interested for this correction. Some idea of the order of magnitude of the correction may be obtained from optical diffraction theory at the higher neutron energies, while at the lowest energies the assumption of isotropic scattering of the neutrons may be reasonable. The correction is smallest when the sample is placed half-way between source and detector. For this case the correction may be computed with the aid of Eq. (12), given in the following section. Expressions for the inscattering correction for other geometries may be found in many of the reports on determinations of total neutron cross sections.[5,7]

The second correction which has to be applied to the experimental data is for background neutrons, i.e., neutrons which are scattered into the detector by the floor and other surrounding materials. The magnitude of this background may be ascertained experimentally by inserting between the source and the detector a shadow cone which has a negligibly small transmission. There is some danger, however, that such a shadow cone may also cut out some of the background neutrons. Another method which has been used to measure the neutron background consists of a determination of the counting rate of the detector as a function of distance from the neutron source. If the assumption is made that the flux of neutrons coming directly from the source varies inversely as the square of the distance from the source and that the room background is independent of distance, the background can be calculated. In most cases, the neutron background is, however, actually not constant, so that this method does not give a reliable background determination.

Because of the uncertainty in determining the background correction, it is again desirable to keep this correction as small as possible. It becomes most important at the lowest neutron energies where usually a detector which is sensitive to slow neutrons has to be used. In particular, when the observations are carried out in the backward direction, using the T(p,n) or Li(p,n) reaction, the correction becomes very large because of the forward maximum in the angular distribution of the neutrons from the source. In order to avoid this difficulty, a highly directional counter has recently been developed by Langsdorf.[8] This counter is surrounded by a very large neutron shield and has a negligible efficiency for detecting neutrons which do not come directly from the source. With this counter Langsdorf was able to measure cross sections down to energies of about 2 kev with a resolution of the order of one kev.

III. ELASTIC SCATTERING AND ANGULAR DISTRIBUTIONS

A neutron is said to be scattered elastically if it loses no energy in the center-of-mass system of reference. This means, however, that in the laboratory system it may lose a maximum energy

$$E_{\max}=E_0\frac{4Mm}{(M+m)^2}, \qquad (2)$$

where m is the mass of the neutron and M the mass of the nucleus under investigation. The energy of the elastically scattered neutrons as a function of the scattering angle φ is given by

$$E=\frac{E_0}{(M+m)^2}[m\cos\varphi+(M^2-m^2\sin^2\varphi)^{\frac{1}{2}}]^2. \qquad (3)$$

Because of the large energy loss in elastic collisions with light nuclei, the experimental distinction between elastic and inelastic scattering is not always easy.

[7] Lampi, Freier, and Williams, Phys. Rev. **80**, 853 (1950).

[8] A. S. Langsdorf, Phys. Rev. **80**, 132 (1950); Phys. Rev. **85**, 595 (1952).

It will be assumed in the present section that it is known either that elastic scattering is the only nuclear interaction which takes place or that the detector employed detects only elastically scattered neutrons. Experiments which enable one to distinguish between elastic and inelastic scattering will be discussed in the next section. A variety of methods for measuring $\sigma_e(\theta)$ has been used; the choice of the method depends both on the nucleus under investigation and on the source of neutrons which is available.

Collimation and Shielded Detectors

The most direct way of studying the angular distribution of scattered neutrons would appear to consist of a measurement of the counting rate of a detector which is moved at a fixed distance around a small sample of the material to be investigated. Since most sources of monoergic neutrons emit neutrons in all directions, the detector will, in general, count many more neutrons which come directly from the source than neutrons which are scattered by the sample. It is necessary, therefore, either to shield the detector from the direct neutrons or to employ a highly directional detector. Both methods are likely to give small counting rates and require the use of large samples or very efficient detectors.

The first extensive measurements of angular distributions of scattered neutrons were carried out in 1939 by Kikuchi[9] with *D-D* neutrons. These authors shielded the detector by means of a shadow cone which was inserted between the target and the counter, and observed the neutrons scattered by a ring of the material. By moving the ring with respect to the detector, they could detect neutrons scattered through various angles. These experiments established the presence of a forward maximum in the scattering of fast neutrons by heavy nuclei. Since the detector used by Kikuchi *et al.* did not distinguish between elastically and inelastically scattered neutrons the experiments were subsequently repeated employing a detector with better energy discrimination.[10] More recently Amaldi[11] has investigated the angular distribution of 14-Mev neutrons using a very similar technique. Instead of rings, Amaldi employed barrel-shaped samples of several sizes and such shape that neutrons scattered by various parts of the sample were scattered through the same angle in order to reach the detector.

The directional detector developed by Langsdorf[8] has also been used for measuring angular distributions. In spite of its very high detecting efficiency the counting rates produced by neutrons scattered from a small sample of material are so low that only very rough distributions could be obtained with the intensities currently available from monoergic neutron sources.

Instead of shielding the detector, it is possible to irradiate the sample with a collimated beam of neutrons. For most available neutron sources and detectors, this procedure gives, however, prohibitively small counting rates. Nevertheless, this method is at present being explored further, and with the development of stronger neutron sources and more efficient counters the method has great promise of success. It will be necessary, however, to investigate the energy distribution of the neutrons emanating from the collimator in order to ascertain what fraction of the neutrons have been degraded in the walls of the collimator.[11a]

There are a few examples of accelerated particle sources which do not emit neutrons in all directions. Just above threshold, the neutrons from endoergic reactions are emitted in a forward cone. Whenever in an endoergic (p,n) reaction the heavy particles are accelerated and the protons used as target nuclei, the neutrons are emitted in a forward cone whose opening angle increases with bombarding energy but which will always be located in the forward hemisphere. The use of such reactions enables one to place the detector into a region in which it will not receive any direct neutrons from the source. In this way the use of a collimator may be avoided. It should be pointed out, however, that the neutrons produced in this manner are monoergic only at threshold. Above threshold there are present in any given direction two groups of neutrons. The energy of one of the groups increases, that of the other decreases with increasing bombarding energy.

In experiments using collimated sources or ring scatterers, the value of the differential scattering cross section is most easily determined in the following manner, if it may be assumed that the sensitivity of the detector to the primary neutrons is the same as that for the scattered neutrons. The detector is first placed at the position normally occupied by the scatterer. If the counting rate in this position is I_0, and the counting rate produced by the scattered neutrons is I, then

$$\sigma(\varphi) = Id^2/(I_0 n), \qquad (4)$$

where d is the distance between scatterer and detector and n the total number of scattering centers.

Observation of Recoil Particles

When one wishes to determine the angular distribution of neutrons scattered by light nuclei, it is often easier to observe the angular distribution or the distribution in energy of the recoiling particles rather than the angular distribution of the scattered neutrons. The choice of method for observing the recoiling particles will depend both on the nucleus under investigation and on the energy of the primary neutrons. In some of the earliest attempts at measuring angular distributions, the recoiling particles were observed in a

9 Kikuchi, Aoki, and Wakatuki, Proc. Phys.-Math. Soc. (Japan) **21**, 232, 410, 656 (1939).

10 H. H. Barschall and R. Ladenburg, Phys. Rev. **61**, 129 (1942).

11 Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo cimento **3**, 203 (1946).

11a P. H. Stelson and W. M. Preston, Phys. Rev. **86**, 132 (1952).

cloud chamber. In view of the uncertainty of ascertaining the sensitive time of a cloud chamber, such observations give only relative angular distributions and not absolute cross sections. Angular distributions of neutrons scattered by protons and deuterons have been measured in a cloud chamber,[12,13] and the most recent determinations indicate that the cloud-chamber technique may give the most reliable angular distributions of neutrons scattered by light nuclei.

Some of the first determinations of the angular distribution of neutrons scattered by protons were carried out by observing recoiling protons in the emulsion of a photographic plate. The early results obtained by this method have later on turned out not to be reliable, but with the development of better photographic emulsions great improvements of this technique have been possible. Measurements of the angular distribution of 12-Mev neutrons scattered by hydrogen by observation of recoil protons in a photographic emulsion are now in agreement with those obtained by other methods.[14]

The best method for observing the angular distribution of neutrons of energies higher than about 5 Mev scattered by light nuclei, particularly hydrogen isotopes, appears to be by the detection of the recoils ejected from a thin foil or a gas cell.[15] The recoiling particles may be detected in a counter telescope or in a photographic plate. For heavier nuclei or lower neutron energies the range of the recoiling particles is so short that the energy loss in the radiator or the foil containing the gas makes the detection of the recoiling particles very difficult. In addition the effect of Coulomb scattering introduces errors which become larger as the energy of the recoiling particles becomes lower.

Particularly for nuclei of elements which are available in gaseous form it is frequently easier to measure the distribution in energy of the recoils rather than their distribution in angle. The energy distribution and the angular distribution are related in a very simple manner.[16] From the conservation laws it follows that the scattering angle θ is related to the energy, E, of the recoiling particle in the laboratory system by

$$\cos\theta = 1 - 2E/E_{\mathrm{max}}. \tag{5}$$

The number of neutrons scattered between angles θ and $\theta + d\theta$ is given by

$$2\pi \sin\theta\sigma(\theta)d\theta = -2\pi\sigma(\theta)d(\cos\theta) = 4\pi\sigma(\theta)dE/E_{\mathrm{max}}. \tag{6}$$

This shows that the angular distribution of the scattered neutrons in the center-of-mass system of reference is directly proportional to the distribution in energy of the recoils in the laboratory system of reference. This method for determining angular distributions from energy distributions has been used successfully for observing the angular distribution of neutrons scattered by hydrogen, helium, and oxygen.[17-19] Instead of using recoils produced in a gas it is also possible to employ a thin radiator. In view of the fact that there will usually be a definite correlation between the direction of the recoil and the direction of the electric field in the counter, considerable care must be taken to assure that ionization tracks moving in all directions with respect to the electric field are collected with equal efficiency and produce pulses proportional to the energy of recoil. Effects like lack of saturation and the influence of electron collection may produce systematic errors in the observed pulse-height distribution. Since it is necessary that the range of the recoils be small compared to the dimensions of the counter in which the recoils are observed, high pressures have to be employed at high neutron energies, and, as a consequence, saturation effects may become large. The determination of the recoil energy distribution for measuring angular distributions does not give information about neutrons scattered through small angles, since the energy measurement does not enable one to distinguish pulses produced by such neutrons from pulses produced by electrons and recoils of heavier nuclei. Furthermore, the original assumption that elastic scattering is the only nuclear interaction, is of importance to this method as inelastic scattering will alter the energy distribution of the recoiling particles.

Poor-Geometry Experiments

As was described in Section II, total neutron cross sections are determined by carrying out transmission experiments in good geometry, i.e., by making the sample sufficiently small that the probability of scattering of neutrons into the detector is small. By using larger samples, it is possible to increase the effect of scattering into the detector and, in this way, to get information about the angular distribution of the scattered neutrons. For this purpose it is desirable to use a geometry in which the effect of scattered neutrons can be calculated as easily as possible. The simplest case is that in which the scatterer is placed half-way between the source and the detector, and in which a circular cylinder of material is used on whose axis both the source and detector are located. In order to calculate the effect of neutrons scattered into the detector, it will be assumed that the source emits neutrons isotropically in all directions and that the response of the detector is the same irrespective of the direction of incidence of the neutrons. It will further be assumed that both source and detector may be considered as points, and that the sample is sufficiently thin that

[12] J. S. Laughlin and P. G. Kruger, Phys. Rev. **73**, 197 (1948).
[13] I. Hamouda and G. de Montmollin, Phys. Rev. **83**, 1277 (1951).
[14] C. F. Powell and G. P. S. Occhialini, *Fundamental Particles* (The Physical Society, London, 1947), p. 150.
[15] Amaldi, Bocciarelli, Ferretti, and Trabacchi, Naturwiss. **30**, 582 (1942); see also reference 1, Section III.
[16] H. H. Barschall and M. H. Kanner, Phys. Rev. **58**, 590 (1940).
[17] J. H. Coon and H. H. Barschall, Phys. Rev. **70**, 592 (1946).
[18] T. A. Hall and P. G. Koontz, Phys. Rev. **72**, 196 (1947).
[19] Baldinger, Huber, and Proctor, Phys. Rev. **84**, 1058 (1951).

multiple events in the sample may be neglected, i.e., that the approximation

$$\exp(-n\sigma)\approx 1-n\sigma \tag{7}$$

is valid. Figure 1 shows the geometry of such an arrangement. d is the distance between source and detector. The maximum angle through which a neutron can be scattered and still reach the detector is φ_m. The number of neutrons which leave the source per unit time between the angles $\varphi/2$ and $\varphi/2+d(\varphi/2)$ is

$$\frac{Q}{2}\sin\frac{\varphi}{2}d\left(\frac{\varphi}{2}\right)$$

where Q is the source strength. Neutrons emitted in this angular interval will encounter $N/\cos(\varphi/2)$ nuclei per cm^2 where N is the number of nuclei per cm^2 in the disk. The number of these neutrons scattered per unit solid angle and per unit time into the direction of the detector will then be:

$$\left[\frac{Q}{2}\sin\frac{\varphi}{2}\,d\left(\frac{\varphi}{2}\right)\right]\frac{N}{\cos\varphi/2}\sigma(\varphi).$$

The resulting flux at the detector, which is at a distance $d/(2\cos\varphi/2)$ from the scattering centers, will be

$$\left(\frac{Q}{2}\sin\frac{\varphi}{2}\,d\frac{\varphi}{2}\right)\left(\frac{N}{\cos\varphi/2}\right)\sigma(\varphi)\frac{4\cos^2(\varphi/2)}{d^2}$$
$$=\frac{2QN}{d^2}\sin\frac{\varphi}{2}\cos\frac{\varphi}{2}\sigma(\varphi)d(\varphi/2)$$
$$=(QN/2d^2)\sigma(\varphi)\sin\varphi d\varphi, \tag{8}$$

and the scattered flux produced by the entire disk is

$$I_1=\frac{QN}{4\pi d^2}\int_0^{\varphi_m}\sigma(\varphi)2\pi\sin\varphi d\varphi. \tag{9}$$

Without the disk the flux received by the detector will be

$$I_0=Q/4\pi d^2, \tag{10}$$

while in the presence of the disk the intensity will be

$$I=I_0+I_1-I_2,$$

where

$$I_2=I_0N\int_0^{\pi}\sigma(\varphi)2\pi\sin\varphi d\varphi \tag{11}$$

is the flux scattered out of the direct beam by the disk assuming that only elastic scattering takes place.

$$I=I_0\left\{1+N\int_0^{\varphi_m}\sigma(\varphi)2\pi\sin\varphi d\varphi-N\int^{\pi}\sigma(\varphi)2\pi\sin\varphi d\varphi\right\}$$

$$I=I_0\left\{1-N\int_{\varphi_m}^{\pi}\sigma(\varphi)2\pi\sin\varphi d\varphi\right\}. \tag{12}$$

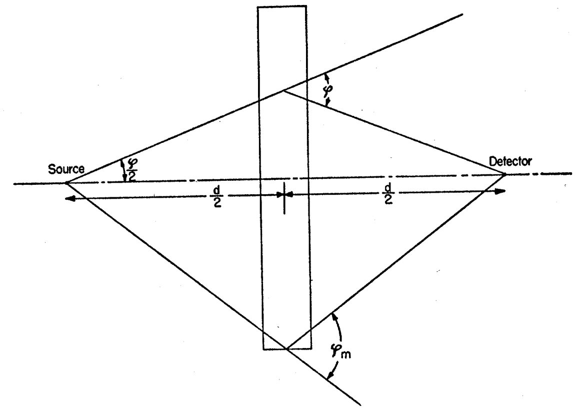

FIG. 1. Poor-geometry scattering experiment.

A poor-geometry transmission experiment will, therefore, give the cross section for scattering through angles larger than φ_m. This theorem was first derived by R. F. Christy.

The angle φ_m may be varied experimentally either by using disks of different diameters or by changing the distance between source and detector. From measurements with different φ_m the angular distribution of the scattered neutrons may be obtained. This method is particularly useful for heavy elements and for small scattering angles of the neutrons.

Since the assumption that the neutron source is isotropic does not hold for most accelerated particle sources, corrections for the variation of neutron flux over the disk must be applied. This can be done, at least approximately, by a suitable choice of the direction with respect to the accelerated particle beam at which the experiment is carried out.[20] The condition which should be satisfied is that the neutron intensity averaged over any concentric circle on the disk is independent of φ.

The condition of an isotropic response of the detector should be taken into account in the design of the detector. Only when recoil detectors are used is this requirement likely to introduce difficulties.

IV. INELASTIC SCATTERING

In Section III it was assumed that either the only nuclear interaction is elastic scattering, or the detector employed is sensitive only to elastically-scattered neutrons. In the present section methods will be discussed for ascertaining what fraction of the scattered neutrons is scattered elastically. In view of the fact that several of the methods for measuring inelastic scattering cross sections do not enable one to distinguish between neutrons which lose most of their energy in an inelastic collision and neutrons which are absorbed by other processes, it will frequently be desirable to include in the inelastic cross section not only scattering but absorption. The cross section for all processes

[20] Barschall, Manley, and Weisskopf, Phys. Rev. 72, 875 (1947).

other than elastic scattering will be referred to as the inelastic collision cross section, in contrast to the inelastic scattering cross section which does not include absorption processes.

Threshold Detectors

A convenient way to distinguish between elastically and inelastically scattered neutrons would be available if a detector could be constructed which is sensitive only to the elastically scattered neutrons. Detectors sensitive only to neutrons above a given energy are called threshold detectors. The ideal threshold detector has zero sensitivity below the threshold and a constant sensitivity above the threshold. There are some neutron-induced reactions whose cross sections approximate such a behavior and which may be used as threshold detectors. While every endoergic reaction has a threshold, the cross section for the reaction rises, in some cases, very slowly above the threshold, particularly when the reaction product is a charged particle which has to escape through the coulomb barrier. In the case of light nuclei one must consider the effect of resonances which may introduce large fluctuations in the cross section. Examples of such undesirable cross-section behaviors are the (n,α) reactions in nitrogen[21] and neon.[22] The $N(n,\alpha)$ reaction which has a threshold of around 0.3 Mev has a negligibly small cross section below one Mev, and above this energy the cross section fluctuates by factors of the order of 10. On the other hand, the (n,p) reaction in sulfur appears to show a behavior more suitable for a threshold detector.[23,24] Particularly desirable characteristics as threshold detectors are exhibited by some of the fissionable materials, in particular Th^{232}, U^{238}, and Np^{237}.[25,26] Present information regarding neutron induced threshold reactions is sufficiently limited to make their use at a variety of primary neutron energies difficult.

It would be most desirable to have a threshold detector available whose threshold can be varied at will. To some extent hydrogen recoil counters have this property[27] if the hydrogen recoils produced in a gas or a thin hydrogenous foil are observed, and only those recoils are counted which have energies larger than a fixed bias energy B. If we assume that the hydrogen scattering cross section varies as $1/v$, which is a good approximation for neutron energies from a few hundred kev to several Mev, the sensitivity of such a detector is zero below $E_0 = B$ and reaches a maximum at $E_0 \approx 3B$. It does not differ by more than 25 percent from the maximum value in the energy range $1.6B < E_0 < 9.5B$. While such detectors have not been used extensively, it would appear that the possibility of their application to measurements of inelastic scattering has considerable promise.

In addition to their use for distinguishing between elastic and inelastic scattering, threshold detectors are also useful for obtaining information regarding the distribution in energy of inelastically scattered neutrons. If a sufficient variety of detectors with different thresholds is available, it is possible to find out what fraction of the neutrons are scattered inelastically below the various thresholds.

The use of threshold detectors is discussed in Section VI of reference 1 where there is also a listing of of additional literature on the subject.

Neutron Spectrometers

For measurements of the distribution in energy of inelastically scattered neutrons, it would be best to employ a fast neutron spectrometer. In spite of many efforts to devise such an instrument, no satisfactory fast neutron spectrometer is available at the present time.

Most measurements of fast neutron spectra have been performed by observing hydrogen recoils in photographic emulsions or cloud chambers. Limitations of the photographic plate technique have been discussed in Section III of reference 1. Since information regarding inelastic scattering is desired for a variety of primary energies and many elements, a serious drawback in the use of photographic plates and cloud chambers is the tediousness of reading and evaluating the proton recoil tracks. A great saving in time and effort would be realized if electric counting methods could be used. Determinations of neutron energy spectra by an analysis of the distribution in energy of proton recoils is made difficult by the dependence of the energy of recoil on the angle between the incident neutron and the recoiling particle. Although collimation of the recoiling particles enables one to obtain a one-to-one correlation between the energy of the neutrons and the energy of the recoils, the resulting reduction in intensity and the presence of backgrounds has prevented the successful application of this technique.

Determinations of the distribution in energy of the products of neutron-induced reactions in light nuclei offer another possibility for measuring energy spectra of fast neutrons. The reasons why this method has not been successful are discussed in Section VII of reference 1.

Published measurements of the distribution in energy of inelastically scattered neutrons have been carried out by means of threshold detectors,[28,29] cloud chambers,[30] and photographic plates.[11a,31]

[21] C. H. Johnson and H. H. Barschall, Phys. Rev. **80**, 818 (1950).
[22] Johnson, Bockelman, and Barschall, Phys. Rev. **82**, 117 (1951).
[23] E. D. Klema and A. O. Hanson, Phys. Rev. **73**, 106 (1948).
[24] E. Bleuler, Helv. Phys. Acta **20**, 519 (1947).
[25] E. D. Klema, Phys. Rev. **72**, 88 (1947).
[26] Nucleonics **8**, 78 (January, 1951).
[27] H. H. Barschall and H. A. Bethe, Rev. Sci. Instr. **18**, 147 (1947).
[28] D. D. Phillips, Ph.D. thesis, University of Texas (1949).
[29] Barschall, Battat, Bright, Graves, Jorgensen, and Manley, Phys. Rev. **72**, 881 (1947).
[30] E. Hudspeth and T. W. Bonner, Phys. Rev. **53**, 928 (1938); H. F. Dunlap and R. N. Little, Phys. Rev. **60**, 693 (1941).
[31] B. G. Whitmore and G. E. Dennis, Phys. Rev. **84**, 296 (1951); P. H. Stelson and C. Goodman, Phys. Rev. **82**, 69 (1951); E. R. Graves and L. Rosen, Phys. Rev. **87**, 239 (1952).

Collimation and Shielded Detectors

As has been pointed out in the section on elastic scattering, observations of the scattered neutrons usually require the use of a shield or collimator in order to reduce the effect of neutrons which reach the detector directly from the source without having been scattered by the sample under investigation. The previously described methods for shielding the detector are also applicable to studies of inelastic scattering. For measurements of inelastic scattering, shielding or collimation can be applied most simply to threshold detectors. If the threshold of the detector lies just below the energy of the primary neutrons, one can be sure that inelastically scattered neutrons which have suffered only a small energy loss will not be included among the elastically scattered neutrons. In this case virtually no information is needed regarding the variation of cross section above the threshold. On the other hand, particularly for investigations of the scattering by light nuclei, energy losses in elastic collisions may reduce the energy below the threshold of the detector. For this reason a knowledge of the variation of cross section with energy is required for studies of light nuclei.

When a threshold detector is used, the inelastic collision cross section may be obtained in the following manner: $\sigma_e(\varphi)$ is measured by moving the detector or the sample. The simplest way of calculating $\sigma_e(\varphi)$ is by substituting the observed counting rates into Eq. (4). By integrating over all values of φ, σ_e may be calculated. The inelastic collision cross section is obtained by subtracting σ_e from the total cross section. In order to obtain some information regarding the distribution in energy and angle of the inelastically scattered neutrons, the experiment may be repeated with different threshold detectors. The results of such experiments can, however, be interpreted only if the energy sensitivity of the various threshold detectors is well known.

Both collimation of the primary neutrons and shielding of the detector have been used for measurements of inelastic scattering. The former method has been applied to a beam of polyergic fast neutrons from the Los Alamos fast reactor.[32] In this case the same threshold detector was used for a measurement of the total cross section as for the detection of the scattered neutrons.

Shielding of the detector only, permits the use of larger samples and results in greater intensities of scattered neutrons. The technique is, therefore, more amenable to measurements on monoergic sources.[9,29] On the other hand, there is some danger that scattering by the shield will alter the spectrum of the primary neutrons and of the neutrons scattered by the sample.

Measurements with threshold detectors determine the number of neutrons which have been removed by inelastic collisions from the primary beam and do not detect the neutrons which have actually been inelastically scattered. This is the reason why inelastic collision cross sections must be obtained in an experiment of the type just discussed, by subtraction from the total cross section. On the other hand, when a device which measures neutron energy is used the inelastically scattered neutrons are observed directly. Few experiments of this type have been performed so far.

There is little experimental information available regarding the distribution in angle of inelastically scattered neutrons. For heavy elements and high neutron energies it is generally believed that the assumption of isotropic scattering of the inelastically scattered neutrons is reasonable since transitions to a large number of energy levels are involved. Many determinations of inelastic scattering cross sections which have been published have been obtained under the assumption of isotropic scattering of the inelastically scattered neutrons.

Poor-Geometry Experiments

In Section III it was shown how poor-geometry experiments may be used to determine the angular distribution of elastically scattered neutrons. The method may be extended to measurements of inelastic scattering. It will now be assumed that the measurements are to be carried out with a threshold detector. For the purpose of this discussion it will be assumed that the detector has an ideal response, i.e., zero sensitivity below an energy B, and constant sensitivity above this energy. If inelastic collisions take place, Eq. (12) should be modified as follows:

$$I/I_0=1-N\left[\int_{\varphi_m}^{\pi}\sigma_e(\varphi)2\pi\sin\varphi d\varphi+\int_{\varphi_m}^{\pi}\int_{B}^{E_0}\sigma_i(\varphi,E)dE2\pi\sin\varphi d\varphi+\int_0^B\sigma_i(E)dE+\sigma_a\right]. \quad (13)$$

The second term in the bracket takes into account the neutrons which have lost energy in inelastic collisions but still have an energy above the threshold of the detector; the third term in the bracket describes inelastic collisions which take neutrons to below the threshold of the detector; the fourth term includes all inelastic collision processes apart from scattering. By performing measurements in different geometries, i.e., by varying φ_m, it is possible to determine the distribution in angle of both the elastic and inelastic scattering. Variations of the threshold B will give $\sigma_i(E)$. If the detector is a biased hydrogen recoil counter, it is possible to obtain simultaneously the cross sections for different effective thresholds B. While this method is, in principle, capable of giving complete information

[32] E. T. Jurney and C. W. Zabel, Phys. Rev. 86, 594(A) (1952).

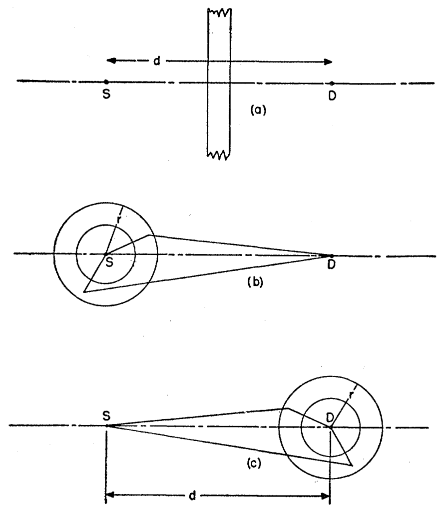

FIG. 2. Geometry for measurements of inelastic collision cross section (a) large plane scatterer; (b) spherical shell around source; (c) spherical shell around detector.

about elastic and inelastic scattering, the following factors reduce the accuracy of the measurements. The non-ideal behavior of threshold detectors introduces large uncertainties in the energy B; since all information is obtained by taking differences between measurements carried out at different thresholds and different angles, high accuracy is required of the measurements in order to obtain reasonable accuracy for the differences; if accelerated particle sources are used, corrections for the anisotropy of the source may introduce large errors and uncertainties; the sample may be too thick for approximation (7) to be valid; poor-geometry experiments require the use of samples of large diameter so that corrections for multiple scattering may become important. Extensive calculations of some of these corrections, in particular, the corrections for multiple scattering in large disks and for the effect of energy losses in elastic scattering by light elements have been carried out by Olum.[33]

Sphere Transmission Experiments

If a poor-geometry transmission experiment is carried out with a very large disk, φ_m approaches π, and Eq. (13) shows that such an experiment measures an inelastic collision cross section since the effect of elastic scattering would cancel. At high neutron energies the elastic scattering takes place almost entirely in a small forward cone, so that the effect of elastic scattering will cancel if φ_m is larger than the maximum angle through which neutrons are scattered elastically. Amaldi *et al.*[11] took advantage of this fact in their measurements of inelastic collision cross sections for Li+D neutrons using the $Cu^{63}(n,2n)$ reaction as a detector. The same result can be accomplished by using scatterers in the form of spherical shells.[34] If a neutron source is surrounded by such a shell, the apparent strength of the source as observed at a large distance is not altered as long as only elastic collisions take place in the scattering material. The apparent source strength will, however, be reduced by absorption processes taking place in the sphere. If the neutrons are detected by means of a threshold detector, inelastic scattering which takes the neutrons to below the threshold of the detector will appear as absorption. Threshold detector measurements of the transmission through a spherical shell placed around the source will therefore yield inelastic collision cross sections. For the calculation of the cross section, it is necessary to know the effective path of the neutrons in the spherical shell. If the shell is sufficiently thin so that multiple collisions in the shell are improbable, the thickness of the shell may be used as the path length to determine N when the cross section is calculated from Eq. (1).

Since some of the neutrons counted by the detector originate in the scattering material, the effective position of the source is altered by the introduction of the shell. In order to minimize this effect it is necessary to choose the radius of the sphere small compared to the distance between source and detector If $d>3r$ (see Fig. 2), errors in calculation of the elastic scattering produced by this effect amount to less than one percent under the assumption of isotropic scattering.[28]

Measurements of the transmission through a spherical shell surrounding the neutron source will give correct inelastic collision cross sections only if the neutron source is isotropic. In general, only natural sources like photoneutron sources satisfy this condition, while most accelerated particle sources are sufficiently anisotropic to preclude this type of measurement. The method may be modified, however, to be usable even with anisotropic sources by surrounding the detector rather than the source by a spherical shell. For a thin shell, the geometry is symmetric in source and detector, i.e., for each possible neutron path in the geometry shown n Fig. 2(b) there is an equivalent path when source and detector are exchanged.[34a]

Anisotropy of the source may introduce errors even in the geometrys hown in Fig. 2(c) if the intensity or energy of the neutrons varies appreciably across the sphere. If the sphere is small compared to the distance between source and detector, this effect may not be appreciable, and it may be further reduced by an appropriate choice of the angle between the line on which source and detector are placed with respect to the direction of the incident charged particle beam from the accelerator, as discussed under Poor-Geometry Experiments in Section III.

[33] P. Olum, AEC report MDDC-353 (1946).

[34] C. H. Collie and J. H. E. Griffiths, Proc. Roy. Soc. (London) **A155**, 434 (1936); Gittings, Barschall, and Everhart, Phys. Rev. **75**, 1610 (1949).

[34a] A general proof of the reciprocity theorem which is valid also for thick spheres was given by H. A. Bethe, Los Alamos report LA-1428 (1952).

Determinations of inelastic collision cross sections for 14-Mev neutrons using transmissions through spheres have been carried out by Phillips[28] who has also discussed the limitations of the technique and the corrections which have to be applied to the measurements. (See also reference 34a.)

Integral Experiments

The spatial distribution of neutrons in a large piece of material depends both on the elastic and inelastic collision cross section. By measuring such a distribution with a threshold detector, it is, in principle, possible to obtain information about these cross sections. For such integral experiments it is most desirable to use a spherically symmetric geometry. A preferably isotropic neutron source may be surrounded by a large sphere of the materials to be studied and the radial distribution of neutrons measured by means of threshold detectors which must be small enough to introduce a negligible disturbance of the neutron flux. Calculations to evaluate the results of such measurements are sufficiently difficult that so far no reliable cross-section determinations have resulted from such measurements.

Time-of-Flight Measurements

Distributions in energy of inelastically scattered neutrons may be determined by their time of flight between the scatterer and a detector. For fast neutrons the times which have to be measured are of the order of 10^{-7} second for distances of the order of a few meters. Such times are about ten times shorter than the best time resolution which has been attained in time-of-flight measurements on slow neutrons.[35] With the advent of scintillation detectors it has become possible to measure times with sufficient accuracy to make meaningful measurements of the time of flight for fast neutrons. At the time of this writing, no measurements of inelastic scattering by the time-of-flight method appear to have been performed. With the usually available accelerated particle sources the counting rates to be expected in such time-of-flight measurements are small enough to have discouraged the exploration of this method.

Observation of Gamma-Rays

Whenever inelastic scattering takes place the bombarded nucleus is left in an excited state and will return to its ground state by gamma-ray emission. Observation of the gamma-rays associated with inelastic scattering may yield information about inelastic scattering cross sections.[36] The most successful measurements of this type are observations on the inelastic scattering of 2.5-Mev neutrons by light elements with the aid of a calibrated pair of Geiger-Müller counters operated in coincidence.[37] In addition to cross sections for inelastic scattering, these measurements yielded values of gamma-ray energies from the form of the absorption curve and from the range of secondary electrons.

If the neutron energy is sufficiently high to excite more than the first excited state of the bombarded nucleus, there is no assurance of a one-to-one correlation between the number of gamma-rays and the number of inelastically scattered neutrons, since the gamma-rays may be emitted in cascade. In addition to this limitation, measurements of the distribution in number and energy of gamma-rays are about as difficult as the corresponding measurements for neutrons. While great progress has been made in recent years in measurements of gamma-ray spectra primarily through the use of scintillation counters, attempts to apply these techniques to studies of inelastic scattering of neutrons have not been very successful, partly because the intense fast neutron flux incident upon the gamma-ray detector produces a high background.

In the neighborhood of almost every fast neutron source many slow neutrons are produced by collisions of the source neutrons with the floor and the walls of the laboratory and also by collisions in air. Capture of these slow neutrons in surrounding materials will result in the production of gamma-rays which may be difficult to distinguish from the gamma-rays produced in inelastic scattering.

V. REACTIONS PRODUCING CHARGED PARTICLES

Measurements of cross sections for neutron-induced reactions in which charged particles are produced are usually simple to carry out provided they are performed in a known neutron flux. In almost all cases the accuracy of the measurement is determined by the accuracy with which the neutron flux can be measured. It will be assumed that the neutron flux can be determined by one of the methods described in reference 1 and that the problem is only to measure the number of reactions per nucleus in the sample.

Fission

Because of the large amount of energy released in the fission process, fission cross sections are easier to determine than any other reaction cross section. The usual procedure[25,38] is to place a thin layer of the fissionable material into an ionization chamber and to count the number of fission processes taking place. The cross section may be obtained from

$$\sigma = C/(n\phi), \tag{14}$$

where C is the counting rate for an incident flux ϕ, and n is the total number of nuclei in the sample. n may be calculated from the weight of the sample or,

[35] W. W. Havens, Jr., and L. J. Rainwater, Phys. Rev. **83**, 1123 (1951).

[36] H. Aoki, Proc. Phys.-Math. Soc. Japan **19**, 369 (1937); I. Nonaka, Phys. Rev. **59**, 681 (1941); I. Nonaka, Proc. Phys.-Math. Soc. Japan **25**, 227 (1943).

[37] Grace, Beghian, Preston, and Halban, Phys. Rev. **82**, 969 (1951).

[38] Ladenburg, Kanner, Barschall, and Van Voorhis, Phys. Rev. **56**, 168 (1939).

in many cases, from the number of alpha-particles emitted. Since in each fission process two fragments traveling in opposite directions are produced, all fission processes may be counted readily, irrespective of the direction of the incident neutrons with respect to the foil of fissionable material. The large energy of the fission fragments enables one to count the fission processes easily above the background of alpha-particles or of other reactions which might take place in the counter.

Equation (14) is based on the assumption that all disintegrations will result in ionizing events which can be counted. For this assumption to be valid, the layer of fissionable material must be very thin compared to the range of the fragments since some fragments will travel parallel or almost parallel to the plane of the foil and will, therefore, produce no or little ionization in the gas. A correction for such events can be applied to the data provided the foil is sufficiently flat and of uniform thickness.

The considerations of the effect of background neutrons given in Section II of the present paper and in Section VI of reference 1 are applicable to the measurements of reaction cross sections. Backgrounds are particularly troublesome in measurements on reactions which can be induced by thermal neutrons. While a cadmium shield surrounding the detector will absorb the strictly thermal neutrons, it is necessary to reduce as much as possible and to determine accurately the effect of epi-thermal neutrons.

Reactions Producing Light Charged Particles

Neutron-induced reactions producing light charged particles such as protons and alpha-particles may be observed in the same manner as fission processes. The smaller energy of the reaction products makes their observation, however, more difficult. Since the reaction energy is in this case of the same order of magnitude as the energy of the fast neutrons, the distribution of the energy between the two charged particles produced in the reaction depends on the direction of their emission with respect to the incident neutrons. If the element to be investigated is prepared in the form of a thin foil on a heavy backing, one of the charged particles will, in many cases, not enter the counting volume. For a given reaction energy there will, therefore, in general be a continuous distribution in the energy released in the counting volume. If several modes of disintegration take place simultaneously, this spread in energy may make the distinction between the various processes impossible.

Even if only one mode of disintegration occurs, it is not always simple to determine the total number of disintegrations taking place. In the most frequently used geometry the neutrons are incident normal to the foil and the counting volume is in the forward hemisphere. In this geometry all disintegrations will produce at least one particle which enters the counting volume and all the reactions may be detected provided the energy of the residual nucleus is high enough to produce an observable pulse. This latter condition is, however, difficult to satisfy if the residual nucleus is heavy, since the heavy nucleus carries little energy and has a short range in the foil. For measurements on heavy nuclei it is, therefore, usually advantageous to bias the detector so that none of the heavy nuclei are detected and to count in a separate experiment, in which the counter is inverted, those disintegrations in which the light particle enters the backward hemisphere. The case which causes the greatest difficulty is that of relatively light nuclei in which the two product particles cannot be distinguished on the basis of their energy and in which some of the reactions produce less ionization in the counting volume than nuclei recoiling from elastic collisions or fast electrons produced by gamma-rays.

Since the foil in which the disintegrations take place must be very thin, reactions taking place in other parts of the counter may produce a large background. In particular, disintegrations produced in the counter gas are likely to be troublesome. This consideration excludes nitrogen as a filling gas, and, at high neutron energies, neon,[22,39] argon,[39] krypton, and xenon have appreciable disintegration cross sections. Background counts will, in addition, result from proton recoils if any water vapor or organic materials are adsorbed on the walls of the counter. In order to reduce this effect, the walls must be carefully cleaned and, if possible, outgassed at high temperature. Disintegrations taking place in the metal walls of the counter and the backing of the foil will likewise contribute to the background. It is, therefore, desirable to line the counter walls with heavy metals which have small cross sections for the emission of charged particles. Ta, Pt, and Au appear to be suitable for such liners.

The difficulties just discussed may be much reduced if the element to be investigated is a gas or forms a gaseous compound. All reactions which have a given reaction energy will release the same amount of energy in the gas. In addition, background effects caused by the wall materials will be less important because larger samples may be used than when the element is placed on a foil. On the other hand, the determination of n, the number of nuclei in the counting volume, is likely to be less accurate than in the case in which a foil is used, unless special precautions are taken to define the active volume of the counter and to reduce end and wall effects.[40] Not all gaseous compounds constitute desirable counter filling gases. If the gas is strongly electro-negative, ion rather than electron collection must be used. The slow motion of the ions can be observed only with amplifiers which have a low

[39] E. R. Graves and J. H. Coon, Phys. Rev. **70**, 101 (1946).

[40] A method suitable for reducing end effects in a cylindrical counter was described by A. L. Cockroft and S. C. Curran, Rev. Sci. Instr. **22**, 37 (1951).

frequency response, and limits the counting speeds severely. This technique has been perfected by P. Huber and his co-workers who have measured reaction and resonance energies with high precision. In these measurements both positive and negative ions were collected in an ionization chamber filled with gases like O_2, CS_2, and SO_2.[41]

Frequently a radioactive nucleus is formed as the product of a nuclear reaction. Observation of the radioactivity may then be used for the determination of the reaction cross section. Such measurements are usually less accurate than direct determinations of the number of reactions taking place, although small reaction cross sections can be detected sometimes more easily by observing an activity, particularly if the element to be investigated cannot be obtained as a gas or gaseous compound. Methods for measuring activation cross sections will be discussed in the next section. Reaction cross sections which have been measured by observations of the resulting radioactivity include the reactions $Be^9(n,\alpha)He^6$,[42] $Al^{27}(n,p)Mg^{27}$,[43] $P^{31}(n,p)Si^{31}$,[43] $S^{32}(n,p)P^{32}$,[23] $Cu^{65}(n,p)Ni^{65}$,[43] and $Zn^{64}(n,p)Cu^{64}$.[43]

VI. REACTIONS PRODUCING UNCHARGED PARTICLES

The present section is concerned with measurements of cross sections for reactions in which no instantaneous emission of energetic charged particles takes place. Such processes are radiative capture (n,γ processes), ($n,2n$) reactions, and reactions in which more than two neutrons are emitted.

Sphere Transmission Experiments

If an isotropic neutron source is surrounded by a spherical shell, a measurement of the transmission through the shell using a threshold detector eliminates the effect of elastic scattering and gives the inelastic collision cross section as was discussed in Section IV. In order to eliminate in addition the effect of inelastic scattering, the threshold detector may be replaced by an energy-insensitive detector such as a long counter.[44] If the sensitivity of this counter is really independent of neutron energy, and only scattering processes take place in the shell, the transmission will be unity. On the other hand, (n,γ), (n,p), (n,α), etc. reactions will reduce the transmission below unity, while a preponderance of ($n,2n$), ($n,3n$), etc. processes will give a transmission greater than one.

At low neutron energies radiative capture is frequently the only absorption process which is energetically possible. The technique of measuring the transmission through a sphere with a long counter was first developed for this case by Hanson.[45] In Hanson's experiments photoneutron sources were used to produce an isotropic flux of low energy neutrons. Since the radiative capture cross sections are usually small, the energy sensitivity of the long counter must be checked carefully. This was done by measuring the transmission through a sphere made of light material which is known to have a negligibly small absorption cross section, such as heavy water or graphite, and by comparing the response of the counter to sources of neutrons of different energies and known strengths.

At high neutron energies the sphere technique may be used to measure ($n,2n$) cross sections provided the cross section for charged particle emission has been measured first and the cross section for radiative capture is known to be small. A limitation of the method is the lack of isotropic high energy neutron sources. A source of 14-Mev neutrons which is approximately isotropic may be obtained by bombarding tritium with low energy deuterons. This technique has been developed by E. R. Graves.[46]

The results of sphere transmission experiments are more difficult to interpret if fission can take place in the material under investigation. In this case the effect of fissions may be subtracted provided the fission cross section and the number of neutrons per fission are known.

Activations

If the final nucleus formed in an (n,γ) or ($n,2n$) reaction is radioactive, this activity may be used to determine the cross section for the process. In contrast to the other methods described in this section, activation measurements give cross sections for a particular isotope rather than for the element. The requirement of an absolute determination of a beta-activity is the principal difficulty of this technique. Methods for absolute beta-counting have been discussed elsewhere.[47] Usually the measurement involves a comparison with a *Ra-DEF* source of known activity. Necessary precautions include the use of as large an acceptance angle of the counter as possible to reduce the effect of scattering of electrons in the sample, and of thin samples and thin counter windows in order to reduce the effect of absorption.

Since radiative capture cross sections for fast neutrons are relatively small, low beta-activities are produced by available fast neutron fluxes. Consequently the requirement of thin samples can frequently not be met conveniently. It was first pointed out by Segrè[48] that measurements of radiative capture cross sections for fast neutrons could be performed with thick samples and without the requirement of absolute beta-counting

[41] A. Stebler and P. Huber, Helv. Phys. Acta **21**, 59 (1948).
[42] Allen, Burcham, and Wilkinson, Proc. Roy. Soc. (London) **A192**, 114 (1947).
[43] E. Bretscher and D. H. Wilkinson, Proc. Cambridge Phil. Soc. **45**, 141 (1949).
[44] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).
[45] A. O. Hanson, AEC report LADC-323 (1952).
[46] E. R. Graves (private communication).
[47] B. P. Burtt, Nucleonics **5**, 28 (August, 1949); H. H. Seliger and L. Cavallo, J. Research Natl. Bur. Standards **47**, 41 (1951).
[48] E. Segrè, AEC report MDDC-228 (1946); D. J. Hughes, Phys. Rev. **70**, 106 (1946).

by taking advantage of previous measurements of radiative capture cross sections using thermal neutrons for which there are usually no intensity difficulties. The method consists of a comparison of the activity induced in a given sample by thermal neutrons with that induced by fast neutrons. At the same time the thermal and the fast neutron fluxes which produce the activities are compared by means of a detector whose sensitivity as a function of neutron energy is known, such as B^{10}. Several measurements of radiative capture cross sections using this technique have been published.[49]

A very similar technique has been used for measuring the $(n,2n)$ cross section of Cu^{63}.[50] While this reaction cannot occur for thermal neutrons, the end point of the positron spectrum emitted by Cu^{62} is about the same as that of the electron spectrum emitted by Cu^{66} which is produced by radiative capture of slow neutrons in Cu^{65}, so that the $Cu^{63}(n,2n)$ cross section may be compared with the $Cu^{65}(n,\gamma)$ cross section.

Observation of Gamma-Rays

Gamma-rays emitted upon capture of neutrons may be used for the observation of capture processes.[51] Attempts to make such observations quantitative encounter the same difficulties as have been described in Section IV. The presence of gamma-rays from other sources would again be a disturbing factor. If transitions to the ground state of the final nucleus take place, some of the gamma-rays from the capture of fast neutrons have higher energies than those resulting from inelastic scattering or slow neutron capture. While it is possible to observe these gamma-rays, such observations do not allow one to obtain the cross section for radiative capture except to set a lower limit on such a cross section.

VII. ACCURACY OF CROSS-SECTION MEASUREMENTS

The highest accuracy can be obtained in cross-section measurements which do not require an absolute flux determination, in particular measurements of total cross sections. The principal source of uncertainty in such measurements lies in the corrections for background and inscattering which were discussed in Section II. An additional limitation is imposed by the neutron source itself. In the case of accelerated particle sources the neutrons must pass through the walls of a vacuum chamber and may be degraded in energy by inelastic collisions in these walls. Since the energy of the neutrons depends on their direction of emission with respect to the incident charged particle beam, some neutrons starting out in a direction other than the direction of observation may be scattered by the target or by material surrounding the target into the detector. These effects will result in an uncertainty of the distribution in energy of the neutrons, and because of the dependence of cross sections on energy, in an uncertainty of the measured cross section. A similar situation obtains in the case of photoneutron sources. Here the most important energy spread of the neutrons is caused by elastic collisions in the target material in which the neutrons are produced, since this target usually consists of a thick layer of D_2O or Be.

In view of these considerations it is difficult to measure total cross sections at a well-defined neutron energy to better than one percent, although some recent determinations of the n-p cross sections are reported to have an accuracy of $\frac{1}{4}$ percent.[52]

Measurements of cross sections involving an absolute flux determination have not nearly reached the accuracy of total cross-section measurements. The principal cause of uncertainty in such measurements is the flux determination which at present has not been carried out to an accuracy of better than 5 percent.[1] The uncertainties introduced by a spread in neutron energy will also be present in such measurements and contribute to the error. In addition it is not always possible to be certain that the flux incident upon the detector is the same as that measured by the flux measuring device. For these reasons, no fast neutron cross section involving an absolute flux determination has been published to an accuracy of better than 10 percent.

Measurements of inelastic cross sections require a knowledge of the sensitivity of the detector as a function of energy for either neutrons or gamma-rays. Although it is possible to obtain rather accurate measurements for a given detector, the interpretation of the meaning of the measured inelastic cross section introduces difficulties in many cases. If, for example, a threshold detector is used to detect neutrons, the deviations from a flat response above threshold will result in different weighting of neutrons scattered inelastically with different energies.

[49] Hughes, Spatz, and Goldstein, Phys. Rev. **75**, 1781 (1949); R. L. Henkel and H. H. Barschall, Phys. Rev. **80**, 145 (1950).
[50] J. L. Fowler and J. M. Slye, Jr., Phys. Rev. **77**, 787 (1950).
[51] D. C. Grahame and G. T. Seaborg, Phys. Rev. **53**, 795 (1938).
[52] Hafner, Frisch, Falk, Coor, and Hornyak, Phys. Rev. **86**, 593 (1952).