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Measurement of Fast Neutron Flux*

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I. INTRODUCTION

MEASUREMENTS of fast neutron flux are of importance for most determinations of the absolute cross sections for the interaction of fast neutrons with nuclei, and also for measurements of the cross sections of charged particles for processes which result in the production of neutrons. Since neutron cross sections are strongly energy dependent, significant determinations of cross sections almost always require the use of monoergic neutrons. For such a purpose methods which are limited to measuring a flux of monoergic neutrons are satisfactory. Methods which can be used for accurate flux determinations of polyergic neutrons are more difficult to devise and have fewer applications. First, methods for flux measurement will be described for applications to monoergic neutrons; their extension to polyergic sources will be discussed separately.

In most applications to accurate flux measurements a source of neutrons is used whose diameter is small compared to the distance at which the measurement is performed. The methods for flux measurements to be described are primarily designed for this case. While there are problems involving measurements on polyergic neutrons moving in all directions, notably in chain reacting systems, no satisfactory method for measuring the flux accurately is available at present. A factor which complicates measurements inside reactors or other solid structures is the fact that the introduction of a flux measuring device is likely to distort the original neutron distribution.

The main difficulty in measurements of neutron flux arises from the fractional and energy dependent sensitivity of detectors to neutrons passing through them.

Different experimental conditions existing for different neutron energy ranges strongly affect the methods used for measuring fast neutron flux; there are, however, rather broad categories into which most of the methods fall. First these will be listed with a brief general discussion of the principles involved and then each method will be discussed in detail together with its possible extensions.

1. Associated Particle Methods

Since neutrons arise only from nuclear reactions, there always exist at the time of their formation one or more charged particles associated with each neutron. Experimental conditions determine whether these particles can be detected. In some cases a one-to-one correspondence exists between neutron and charged particle, and the counting of these charged particles with known efficiency determines the associated neutron flux.

2. Recoil Particle Methods

This method depends on the fact that in some energy ranges the only type of interaction of neutrons with certain nuclei is elastic scattering. If this condition obtains, then a simple attenuation experiment on the neutrons themselves, using almost any detector, will establish the value of the scattering cross sections from

$$I/I_0 = e^{-N\sigma t}. \quad (1)$$

Here I/I_0 is the transmission, t the thickness in cm of the attenuating material, N the number of attenuating nuclei per cm^3, and σ the elastic-scattering cross section in cm^2. In order to determine σ, it is not necessary to

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know the flux of neutrons, provided the incident flux is the same with and without the attenuator in place, but once the cross section has been determined it may be used to measure an unknown flux if the recoiling particles can be detected with a known efficiency.

More generally, this method is applicable not only to those cases in which elastic scattering is the only process occurring, but to all cases in which a single type of nuclear interaction can be measured by an attenuation experiment. For instance, at very low neutron energies the greatly predominant interaction in some elements (e.g., B^{10}) is neutron capture leading to an easily detectable charged particle; thus the total cross section is essentially equal to the capture cross section. In principle, one could also perform a "poor geometry" transmission experiment with fast neutrons in such a way that the elastic scattering is eliminated and the attenuation arises only from another single process.

3. Methods of Total Source Strength

A. Thermalization Method

The total neutron-source strength is determined by immersing the source in a moderating material which contains an appreciable amount of absorber with a high cross section and integrating the rate of absorption over the whole moderator. Since the leakage rate is small and determinable, the source strength, i.e., the rate of production, is equal to the rate of absorption. It should be pointed out that this method does not discriminate between neutrons of various energies which may come from the source nor is it sensitive to any angular asymmetry of the neutron source.

Instead of introducing an absorbing material into the moderator it is also possible to measure the flux of thermal neutrons at such a distance from the source that the thermal flux is insensitive to the primary energy. This method is used primarily to compare the strengths of radioactive sources, but has also been applied to measurements of the cross sections of (α, n) reactions.

B. Radioactive Product Method

In some charged particle reactions which may be used as neutron sources, a radioactive product is formed. By determining the radioactivity produced one may obtain a measure of the number of neutrons which were emitted from the source.

4. Long Counter and Similar Methods

In this method a detector is used whose response as a function of neutron energy is known and is preferably independent of neutron energy, but whose absolute sensitivity need not be known. One depends then on a knowledge of neutron flux at, at least, one energy and extending the measurements to other energies on the basis of the known energy response of the detector.

5. Method of Reaction Cross-Section Comparisons

This method, as the "long counter" method, yields only a secondary flux determination. It may be used to compare a known with an unknown nuclear reaction cross section in the same flux. It is possible, however, to establish in this way, secondary standards which are of great value.

It is clear that the absolute counting of neutrons depends on counting charged particles which are detected with known efficiency.

II. THE ASSOCIATED PARTICLE METHOD

The most straightforward method of determining the absolute number of fast neutrons emitted by a source is to take advantage of the fact that certain nuclear reactions which act as such sources emit an energetic charged nucleus with each neutron. Practical examples to which the detection of such particles has been applied are

$$D+D\rightarrow \mathrm{He}^3+n+Q_1 \tag{2}$$

$$D+T\rightarrow \mathrm{He}^4+n+Q_2. \tag{3}$$

At sufficiently high bombarding energies other reactions which are commonly used as sources of monoergic neutrons are also amenable to this technique. A promising example is

$$p+T\rightarrow \mathrm{He}^3+n+Q_3. \tag{4}$$

At the present time the associated particle method has been used successfully to determine the number of fast neutrons emitted in a small solid angle by observing the number of He^3 particles in reaction (2) or He^4 particles in reaction (3) emitted in the corresponding solid angle. There is every reason to believe that the method could be extended to determine the total number of neutrons emitted in all directions from a reaction of the above type. In view of the limited amount of experience that has been attained in the application of the associated particle method to problems of absolute neutron flux determinations, the present discussion will be limited to a presentation of the characteristics of reactions (2) and (3). Only a restricted number of suggestions will be made about the difficulties inherent in the application of the method.

The Q's of reactions (2) and (3) are 3.27 Mev and 17.60 Mev, respectively. The energy, E_3, of the neutron emitted at a given angle θ_3 with respect to the incident deuteron direction in the laboratory system of coordinates and for an incident deuteron energy E_1, can be calculated from collision mechanics.[1] The associated He^3 particle is emitted at an angle θ_4 with respect to the incident deuteron direction calculated from

$$\sin\theta_4=(M_3E_3/M_4E_4)^{\frac{1}{2}}\sin\theta_3, \tag{5}$$

where M_3 and M_4 are the masses of the neutron and

[1] Hanson, Taschek, and Williams, Revs. Modern Phys. **21**, 635 (1949).

He^3 particle and the energy of the He^3 particle is

$$E_4=E_1+Q-E_3. \tag{6}$$

Q is considered as positive for an exoergic reaction. By means of these equations it is possible to calculate the angle for particle observation that corresponds to a given angle of neutron observation.

In practice it is more usual to observe the charged particles at some fixed angle and to vary the incident deuteron energy E_1 or neutron angle θ_3 in order to obtain neutrons with the desired energy. This is particularly true since the deuterium or tritium gas target should be confined in a chamber which contains as little scattering material as possible so that the neutron detector may receive a minimum number of scattered neutrons. This criterion necessitates a simple mechanical design for the particle detector connected to the gas target and makes it rather impractical to consider changing the angle θ_4.

A gas target chamber which allows observation of particles at a variable angle has been used[2] as such a neutron source, but it was not designed for accurate absolute neutron flux determinations. In the cases where the differential cross section for a neutron producing reaction is known as a function of angle and energy, it is not necessary to measure the charged particles at a variety of angles θ_4 since this differential information allows a calculation of the number of neutrons emitted at any angle, θ_3, from an observation of the number of charged particles emitted at a fixed angle, θ_4.

For a given design of reaction target chamber the charged particle detector will subtend a known solid angle for receiving associated particles from the neutron producing reaction. In general, the neutron detector or neutron activated experimental device will not subtend the same solid angle. It is, therefore, necessary to correct the observations to take account of this geometric difference.

In addition to the different apertures subtended by each detector, there is a correction factor resulting from dependence of solid angle upon the angle of observation in the laboratory system of coordinates. If $I_4(\theta_4)$ represents the intensity of charged particles per unit laboratory solid angle centered about θ_4, then the intensity of neutrons per unit solid angle centered about θ_3 is given by

$$I_3(\theta_3)=I_4(\theta_4)\frac{\cos(\pi-\phi-\theta_4)\sin^2\theta_4}{\cos(\phi-\theta_3)\sin^2\theta_3}, \tag{7}$$

where ϕ is the angle between the direction of the incident particle and the emitted neutron in the center-of-mass system of coordinates.

If the gas taget is arranged with a particle detector at a fixed angle, as suggested above, it is necessary to know the differential cross section for the reaction as a function of angle. Such information can be obtained for the $D(D, n)He^3$ reaction from the work of Blair, *et al.*,[3] who observed the He^3 disintegration products, and from the observations of the neutron flux by Hunter and Richards.[4] These data are sufficient to allow an application of the associated particle method of measuring the flux of neutrons to the $D-D$ reaction in the range of incident deuteron energy from 0.5 to 3.7 Mev.

For lower deuteron energies the emitted He^3 has such a small range that it is difficult to detect with a proportional counter.[5]

The associated reaction, $D(D, p)H^3$, emits protons of sufficient energy to be readily detectable. These protons may serve as a monitor of the yield of neutrons from the $D-D$ reaction. Indeed, if the ratio of the number of protons emitted in the $D(D, p)H^3$ reaction to the number of neutrons emitted from the $D(D, n)He^3$ reaction is accurately known as a function of incident deuteron energy, E_1, and emitted particle angles, θ_3, the proton monitor can be made to serve as a quantitative measure of the number of neutrons emitted in reaction (2). Some information of this type is available from the work of Coon *et al.*,[6,7] McNeill *et al.*,[5] Erickson *et al.*,[8] and Allred *et al.*[9]

Similarly, it is necessary to know the differential cross section for the $T(D, n)He^4$ reaction to apply this method for the determination of neutron flux at a given angle from this reaction. In this case the measurements available are those of Bretscher and French, Allan and Poole, and Taschek *et al.*[10] The results of Taschek *et al.* are presented in Fig. 9 of reference 1. These authors observed the disintegration particles emitted in the angular range of 45° to 90° in the laboratory system of coordinates and at incident deuteron energies of 1.0 to 2.5 Mev. The curves shown in Fig. 9 of reference 1 have been extrapolated to cover the center-of-mass angular range of 0° to 180° by applying a Legendre polynomial analysis of the data. Bretscher and French, and Allan and Poole have measured the yield of alpha-particles emitted at 90° for incident triton energies up to 200 kev and have shown that the angular distribution is spherically symmetric at these low bombarding energies.

If the total flux of neutrons from reactions (2) and (3) is to be determined by the associated particle technique, one can choose to measure either the total incident deuteron current and gas target thickness or the number of associated particles at some fixed angle.

[2] R. F. Taschek, Rev. Sci. Instr. **19**, 591 (1948).

[3] Blair, Freier, Lampi, Sleator, and Williams, Phys. Rev. **74**, 1599 (1948).

[4] G. T. Hunter and H. T. Richards, Phys. Rev. **76**, 1445 (1949).

[5] McNeill, Thonemann, and Price, Nature **166**, 28 (1950); K. G. McNeill and G. M. Keyser, Phys. Rev. **81**, 602 (1951).

[6] Coon, Davis, Graves, Manley, and Nobles, AEC report MDDC 206.

[7] Coon, Davis, Graves, and Manley, AEC report MDDC, 207.

[8] Erickson, Fowler, and Stovall, Phys. Rev. **76**, 1141 (1949).

[9] Allred, Phillips, and Rosen, Phys. Rev. **82**, 782 (1951).

[10] E. Bretscher and A. P. French, Phys. Rev. **75**, 1154 (1949); D. L. Allan and M. J. Poole, Proc. Roy. Soc. (London) **204A**, 488 and 500 (1951); Taschek, Hemmendinger, and Jarvis, Phys. Rev. **75**, 1464A (1949).

For the former choice the total cross section for neutron production can then be obtained by integrating the known differential cross section over all angles. There is considerable uncertainty introduced by this technique since the differential cross section has not been determined from associated particle observations throughout the entire angular range and must be extrapolated before the integration can be made. However, the contribution to the integral in the forward and backward direction, where the differential cross section has not been measured, is small in view of the small solid angles subtended in these directions. The latter possibility, measuring the number of associated particles at some fixed angle, involves a similar knowledge and uncertainty in the ratio of charged particles detected to neutrons emitted in 4π solid angle. On the other hand, it does not require accurate measurements of incident deuteron current and target gas pressure.

A special case of the associated particle method, which has application in some cases, especially where backgrounds are large, uses coincidences between neutrons and the associated charged particles. Suppose, for example, that one wishes to measure the reaction cross section of an element A which disintegrates with emission of a charged particle for a given neutron energy E_n. The incident particle energy is so chosen that neutrons of the desired energy are emitted at a convenient angle. Due consideration must be given to the angle at which the associated particles will be emitted, as well as to their energy. Element A is deposited inside a counter in such a manner that one can determine the number of atoms/cm^2 of A in the path of the neutron beam defined by the acceptance aperture of the associated particle counter. It is also necessary that the efficiency of the counter be constant over the area in which the defined neutrons are intercepted. The counter containing the element A, the neutron counter, will intercept, aside from the neutrons which correspond to the associated particles being detected, primary neutrons which arise ouside the reaction volume seen by the associated particle counter as well as background neutrons. It is necessary, therefore, to discriminate against reactions produced in A by such neutrons. To do this, one counts the particles entering the proportional counter in coincidence with the reactions produced in the neutron counter. It is evident that the differential cross section as a function of angle for the neutron producing reaction need not be known.

It is also to be noted that although the number of associated particles counted serves to define the number of neutrons entering the neutron counter, and hence, the neutron flux, it is not necessary to count all associated particles entering the proportional counter, since the number of coincidence counts is taken as a measure of the number of neutron interactions. It is only essential that neither the associated particles nor the neutrons suffer excessive scattering between their point of origin and their respective counters, since otherwise a neutron corresponding to a given associated particle might not enter the solid angle defined by the neutron counter.

The above technique made possible the utilization of the 10-Mev Los Alamos cyclotron for neutron cross-section measurements with essentially monoergic $D-D$ neutrons, even though the intensity of the neutron background was as much as 1000 times the intensity of the defined neutrons from the $D-D$ reaction.[11] At lower deuteron energies and perhaps also at high energies with the collimated deuteron beams obtained from electrostatic accelerators, the backgrounds are not so large as from cyclotrons and the coincidence variant of the associated particle method is generally unnecessary.

To summarize, the associated particle technique for absolute determination of neutron flux is inherently a very precise method. At the present time the angular distributions of only the $D(D, n)He^3$ and the $T(D, n)He^4$ reactions have been measured with sufficient accuracy to warrant using this method for neutron measurements requiring neutron flux determinations to an accuracy of better than 10 percent. Further work on neutron reactions such as $T(p, n)He^3$ is required to extend the method with comparable accuracy to neutrons emitted from other reactions.

III. RECOIL PARTICLE METHOD

The earliest attempts to determine a fast neutron flux absolutely were based on observations of recoils from scattered neutrons. In 1935 Alexopoulos[12] reported on a determination of the yield of the $D-D$ reaction using this method. The first quantitative measurement using this technique was carried out by Ladenburg and Kanner[13] in 1937.

The method is based on the fact that total cross sections can be measured without knowledge of the absolute neutron flux by a transmission experiment in good geometry. If it can be shown that no processes other than scattering take place, an observation of the number of recoiling nuclei from a known number of atoms in a thin foil or gas will give the neutron flux, since the flux, nv, in units of cm^{-2} sec^{-1} is given by

$$nv = C/N\sigma, \tag{8}$$

where C is the number of recoils per sec, N the number of atoms from which recoils are observed, and σ the scattering cross section in cm^2.

The choice of a suitable scattering material is influenced by the following considerations.

The accuracy of the measurements depends directly on the accuracy with which the scattering cross section is known. Nuclides for which the cross section varies rapidly with neutron energy are not suitable, since the flux measurement will then depend in too sensitive a

[11] Curtis, Fowler, and Rosen, Rev. Sci. Instr. **20**, 388 (1949).
[12] K. D. Alexopoulos, Helv. Phys. Acta **8**, 601 (1935).
[13] R. Ladenburg and M. H. Kanner, Phys. Rev. **52**, 911 (1937).

way on an accurate knowledge of the neutron energy spectrum. This fact usually excludes materials which have resonances in the energy range under investigation.

It is in general not possible to observe all the recoils; some of them will have such low energy that they will be lost in the background noise of the detector or might be indistinguishable from electrons produced by gamma-rays, or they will have most of their range in the radiator. In order to be able to extrapolate the observed distribution in energy or angle to zero energy or zero neutron scattering angle, it is therefore desirable to know the angular distribution of the elastically scattered neutrons and to avoid nuclides which scatter the neutrons inelastically.

The ease with which recoils may be observed depends on their energy. At lower neutron energies (below 1 Mev) it is usually desirable to have as energetic recoils as possible, and consequently one favors the lightest nuclides. At high energies (above 5 Mev) the ranges of the lightest recoils become so long that it may become difficult to stop them in the detector, and one might therefore prefer a somewhat heavier nuclide.

On the basis of these considerations, it is apparent that, at least at the lower energies, it is best to use proton recoils. The scattering cross section of hydrogen shows no resonances and is known to about two percent up to 1.5 Mev and to better than five percent up to neutron energies of 14 Mev.[14,15] No processes other than elastic scattering need be taken into account since the contribution of capture to the total cross section is negligible for fast neutrons. The angular distribution of neutrons scattered by protons is believed to be isotropic in the center-of-mass system at low energies[16,17,18] and shows a deviation from isotropic scattering of probably less than five percent at a neutron energy of 14 Mev.[19]

Deuterium, like hydrogen, has no known resonances for neutron scattering, and the total cross section is known to better than ten percent.[15] On the other hand, it has been found that the angular distribution of the scattered neutrons is strongly anisotropic in the center-of-mass system even at low neutron energies,[17,18,20] but measurements of the angular distribution have so far been carried out only at a few energies and not with high precision. In addition, there is the possibility that neutrons produce disintegrations in deuterium, although it appears that the cross section for this process is small.[21,22] In view of these uncertainties, hydrogen is preferable to deuterium as a scatterer, even though the shorter range of the recoiling deuterons offers some advantages at high neutron energies.

All nuclides heavier than deuterium are likely to show resonances in their neutron cross section.[15] Virtually no information is available on the angular distribution of the scattering, except for helium, for which a resonance for 1-Mev neutrons[15] produces rapid changes of the angular distribution with neutron energy.[23]

1. Counter Method

Even if all information regarding the nuclear interactions of the neutrons is available, the problem of establishing what fraction of the recoils are observed still offers considerable difficulties. Two methods have been used for this purpose: (a) All recoils which produce ionization pulses of more than a predetermined bias voltage are counted; (b) all recoils which are emitted into a known solid angle are counted.

Method (a) requires a knowledge of the relation between pulse height and energy of recoil. Difficulties which should be mentioned are:

Effects of electron collection. If electron collection is used without special precautions, the pulse height depends on the position at which the ions are formed. In order to take this into account, an accurate knowledge of the range-energy relation is needed.

Saturation. The amount of recombination may depend on the direction of recoil with respect to the collecting field.

Energy loss in the foil, if a radiator is used. A knowledge of the range-energy relation in the foil material is required to calculate this effect.

Wall effects, if a gas is employed.

Variations of the energy necessary to form an ion pair with particle velocity.

In method (b) it is not always easy to calculate the effective solid angle because of the finite size of the radiator. At low energies Rutherford scattering of the recoils, both by the counter gas and by the diaphragms, may introduce appreciable errors.

In most experiments carried out at neutron energies below 6 Mev, method (a) has been used, while at higher energies method (b) is preferred.

Considerable effort has been spent on devising counters suitable for the use of method (a) and on calculations of the various effects which affect the pulse heights of recoils. The book *Ionization Chambers and Counters* by Rossi and Staub,[24] gives an excellent summary of the information available on this subject. It is interesting to note that some of the careful work reported in this summary failed to show the presence of the second group of neutrons now known to be produced in the Li(p, n)Be^7 reaction (see Fig. 7.15 d in reference 16); this is an example of the difficulties encountered in this type of measurement.

Counters and associated equipment suitable for

[14] Lampi, Freier, and Williams, Phys. Rev. **80**, 853 (1950).
[15] R. K. Adair, Revs. Modern Phys. **22**, 249 (1950).
[16] B. B. Rossi and H. H. Staub, *Ionization Chambers and Counters* (McGraw-Hill Book Company, Inc., New York, 1949) p. 166–171.
[17] J. H. Coon and H. H. Barschall, Phys. Rev. **70**, 592 (1946).
[18] I. Hamouda and G. de Montmollin, Phys. Rev. **83**, 1277 (1951).
[19] H. H. Barschall and R. F. Taschek, Phys. Rev. **75**, 1819 (1949).
[20] E. Wantuch, Phys. Rev. **84**, 169 (1951).
[21] J. H. Coon and R. F. Taschek, Phys. Rev. **76**, 710 (1949).
[22] Griffith, Remley, and Kruger, Phys. Rev. **79**, 443 (1950).
[23] T. A. Hall and P. G. Koontz, Phys. Rev. **72**, 196 (1947).
[24] See reference 16, Chapter 7.

method (b) were first used by Amaldi *et al.*[25] and have also been described in reports on experiments carried out at Los Alamos on (n, p), (n, D), and (n, T) scattering[19,21,26] and by Kinsey, Cohen, and Dainty.[27]

The most common procedure is to use a thin radiator for method (a) such that all proton recoils from the radiator with an energy greater than a predetermined value are counted and the flux may be obtained from Eq. (8). If the stopping power of the radiator material is accurately known, it is possible to use instead a radiator which is thick compared to the longest range of recoiling protons. Advantages of the use of a thick radiator are its high detecting efficiency if one wishes to measure a small flux, the stronger discrimination against low energy neutrons,[28] and the relatively much smaller effect of ionization events which may originate in the walls or the gas of the counter. Allen and Wilkinson[29] have found excellent agreement between the calculated and measured energy distribution of the protons from a thick radiator and were therefore able to measure a flux (2.15-Mev neutrons) with high precision.

In all flux measurements using the scattering technique, care must be taken to reduce and to take into account the effect of neutrons scattered in the counter itself. For this purpose the wall of the counter between source and radiator or gas should be as thin as possible. A gas-filled scattering detector is usually more sensitive to neutrons scattered in the walls of the counter than one using a radiator, since backscattered neutrons will produce recoils from the radiator which will usually not enter the counting volume.

Care must be taken to ascertain the number of atoms which are effective in producing recoils. Unless the counter is baked out or carefully cleaned, water vapor may be adsorbed on the walls and produce proton recoils. It is, therefore, advisable to design the counter so that background counts can be taken with the radiator or scattering gas removed. If a solid radiator is used to produce recoiling protons, it is necessary to have a material of known composition. Most experiments of this kind have been carried out with polythene or glycerol tristearate radiators.

2. Photographic Plate Method

A variation of method (b) is to be found in the use of a nuclear emulsion as both radiator and detector. In this case the neutrons collide with protons in the photographic emulsion. After the plate is processed, the trajectories of the proton recoils are evidenced by the developed silver grains which lie along the path of the proton.

In order to make a neutron flux measurement by this method, one exposes plates so that the plane of the emulsion makes an angle of approximately five degrees with the direction of the incident neutrons. Smaller angles are to be avoided because of the rather short mean free path for neutrons in nuclear emulsions. After exposure the plates are processed by a technique which is suitable to the type and thickness of the emulsion used.

Detailed discussions of the types, photographic characteristics and composition of nuclear emulsions commercially available, as well as the processing techniques applicable, have been published.[30–32]

For the analysis of the plates a method similar to the standard techniques used in the measurement of neutron energy spectra with nuclear plates is applied. The chief difference is that, since one is concerned with monoergic neutrons, it is only necessary to count the tracks of proton recoils projected into a given solid angle. The solid angle chosen should be as large as possible consistent with adequate track lengths, but less than 25° in the vertical direction, if one is to make use of a constant shrinkage factor for the processed emulsion.[32]

From a determination of the number of proton recoils projected from unit emulsion volume into a given solid angle, one can calculate the incident neutron flux by making use of the concentration of hydrogen in the photographic emulsion and the $n-p$ differential scattering cross section.

Although this method has the advantage over counters that one can better discriminate against background neutrons and avoid most of the difficulties mentioned for the counter methods, there are other more serious difficulties and limitations which should be emphasized.

The most serious difficulty concerns the accurate delineation of the solid angle in which proton tracks are counted, and it would appear that only with extreme difficulty can one hope to define this solid angle of acceptance of proton recoils to better than ± 15 percent for neutrons of about 1-Mev energy and to ± 10 percent for neutrons of energy greater than 3 Mev.

Another serious difficulty arises in the determination of the number of hydrogen atoms in the volume of unprocessed emulsion analyzed. This involves a knowl-

[25] Amaldi, Bocciarelli, Ferretti, and Trabacchi, Naturwiss. **30**, 582 (1942).
[26] Coon, Bockelman, and Barschall, Phys. Rev. **81**, 33 (1951).
[27] Kinsey, Cohen, and Dainty, Proc. Cambridge Phil. Soc. **44**, 96 (1948).
[28] H. H. Barschall and H. A. Bethe, Rev. Sci. Instr. **18**, 147 (1947).
[29] V. W. Allen and D. H. Wilkinson, Proc. Cambridge Phil. Soc. **44**, 581 (1948).
[30] C. F. Powell, Nature **145**, 155 (1940); C. F. Powell, Proc, Roy. Soc. (London) **A181**, 344 (1943); J. H. Webb, Phys. Rev. **74**, 511 (1948); W. M. Gibson and D. L. Livesey, Proc. Phys. Soc. (London) **60**, 523 (1948); D. L. Livesey and D. H. Wilkinson, Proc. Roy. Soc. (London) **A195**, 123 (1949); R. A. Peck, Phys. Rev. **73**, 947 (1948); L. L. Green and W. M. Gibson, Proc. Phys. Soc. (London) **62**, 407 (1949); J. C. Grosskreutz, Phys. Rev. **76**, 482 (1949).
[31] C. F. Powell and G. P. S. Occhialini, *Nuclear Physics in Photographs*, (The Clarendon Press, Oxford, England, 1947). O. R. Frisch, *Progress in Nuclear Physics*, (Butterworth-Springer Ltd, London, England, 1950) (see article by J. Rotblat on photographic emulsion technique).
[32] J. Rotblat and C. T. Tai, Nature **164**, 835 (1949).

edge of the hydrogen concentration in the unprocessed emulsion, as well as of the average thickness of the unprocessed emulsion over the area of the plate analyzed. Because of variation of the moisture content of emulsions with changes in humidity, and the difficulty in determining precisely the unprocessed emulsion thickness over the plate area analyzed,[33] the above determination is usually subject to an error of approximately 12 percent.

Finally there are limitations imposed by the actual reading of the plates. Under good conditions an observer can count, within an accurately defined solid angle, about 50 tracks per hour. The lower limit of neutron energy for this method is approximately 0.5 Mev. For energies lower than this the tracks cannot be counted with 100 percent efficiency[34] and also the solid angle errors incurred become prohibitive.

A variation of method (a) under counter techniques is applicable for neutron energies of approximately 2 Mev and higher. In this method one exposes the nuclear plate so that the plane of the emulsion is perpendicular to the neutron beam direction. One then counts all tracks for which the horizontal and/or vertical projection is greater than the minimum track length which can be unambiguously identified as the result of a recoil proton. (This length is approximately 5 microns in a processed Ilford C-2 or Eastman NTA emulsion.) For 2.5-Mev neutrons, for example, the 5-micron "bias" implies that one would count all protons projected between 0° and 126° with respect to the neutron direction in the center-of-mass coordinate system.

Since the energy of a recoil proton is given by $E_p=E_n\cos^2\theta$ and the projected range of this proton in the plane of the nuclear emulsion is given by $R_p=R\sin\theta$, it is a simple matter to determine θ for a given value of neutron energy (E_n) and projected proton range R_p. By this means one can define the solid angle within which tracks are counted to better than ± 5 percent. This method has the advantages that it is simple to use, does not depend upon a precise measurement of emulsion shrinkage, requires less neutron intensity, and permits reasonably good counting statistics in a matter of a few hours for an optimum exposure. The method has the disadvantage that it does not permit as good discrimination against background tracks (on the basis of proton energy and direction) as does the previous method.

A nuclear-plate method which permits accurate solid angle determinations without sacrificing discrimination against background neutrons is one in which the nuclear plate is used only as a detector, and a hydrogenous radiator is used in much the same way as outlined for the counter technique. Here, a thin section of hydrogenous material is placed directly in the neutron beam and a known fraction of the projected recoil protons is recorded.[35] The radiator-detector geometry is arranged so that any given area of plate subtends an accurately calculable solid angle at the radiator. In analyzing such a plate, it is necessary to search only the surface of the emulsion for tracks and count only those tracks which proceed in such a direction as to have been made by protons originating in the hydrogenous radiator. With this method one can again measure neutron fluxes down to 0.5 Mev, but with considerably improved accuracy and at a considerable saving in analysis time. In order to measure neutron fluxes for low energy neutrons (i.e., down to 0.5 Mev) it is necessary to use thin radiators, which imples a relatively high neutron flux. Below neutron energies of 10 Mev, it is desirable to utilize a neutron collimator which is so arranged as to permit the neutron beam to strike the radiator but not the detector.

It is, in principle, feasible to replace the H^1 radiator by a Li^6 radiator and go down to lower energies. This would not be an absolute flux measurement since one would have to utilize the differential cross section with energy and angle of the $Li^6(n, \alpha)H^3$ reaction, which is as of now available only with poor accuracy and over a very limited region of angles and energies.

3. Method of Integration of Ionization Current

A variant of the recoil particle method, still based upon the knowledge of the $n-p$ scattering cross section, measures integrated ionization current from the proton recoils instead of individual pulse heights. Its inherent advantage over pulse-height methods is that all the energy deposited by proton recoils is measured and no extrapolation to zero pulse height is necessary. For absolute flux measurements an additional parameter must be known, i.e., W, the energy necessary to produce an ion pair.

The number of collisions per second in N hydrogen atoms placed in the flux nv of energy E_n is

$$(nv)\sigma_{(np)}N. \tag{9}$$

These collisions give rise to

$$(nv)\sigma_{(np)}\cdot N\cdot E_n/2W \text{ ion pairs/sec}, \tag{10}$$

assuming isotropic scattering of the protons. The measured current, if all ions are collected, is then

$$\frac{(nv)\sigma_{(np)}NE_n}{1.25\times 10^{13}W} \text{ microamperes}. \tag{11}$$

From Eq. (11) (nv) can be obtained if N can be accurately determined. This determination, i.e., the one of fixing the active volume of the counter, presents the principal experimental difficulty. A method of doing this is to line the walls with a plastic having the same chemical composition as the counter gas. For this purpose the chamber may be filled with ethylene and the

[33] J. M. McAlister and D. W. Keam, Proc. Phys. Soc. (London) **A64**, 91 (1951).
[34] N. Nereson and F. Reines, Rev. Sci. Instr. **21**, 534 (1950).
[35] Allred, Phillips, Rosen, and Tallmadge, Rev. Sci. Instr. **21**, 225 (1950).

walls may be lined with polythene. It was shown by Wilkinson[36] that the mass stopping power of ethylene and of polyethylene are effectively identical. In view of this fact, the density of ionization in the chamber will be the same as that in an infinite volume of the gas. Neutron flux measurements using such a "homogeneous ionization chamber" have been described by Bretscher and French[37] and their chamber is discussed in Rossi and Staub.[38]

Since a detector measuring current is also sensitive to X- and gamma-radiation, to recoils of nuclei other than protons, and neutron reaction products, it is necessary to balance out all but the ionization current produced by proton recoils. This has been done by Bretscher and French[37] by measuring the difference in ionization current in two chambers which have the same response to background effects, but different response to neutrons. To accomplish this, two methods were employed. In the first, the chambers were filled with different hydrocarbons: The first chamber was filled with ethylene (C_2H_4) and the walls were made of polythene ($(CH_2)_x$); the second chamber was filled with acetylene (C_2H_2) and the walls were made of polystyrene ($(CH)_8$).

The second method for balancing out background effects made use of the different amount of energy transmitted by a neutron to H compared to D. Consequently, one chamber was filled with C_2H_4 and had walls made of ordinary polythene, while the second chamber was filled with C_2D_4 and the walls were made of heavy paraffin wax. A difficulty of this method is that because of the anisotropic and not well-known angular distribution of neutrons scattered by deuterium,[17,21] the energy transfer to the deuterium cannot be calculated accurately.

Another difficulty which may be encountered in using this method is a possible variation of W with energy. The recent work of Jesse, Forstat, and Sadauskis[39] has shown that argon may safely be used in such a counter because in argon W does not appear to depend on energy. It is clear that this kind of detector may be used to extrapolate a cross section known at one energy to different energies, i.e., to act as a flux monitor even if the absolute sensitivity is unknown.

IV. METHODS OF TOTAL SOURCE STRENGTH

1. Thermalization Methods

The basis for this method was originally given by Amaldi and Fermi[40,41] and immediately used for comparisons of integrated neutron fluxes from various sources. A neutron source of unknown strength is placed inside a moderating medium (water, graphite, etc.) large enough that few neutrons can escape. Measurements of the activation of foils or other detectors as a function of distance from the source allow one to integrate, over the volume of the moderator, the number of neutrons/cm^3 lying in the energy interval to which the detector is sensitive, and thus obtain an absolute value of the total number of neutrons emitted by the source. Various corrections have to be applied, such as those for the neutrons absorbed by the H in water or by other constituents of the moderator if these are appreciable; the depression in neutron density caused by the detector and source; the finite geometry effect in the absolute counting of the number of disintegrations in the detector, etc. Applications of this method to making absolute total source strength measurements of high accuracy have been reported elsewhere.[42,43] The method has the advantage that neutrons of different primary energies are detected with the same efficiency because after a few collisions (about 10) a neutron with a primary energy of several Mev has only a few kev energy. At such an energy, its mean free path is approximately 1 cm and more than 100 more collisions are necessary before capture in hydrogen. This means that neutrons of various primary energies pass through the region of absorption of the detector inside the moderator and so are detected with equal sensitivities after integration over the moderator volume. It is thus possible[42,43] to use as a secondary flux standard a natural source of neutrons such as RaBe, which has been accurately calibrated by this method, for comparison with a source of unknown strength even though the spectra differ widely.

It will now be assumed that a natural source of known strength is available and the problem is to determine the neutron flux through a given area from an accelerated particle source such $T(p, n)He^3$.[44] In this case the neutron energy at each angle is known for a given energy of the incident particles, but the total source strength and the angular distribution are not known. If the target is surrounded by a bath roughly a meter cube containing a 200 g/liter solution of $MnSO_4$, about 99 percent of the neutrons will be absorbed by the Mn in the absorption band near 300 ev. The 155-min activity of the Mn can be measured after sufficient neutron irradiation by taking a sample of the thoroughly stirred solution and either counting it directly in a standardized geometry with an immersion Geiger counter or by counting the dry residue from evaporation or precipitation. Both methods give essentially a thick source of the β's being counted. A procedure for precipitation of MnO_2 out of the solution, which has been applied to a measurement of the

[36] D. H. Wilkinson, Proc. Cambridge, Phil. Soc. **44**, 114 (1948).
[37] E. Bretscher and A. P. French, British reports BR 386 and BR 517.
[38] See reference 16, p. 182.
[39] Jesse, Forstat, and Sadauskis, Phys. Rev. **77**, 782 (1950).
[40] E. Amaldi and E. Fermi, Phys. Rev. **50**, 899 (1936).
[41] Amaldi, Hafstad, and Tuve, Phys. Rev. **51**, 896 (1937).
[42] R. L. Walker, AEC report MDDC 414 (1945).
[43] R. D. O'Neal and G. Scharff-Goldhaber, Phys. Rev. **69**, 368 (1946).
[44] Jarvis, Hemmendinger, Argo, and Taschek, Phys. Rev. **79** 929 (1950).

$D(D, n)He^3$ cross section has been discussed by Coon *et al.*[6] The liquid immersion measurements have been described in connection with measurements of the $Li(p, n)Be^7$ cross section.[45]

Unpublished Los Alamos results of Jorgensen, Bright, and Hoogterp show that KI may be used as conveniently in solution as $MnSO_4$. In this case the immersion counter technique is essentially the same as for the Mn bath, but the 25-minute half-life of I makes possible rapid re-use of the bath, which is a decided advantage in many cases.

A comparison of the activity induced in the bath per monitor count for the unknown source with the activity produced by the standard natural source gives directly the total source strength of the unknown source. The following procedure may be used. The bath constant, k, is first determined from

$$k=A_s/\{Q_s[1-L_s][1-\exp(-t_r/\tau)]\} \text{ counts per neutron,} \quad (12)$$

where A_s = activity of the bath at the end of the irradiation produced by the natural source neutrons in the time t_r; Q_s = number of neutrons per unit time from the natural source; L_s = fraction of source neutrons leaking from the bath; t_r = duration of the exposure to the natural source; and τ = mean life of activity. The bath constant, k, has to be checked frequently to make sure that no changes have occurred in the bath.

In making an exposure of the bath to neutrons from the unknown source, the bath activity is again determined. For a source produced by accelerated particles, the flux is usually desired in terms of neutrons per monitor count instead of unit time. This monitor count may be charge collected on the target in microcoulombs, the number of protons or He^3's from the reaction $D(d, n)He^3$, or the number of He^4's from $T(d, n)He^4$. For bath exposures to these sources the irradiation may not be uniform in time because of fluctuations in beam current; such fluctuations can be corrected for by dividing the run into subintervals of approximately constant irradiation. The specific saturated activity of the bath per monitor count is then

$$A_0\Big/\left\{\Sigma_i\frac{\Delta M_i}{\Delta t_i}\left[1-\exp\left(-\frac{\Delta t_i}{\tau}\right)\right]\left[\exp\left(-\frac{t_i}{\tau}\right)\right]\right\} \equiv A_0/I \text{ counts per monitor count,} \quad (13)$$

where A_0 = activity produced at the end of the irradiation by the unknown source; ΔM_i = monitor count during the subinterval Δt_i; and t_i = time between the end of Δt_i and the end of the irradiation. The quantity $A_0/kI(1-L)$ is then the total number of neutrons from the unknown source per monitor count, where L is the fraction of the neutrons from the unknown source leaking out of the bath.

A simpler way to take into account the fluctuations in beam current during the irradiation is to use a "leaky" current integrator to measure the integrated beam current.[46] In such a device a resistor is placed across the condenser on which the charge carried by the beam is stored. The values of the capacity C and the resistance R are chosen such that $RC=\tau$.

In order to obtain the flux of neutrons at a definite angle it is in addition necessary to know the angular distribution of neutrons from the unmoderated source. This angular distribution must be measured either with a detector whose energy sensitivity is known over the energy range produced by the source or preferably by a detector whose response is independent of energy, such as a "long counter."[47] The total number of neutrons per monitor count as measured by the bath is

$$N_{\text{tot}}=\frac{1}{2}\int_0^\pi \sin\theta N(\theta)d\theta, \quad (14)$$

where $N(\theta)$ is the number of neutrons per monitor count and per unit solid angle at θ. The integral of the angular distribution measured in arbitrary units can be normalized to the total either numerically or analytically. In this way the absolute number of neutrons per steradian may be determined at each angle. Some reactions are known to produce an isotropic distribution of neutrons in the center-of-mass system, for example, the reaction $T(d, n)He^3$ at low bombarding energies.[10] In such case it is only necessary to calculate the angular distribution in the laboratory system in order to obtain the neutron flux at a given angle of observation. For anisotropic reactions like $T(p, n)He^3$ it is desirable to cover as much of the angular range as possible and then fit the angular distribution in the center-of-mass system with a cosine series in order to obtain values for back angles at which direct measurements are difficult.

One of the principal disadvantages of this method of measuring fast neutron flux is that a measurement of an unknown neutron cross section cannot be made simultaneously with the flux measurement. A monitor must be relied upon to bridge the time between the total source-strength measurement in the bath and the actual use of some of the neutrons in determining a cross section. A further disadvantage, which also leads to inaccuracies in the flux measurement, is the necessity of making angular distribution measurements on the unknown source.

A simplified method for comparing the strength of neutron sources by observing the flux of thermal neutrons in a graphite column has been described by Walker.[48] A "point" source of fast neutrons is placed in a large graphite block (5×5×9 feet). The neutrons are slowed down by collisions with carbon nuclei until

[45] R. F. Taschek and A. Hemmendinger, Phys. Rev. **74**, 373 (1948).

[46] S. C. Snowdon, Phys. Rev. **78**, 299 (1950).

[47] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).

[48] R. L. Walker, Phys. Rev. **76**, 244 (1949).

they reach thermal energies. The spatial distribution of the thermal neutrons will depend on the energy of the primary fast neutrons, since the number of collisions required to thermalize the neutrons will be larger, the higher the primary energy. Using "age" theory[49] it is possible to calculate the spatial distribution of thermal neutrons in the graphite column for different primary energies. In Fig. 4 of Walker's paper, the thermal flux per primary fast neutron is plotted against the neutron "age" for different distances from the source. By choosing a distance from the source at which the curve is as flat as possible, one can find a position at which the thermal flux will be approximately proportional to the primary source strength and insensitive to the primary neutron energy.

It was found that the optimum distance from the source was 58 cm. At this distance the thermal flux curve is flat within about 15 percent for neutron ages up to 500 cm^2. While it is not possible to assign a definite energy to this age, it is believed that the thermal neutron flux at a distance of 58 cm varies with the primary neutron energy by less than 15 percent up to neutron energies of the order of 7 Mev.

The thermal flux may be measured in this type of experiment with any detector which is sensitive to thermal neutrons. Because of its high sensitivity, a BF_3 counter is most convenient to use. Some care must, however, be taken to avoid alteration of the flux by the detector.

2. Radioactive Product Method

A variation of the integration method can be used to determine the total source strength in the case of the $Li^7(p, n)Be^7$ reaction (possibly others). This method allows the use of the flux for a cross section measurement at the same time as the total number of neutrons emitted by the source is being measured. In the case of the $Li(p, n)$ reaction the 55-day activity of the Be^7 formed during a particular run at a fixed proton energy is measured by the Li^{7*} gamma-ray decay.[45] To make the source-strength determination absolute it is necessary to measure the Be^7 activity per monitor count when the source has been immersed in a bath, and then compare the bath activity with that produced by a standard source. In this way the Be^7 activity per monitor count may be obtained in terms of the total number of neutrons/monitor count, but with the advantage of allowing a cross-section measurement to be made at the same time. If it is desired to carry out measurements at different neutron energies in rapid succession, it is possible to measure the increase in the Be^7 activity for each run by placing a Geiger counter near the thin-walled target in a reproducible geometry. It is usually possible to make several runs on one target before the activity becomes too large for good measurements (the background for a run is the last previous activation).

[49] See for example, E. Fermi, *Nuclear Physics* (University of Chicago Press, Chicago, 1949).

Angular distributions of the neutrons from the source must still be determined, with one exception, which represents perhaps the most useful application of the method. This exception is the region just above the threshold for the $Li^7(p, n)Be^7$ reaction, where the neutrons emerge in a narrow cone with an energy of 29 kev. Since cross-section determinations which require a flux measurement at such a low energy are particularly difficult the method is of considerable use. If the element for which the cross section is desired is uniformly distributed over an area larger than the diameter of the cone of neutrons, the total neutron flux passes through the known number of atoms/cm^2, and the exact area of beam need not be known. At the same time the total neutron flux is measured by the Be^7 activity and no knowledge of the angular distribution is necessary. Since the cone angle opens rather rapidly with increasing proton energy, the latter must be kept very constant, if most of the area of the detector is to be filled. Another possibility is to set the mean proton energy just at threshold so that small fluctuations in proton energy may carry the energy above and below threshold, provided the cone of neutrons does not exceed the detector area.

Chemical or counting methods for determining the actual amount of Be^7 absolutely could probably be devised to give a direct measurement of the total number of neutrons emitted during a run, but this has not yet been done.

The principal limitation to this method lies in the nature of the $Li^7(p, n)Be^7$ reaction itself, since it has been shown [50] that Be^7 has an excited state at an energy of 430 kev. The Be^7 activity probably still measures the total number of neutrons, but the branching ratio of the $Li(p, n)$ reaction must be known in order to determine the number of neutrons in each energy group. Below the threshold for the second group the method should still be reliable, and, because of the high neutron intensities obtainable from the $Li(p, n)$ reaction, will remain of considerable importance for neutron energies up to about 600 kev.

V. LONG COUNTER AND SIMILAR METHODS

In this method absolute measurements are not made and the properties of energy independent detectors are used in somewhat different ways. The most common of these is similar to the bath integration. An energy insensitive detector gives a counting rate from a known standard neutron source which is

$$N_1 = (Q/4\pi)\cdot\Omega\cdot S \text{ counts/min}, \qquad (15)$$

where Q = total neutrons/min from the standard source; Ω = solid angle subtended at the source by the detector; and S = sensitivity of the detector in counts/neutron. Normally the solid angle subtended by a detector of this kind cannot be determined with high accuracy. If,

[50] Johnson, Laubenstein, and Richards, Phys. Rev. **77**, 413 (1950).

however, the standard source is placed at the same position as the unknown source (which has a different energy) then the counting rate of the long counter is

$$N_2 = q \cdot \Omega \cdot S \text{ counts/monitor count}, \quad (16)$$

where q is the number of neutrons per monitor count and per unit solid angle, while the solid angle and sensitivity are the same as for the standard source. The neutron flux per unit solid angle from the unknown source is then

$$q = N_2/N_1 \cdot Q/4\pi. \quad (17)$$

Since the accelerated particle sources are axially symmetric around the incident beam except for scattering and backgrounds, an unknown cross section may be measured at an angle $+\theta$, while the flux is measured at $-\theta$ with a long counter.

One of the inherent difficulties of this method is the fact that the efficiency of the energy insensitive detector is not completely independent of energy over a wide range; the sensitivity of detectors of the long counter type[44] has a maximum for neutrons of about 2-Mev energy and decreases both at energies below 100 kev and at high energies, such as those of some of the neutrons produced by RaBe sources. Every modification of the counter requires a careful check of energy dependence before it can be used with confidence.

In the use of the long counter as mentioned above, a flux is measured directly by comparison with that from a standard neutron source. Since flux measurements are most often made to determine cross sections, the situation may arise that at one neutron energy a cross section is known to a higher accuracy than the source strength of the standard RaBe source (about 5 to 7 percent). If it is desired to extend the known cross section to other energies with high accuracy, the long counter may simply be used as a flux monitor and the absolute cross section normalization be made at the energy where the cross section is accurately known. This method is most advantageous for flux measurements in the region of a few tens of kilovolts, since the use of most counters leads to serious difficulties even at energies above 100 kev. The relative insensitivity of the long counter to background neutrons of low energy and its high over-all sensitivity makes it particularly useful in connection with accelerated particle sources, which generally have very low intensities at low neutron energies. One of the principal disadvantages is that just at these lowest energies the sensitivity of most long counters decreases rapidly. It is possible, however, to use an Sb—Be natural source,[51] calibrated in a Mn bath against a RaBe standard source, to determine the sensitivity of the long counter at 24 kev. Adjustments in the detector geometry,[47] such as boring holes near the central counter, may then be made to flatten the response in the interesting region.

[51] A. Wattenberg, Preliminary Report No. 6, Nuclear Science Series.

It has been found that the sensitivity of the 8-inch shielded long counter described by Hanson and McKibben decreases to about 95 percent for RaBe neutrons and to 67 percent for 14-Mev neutrons, but then remains essentially constant to 18 Mev. Such a counter can be modified to give the same sensitivity for 14-Mev and RaBe neutrons by extending the paraffin at the back and moving the BF_3 counter farther back. This probably corresponds to enlarging an integrating bath to reduce the leakage flux for high energy neutrons.

Although considerably more difficult to use, the balanced ionization current counter mentioned on page 8 is more likely to have a known energy dependence and can be used in a similar extrapolation of energy range. Disadvantages of this method are that the low intrinsic sensitivity makes its use difficult at low energies, and at high energies the long proton ranges produce serious wall effects.

VI. REACTION CROSS-SECTION COMPARISONS

It is clear from the preceding that the basic flux measurements are difficult and tedious to make for fast neutrons. For this reason it becomes desirable to establish as a secondary standard a reaction cross section which is easily observable and reproducible, and the element for which can be placed in a well-defined geometry without great difficulty. Such a cross section may be determined at a single energy and one of the methods of energy extension may then be used to cover a larger energy region. A smoothly varying cross section is desirable in the secondary standard so that it may be accurately measured and used over a wide energy range.

Isotopes of the fissionable elements satisfy some of these characteristics. Because of their high energy but short range, fission fragments are easily detected with simple pulse counters. An excellent discussion of the design and use of fission detectors is given in Chapter 9 of Rossi and Staub.[16] A particularly favorable situation arises if the element whose cross section is to be measured can be put into the form of a thin foil of known mass; in this case a double detection chamber with the unknown and fission foil back-to-back allows a direct comparison of cross sections in almost exactly the same neutron flux.

For measuring a flux of fast neutrons above 1 Mev in the possible presence of an appreciable low energy background, "threshold" reactions become useful as secondary standards. In general, the cross sections for such reactions have not yet been measured with sufficient precision to make them useful for accurate flux standards, but with more work on the reactions and better variable energy neutron sources one may expect threshold detectors to come into common use.

Examples of such reactions are the following. Among the fissionable nuclides, Np^{237} and U could be used for neutrons of energies above the respective fission thresholds of these elements (0.4 and $\sim$1 Mev, respectively).

The fission cross section of Np^{237} was measured by Klema[52] and varies smoothly with energy. Recently the fission cross section of U has also been published.[53] Since the latter cross section is relatively accurately known (to about 15 percent) and since U is readily available, the fission of U is a useful reaction as a secondary flux measuring device. Among the lighter elements there are many examples of reactions which might be used as threshold detectors. A summary of such reactions is contained in a report by Feld *et al.*[54] and in a paper by Cohen.[55] It is to be expected that resonance effects will produce rapid variations with energy of the cross sections for these reactions in the lighter elements. Few of the cross sections have been measured with sufficient accuracy to serve as secondary standards. Reactions on which some experimental information is available are $P(n, p)Si$, $S(n, p)P$, $Al(n, p)Mg$ with effective thresholds at 1.4,[56] 1.5,[57] and about 2.5[58] Mev; and for neutrons of higher energy, $Cu^{63}(n, 2n)Cu^{62}$ and $C^{12}(n, 2n)C^{11}$ with thresholds at 11.4 Mev[59] and 20 Mev,[60] respectively.

The number of reactions taking place in the threshold detector is usually determined from induced β-activity. Absolute neutron flux measurements using such secondary standards, therefore, require absolute β-counting, which in turn may introduce uncertainties into the measurement. Determination of the cross section of some threshold reactions for 14-Mev neutrons have been carried out by Forbes[61] who exercised great care to obtain an absolute β-count.

It has been pointed out[28] that biased hydrogen recoil detectors have a threshold response such that their sensitivity varies only slowly with energy above the threshold. Counters suitable for this purpose have been described.[62] It is necessary, however, to calibrate the response of a given counter by some other method.

Apart from threshold reactions, reactions in very light nuclides have promise for reaction cross-section comparisons. In particular the following reactions might be considered:

$$He^3+n\rightarrow H^3+H^1+0.76\ \text{Mev} \quad (18)$$

$$Li^6+n\rightarrow He^4+H^3+4.64\ \text{Mev} \quad (19)$$

$$B^{10}+n\rightarrow Li^7+He^4+2.78\ \text{Mev} \quad (20)$$

$$N^{14}+n\rightarrow B^{11}+He^4-0.28\ \text{Mev} \quad (21)$$

$$N^{14}+n\rightarrow C^{14}+H^1+0.60\ \text{Mev}. \quad (22)$$

All these reactions have the disadvantage that their cross sections vary rapidly with energy. Reactions (21) and (22) show the most marked resonance effects among these.[63] None of the cross sections are known to better than about 25 percent for fast neutrons at the present time so that they can be used only for very rough measurements. The main disadvantage of reaction (19) is that no gaseous compound of Li is available as counter filling gas. If a foil with a thick backing is used, there is no one to one correlation between the energy of the particles observed in the counter and the primary neutron energy. On the other hand, the development of LiI crystals for scintillators[64] holds promise for the use of Li.

A drawback of reaction (20) is the fact that a fraction of the disintegrations leave the Li^7 nucleus in an excited state 0.48 Mev above the ground state and the branching ratio for this process varies rapidly with the energy of the incident neutrons.[65] On the other hand, an advantage of the reaction is the availability of a gaseous compound, BF_3, which can be used to fill counters; this allows both particles to be detected simultaneously and assures a uniform distribution of the element.

For fast flux measurements an undesirable characteristic of reactions (18), (19), (20), and (22) is their large cross section for thermal and epithermal neutrons. Cadmium shielding of the detector is always advisable and adequate for the strictly thermal neutrons; for the remainder of the neutron background up to about 1 kev the best procedure is to minimize their production as much as possible by keeping source and detector close to each other, but far from degrading materials, especially those containing hydrogen. If it is not possible to avoid the epithermal neutrons, a first-order correction can be made by measuring the detector counting rate as a function of distance from the target; the direct flux should vary as $1/r^2$ while the undesired neutrons will give an approximately constant room background. Another method for distinguishing between disintegrations caused by epithermal and by fast neutrons is to measure the energy of the disintegration pulses. In reaction (20) this is possible only at primary neutron energies well above 500 kev, because of the effect of the excited state of Li^7. A further difficulty for those flux measuring isotopes whose cross sections increase rapidly as the neutron energy decreases (speaking now, however, of neutron energies above about 50 kev) is the fact that for neutrons from most accelerated particle sources there is a rather large difference in energy between the neutrons emerging at 0° and those emitted near 180°. Since the beam tube from the accelerator enters the target at the 180° angle, care must be taken to reduce the scattering material here (such as flanges, valves, etc.) as much as possible to prevent a large

[52] E. D. Klema, Phys. Rev. **72**, 88 (1947).
[53] Nucleonics, **8**, 78 (January 1951).
[54] Feld, Feshbach, Goldberger, Goldstein, and Weisskopf, AEC Report NYO-636, Tables VII–1 and VII–3.
[55] B. L. Cohen, Nucleonics, **8**, 29 (Feb. 1951).
[56] R. F. Taschek, shown in Goldsmith, Ibser and Feld, Rev. Modern Phys. **19**, 259 (1947).
[57] E. D. Klema and A. H. Hanson, Phys. Rev. **73**, 106 (1948).
[58] E. Bretscher and D. H. Wilkinson, Proc. Cambridge Phil. Soc. **45**, 141 (1949).
[59] J. L. Fowler and J. M. Slye, Phys. Rev. **77**, 787 (1950).
[60] E. M. McMillan and H. F. York, Phys. Rev. **73**, 262 (1948).
[61] S. G. Forbes, Phys. Rev. (to be published).
[62] J. H. Coon and R. A. Nobles, Rev. Sci. Instr. **18**, 44 (1947).
[63] C. H. Johnson and H. H. Barschall, Phys. Rev. **80**, 818 (1950).
[64] Hofstadter, McIntyre, Roderick, and West, Phys. Rev. **82**, 749 (1951).
[65] Petree, Johnson, and Miller, Phys. Rev. **83**, 1148 (1951).

number of scattered lower energy neutrons from entering the detector. When the disintegration pulses from light elements are observed in a counter, care must be taken not to count recoiling nuclei. Pulses produced by recoils can usually be biased out when exoergic reactions are used.

VII. FLUX MEASUREMENTS FOR POLYERGIC NEUTRONS

As was pointed out in the introduction, most of the methods for measuring fast neutron flux are designed for applications to a unidirectional flux of monoergic neutrons. Since, occasionally, it is necessary to measure a flux of polyergic neutrons, some comments about the usefulness of the previously discussed methods for such a problem might be worthwhile.

1. Recoil Particle Method

If this method is to be used, it is necessary to determine simultaneously with the flux measurement the spectrum of the polyergic neutrons. This is, in principle, possible either by determining the energy distribution of all the recoiling particles or by measuring the energy distribution of those recoils which are emitted within a given angle.

The technique of determining the energy distribution of all the recoiling particles in a counter was discussed by Baldinger, Huber, and Staub.[66] These authors showed that if the scattering of the neutrons by the detecting nuclei is isotropic in the center-of-mass system of reference and if the entire range of the recoiling particles is contained in the counting volume, the distribution in energy of the primary neutrons, $S(E)$, is related to the distribution in energy of the recoiling particles, $H(E)$, by

$$S(E)=([E_r/N\sigma(E)])([dH(E)/dE_r]), \qquad (23)$$

where N is the number of detecting nuclei/cm^2, $\sigma(E)$ the scattering cross section of the detecting nuclei, and E_r the energy of recoil. The principal difficulty of this method is that the flux is obtained by taking the derivative of the distribution in energy of the recoils, a fact which tends to make the method very inaccurate. Furthermore, the necessity of containing the entire range of the recoils in the counter requires sufficiently high gas pressures for neutrons of high energy that the operating characteristics of the counter may become very unfavorable. On the other hand, if a detecting gas is used, the method has the advantage of being insensitive to the direction of the incident neutrons.

Instead of measuring the distribution in energy of all the recoils, it is also possible to measure the distribution in energy of a collimated beam of recoils. If this is to be done by means of counters, background difficulties usually require the use of coincidences to identify the appropriate recoils. The energy distribution of the recoils may then be determined from the range distribution either by varying the pressure in the counter telescope or by introducing stopping foils, or it can be measured directly by adding the pulse heights in several counters electronically. None of these methods has been perfected to give high accuracy.

The distribution in energy of recoils can also be determined using nuclear plates as detectors. This method has been successfully used to measure the flux of polyergic neutrons. Above 5 Mev the accuracy was approximately ten percent, and better accuracies are certainly attainable even at considerably lower energies, provided the magnitude of the neutron flux permits use of sufficiently thin radiators.

If photographic plates are used as both radiator and detector to measure the flux of polyergic neutrons, one experiences the same difficulties as previously discussed.

2. Methods of Total Source Strength

The thermalization method is probably the most accurate one for measuring a flux of polyergic neutrons. In particular, the activity induced in a bath should be independent of the neutron energy provided the bath is sufficiently large.

3. Long Counter Method

Within the neutron energy range in which the long counter is known to have a sensitivity independent of neutron energy, it may be used for measuring the flux of polyergic neutrons.

4. Method of Reaction Cross-Section Comparisons

This method cannot be used for polyergic neutrons, unless the spectrum of the neutrons is known, since all reaction cross sections vary with neutron energy. In principle, it would be possible to deduce the neutron spectrum from the energy distribution of the reaction products in the case of reactions (18) to (22), but so far this has not been successful. Difficulties are caused by recoil nuclei produced by neutrons of high energy, by the effect of resonances, by the excited state in Li^7 in the case of reaction (20), by the simultaneous occurrence of reactions (21) and (22).

Some work has been done on the problem of measuring neutron fluxes for fast neutrons moving in all directions by observing, in lithium loaded photographic emulsions, trajectories of the products of reaction (19).[67] Up to the present, these experiments have not shown a great deal of promise.

VIII. SUMMARY

The method of fast neutron flux measurement which almost certainly is capable of highest accuracy is the associated particle method. With presently available reactions and techniques it seems quite possible to make direct flux measurements, i.e., number of neu-

[66] Baldinger, Huber, and Staub, Helv. Phys. Acta **11**, 245 (1938).

[67] G. R. Keepin and J. H. Roberts, Phys. Rev. **76**, 154 (1949).

trons per unit solid angle, to about one percent in the energy range above 3 Mev using the $D(D, n)He^3$ reaction and above 13 Mev using the $T(D, n)He^4$ reaction. Such accuracy, however, has not yet been attained, primarily because no serious attempts at the problem have been made. It appears quite likely that a moderating bath could be used with either of these sources to calibrate a natural source with almost as good accuracy; again this has not, as yet, been done. Such an accurate calibration of a moderating bath does not imply that equally accurate measurements of flux can be made on sources which produce neutrons of energies less than 2 Mev, since in this case the angular distribution of the neutrons must be measured.

For accelerated particle sources of neutrons using endoergic reactions such as $T^3(p, n)He^3$ and $Li^7(p, n)Be^7$, which are the most useful at present for energies below 3 Mev and particularly in the tens of kev range, the techniques for observation of the associated particles are much more difficult and essentially undeveloped. Thus at neutron energies below 3 Mev, proton recoil methods appear to be most likely to achieve high accuracy until techniques are developed for detecting the He^3 particles from the $T^3(p, n)He^3$ reactions. It appears possible to measure the $n-p$ scattering cross section with about one percent accuracy.[68] Probably the best accuracy one can expect in an absolute flux measurement using proton recoils from a thin radiator to produce pulses in a detector such as a pulse ionization chamber with plane parallel geometry, a proportional counter, Frisch grid counter or coincidence proportional counter is about two percent to three percent and this with great difficulty. The accuracy to be expected from a counter measuring total ionization current should be about the same. The ionization chamber method has the added advantage that neutrons down to a few tens of kev may be detected while the counters in which pulses are observed become difficult to use below about 200 kev.

A critical comparison of the various recoil particle methods is contained in a paper by Allen, Livesey, and Wilkinson.[69] These authors also carried out absolute flux measurements for $D-D$ neutrons using the recoil particle technique with four different detectors, i.e., a homogeneous ionization chamber,[37] a counter telescope,[27] a gas-filled pulse counter, and a counter with a thick radiator.[29] The flux determinations on 2.15-Mev neutrons using these four detectors showed a maximum variation of six percent.

At isolated energies special properties of nuclear reactions may be used to give comparable accuracies, e.g., the radioactive product method at the $Li^7(p, n)Be^7$ threshold. These can, however, only serve to fill in at energies at which measurements are difficult so that this method is not of general applicability.

It seems profitable to make use of the absolute methods to measure very accurately one or a few cross sections of reactions which can be easily reproduced as secondary standards. Wherever the absolute methods fail or give poor results, the method of energy extension should be used to enlarge the energy range of the secondary standards as much as possible. To this end, the techniques for making energy insensitive detectors and ascertaining their energy response need considerable development together with calculations on their properties.

It may be pointed out in conclusion that the present accuracies of neutron cross-section measurements for energies above about 10 kev are no better than about five percent at the best, except for total cross sections. This is a direct result of the difficulties involved in absolute flux determinations.

[68] Storrs, Cooper, Frisch, and Zimmerman, M.I.T. Laboratory for Nuclear Science and Engineering, Progress Report, February 28, 1951.

[69] Allen, Livesey, and Wilkinson, Proc. Cambridge Phil. Soc. 46, 339 (1950).