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REVIEW OF NEUTRON DETECTION METHODS AND INSTRUMENTS

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PREFACE

This report presents a comprehensive overview of neutron detection techniques and a review of commonly used neutron detectors, their characteristics and applications, and their commercial availability. This concise compilation of information and data, collected from numerous sources, is intended to be both a basic source reference and an introduction for those unfamiliar with the field of neutron detection.

The extensive bibliography provides additional information and details on the detection techniques mentioned in this report. Of particular value are H. H. Barschall's article on "Detection of Neutrons" in Handbuch der Physik, Volume XLV, published by Springer-Verlag, Berlin (1958), W. D. Allen's book Neutron Detection, published by George Newnes, Ltd., London (1960), J. B. Marion and J. L. Fowler's monograph on Fast Neutron Physics, Part 1, Interscience, New York (1960), and W. J. Price's Nuclear Radiation Detection, McGraw Hill Book Co., New York, (1958).

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REVIEW OF NEUTRON DETECTION METHODS AND INSTRUMENTS

ABSTRACT

This report is an overview of neutron detection methods and neutron detector types. A brief description of the neutron-induced reactions most useful in neutron detection and a discussion of several classes of neutron detector types and their applications are included, as is an extensive bibliography. A list of commercially available neutron detectors and their characteristics is appended.

INTRODUCTION

Because the neutron is an uncharged particle, it cannot be detected until it has undergone a nuclear interaction to produce detectable ionizing radiation. The problem of neutron detection is further complicated by the fact that neutrons often occur together with gamma radiation, to which most neutron sensors have a similar response, making the identification of neutrons more difficult.

Neutron detection thus relies on the interaction of neutrons with matter, a process that generally tends to degrade their energy continually, down to the energy region where they are absorbed and generate detectable nuclear particles and radiation. Although neutrons can be absorbed at higher energies, it is more common to allow the neutrons to degrade in energy to a state in which the neutron energy spectrum approaches thermal equilibrium with the surrounding medium. The thermalization of a fast neutron (e.g., 1 MeV) can take from a few to a few hundred microseconds; slow neutron lifetimes can be as long as a few tens of milliseconds, until they are ultimately eliminated by nuclear absorption.

Because of these factors and because the reaction probability of neutron detection materials depends on neutron energy, instruments for neutron detection are more complex than those designed for detecting charged particles or other ionizing radiation. For the same reasons, it is also evident that detection of slow neutrons is easier than the detection of fast or intermediate energy neutrons, particularly if the energy spectrum of these neutrons is to be measured.

The neutron energy spectrum can be divided into four energy regions, based on the types of neutron reactions typical of each region and on some convenient energy limits inherent in the response of detector materials and their instrumentation.

The slow neutron energy region encompasses the range between 0 and 0.4 eV. This is also referred to as the thermal region, although thermal neutrons actually have a Maxwellian distribution with a mean energy of 0.025 eV (equivalent to a neutron

velocity of 2200 m/sec). The 0.4 eV upper limit of this energy range is determined by the "cadmium cut-off" energy, a convenient measurement limit. The cross sections of most reactions used to detect neutrons in this energy range vary inversely with their velocity.

The intermediate neutron energy region extends from the cadmium cut-off energy of 0.4 eV up to 200 keV. This spans an energy range containing a number of reaction cross sections that exhibit pronounced irregularities known as resonances. For this reason this energy region is also referred to as the resonance region.

The fast neutron energy region comprises the energy range between 200 keV and 20 MeV and is the energy range in which most neutrons originate. Its lower energy limit, which forms a convenient upper limit for the intermediate range, is also a lower limit for the efficient application of fast neutron detectors. Its upper limit of 20 MeV is the threshold for the nuclear break-up process and the relativistic region and is an upper energy limit of the low energy neutron physics field under consideration.

The high energy neutron region, or relativistic region, is the energy region above 20 MeV. The detection of neutrons in this energy range is beyond the scope of this review and will not be discussed.

The field of neutron detection can be divided according to the neutron detector type and according to the application of the detector. Following an introductory summary of neutron-induced reactions used in the detection of neutrons, we review the field of neutron detection from these two points of view. The appendix of this report lists commercially available neutron detectors and their characteristics.

CHARACTERISTICS OF NEUTRON-INDUCED REACTIONS

Our summary of neutron-induced reactions that form the physical basis of neutron detection is based on the classification adopted by Barschall (BA56). Five specific classes of neutron interaction with matter are pertinent in the consideration of neutron detectors. All neutron detection systems consist of instruments that incorporate materials to bring about one of these neutron-induced reactions and to provide a means of measuring or indicating the results of the nuclear interaction. The five classes are elastic scattering, exoergic charged particle reactions, fission reactions, radiative capture, and endoergic reactions.

Elastic Scattering

Elastic scattering is widely used in detecting fast neutrons. It is usually observed through the ionization produced by the recoiling nucleus. The choice of nuclide to be used in a recoil detector depends on two major considerations. First, as can be seen from kinematic analyses (SE53, BL55A), the maximum energy transfer in a collision of a neutron with a nuclide can be expressed

$$\frac{E_R}{E_n} = 1 - \left(\frac{A - 1}{A + 1}\right)^2 ,$$

where E_R is the maximum recoil energy, E_n the energy of the incident neutron, and A the atomic weight of the nuclide. From this expression we see that the maximum energy of the recoiling nucleus is highest for nuclides of low atomic weight. For this reason recoil detectors rely primarily on hydrogen, deuterium, and helium.

The second consideration arises from the energy dependence of the scattering cross sections of these nuclides in the fast energy region. Below 1 MeV, hydrogen has considerable advantage over deuterium and helium because of its higher neutron-proton scattering cross section. For the detection of neutrons above 1 MeV, helium is favored because of the broad resonance in the neutron-helium scattering cross section in the 1 to 2 MeV range. At energies above the helium resonance region the anisotropic scattering characteristic of deuterium makes its use more desirable for certain applications.

Although the high neutron scattering cross sections of hydrogen, deuterium, and helium at energies below 0.5 MeV favor the use of the recoil method in detecting neutrons at this level, its extension into that energy range requires electronic discrimination techniques (e.g., pulse shape discrimination) to differentiate between ionizing events produced by neutrons and by gamma rays.

The advantages of the recoil method of detection are (1) slow neutrons are easily discriminated because of the negligible energy transfer to the recoiling nucleus, (2) stable hydrogenous compounds are readily available, and (3) the total H(n, p) scattering cross section is known with good accuracy.

Applications of elastic scattering to the detection of fast neutrons are numerous. For example, proton recoil has been widely used in proportional counters and liquid scintillators. Deuteron recoil in liquid scintillators has been applied to time-of-flight spectroscopy with the advantage of lower gamma ray sensitivity and avoidance of the competing radiative capture reaction in hydrogen. High pressure ^{4}He proportional counters, used extensively in the nuclear safeguards program, have a higher efficiency and lower gamma ray sensitivity than those filled with hydrogen or methane.

Exoergic Charged Particle Reactions

In exoergic neutron-induced charged particle reactions the reaction products have a greater kinetic energy than the original particles, i.e., the reaction energy, Q, is positive. The common characteristics of these reactions are (1) their very high reaction cross sections at low neutron energies, which make them specifically adaptable to the detection of slow neutrons, and (2) the prompt emission of easily detectable high energy charged particles. These reactions are extensively used as the detection basis of proportional and scintillation counters, as well as for foils and

photographic emulsions. Although primarily used to detect slow neutrons, their use in detecting fast neutrons can be extended by using a neutron moderator.

The following four exoergic charged particle reactions are widely used in the detection of neutrons.

$^{10}B(n,\alpha)^{7}Li$

This reaction has long been used in the detection of low energy neutrons. The ^{10}B cross section has a value of 3837 barns at 0.025 eV and decreases according to the 1/v relationship with increasing energy up to 100 keV. The $^{10}B(n,\alpha)^{7}Li$ reaction proceeds both to the ground and first excited (0.4774 MeV) states of ^{7}Li as follows:

$$^{10}B + n \rightarrow {}^{7}Li + \alpha + 2.792\ MeV$$

$$^{10}B + n \rightarrow {}^{7}Li^{*} + \alpha + 2.31\ MeV$$

$$^{7}Li^{*} \longrightarrow {}^{7}Li + \gamma + 0.4774\ MeV.$$

For thermal neutrons, only ~6% of the reactions lead to the ground state, so that in 94% of the capture events a 480 keV prompt gamma ray is emitted from the decay of the excited state of ^{7}Li.

The high thermal cross section and the simultaneous emission of the alpha particle, ^{7}Li recoil, and gamma ray offer a number of possibilities for neutron detection techniques. In addition, the occurrence of boron in a variety of forms makes it versatile for application in low energy neutron detection. At higher neutron energies, however, this reaction yields a more complex distribution of reaction products that, together with the existence of competing reactions [e.g., (n, p), (n, t), and (n, d)], makes its application to higher energies more difficult.

$^{3}He(n,p)T$

The chief use of ^{3}He is as a thermal neutron detector. Although its thermal cross section of 5327 barns at 2200 m/sec exceeds that of the $^{10}B(n,\alpha)$ reaction, the high cost of ^{3}He often prevents it from being used competitively with ^{10}B in gas-filled counters. One of the advantages of this reaction is the smooth variation of the reaction cross section up to 2 MeV, which also makes it applicable to neutron spectrometers in the MeV range. Another advantage of this reaction is the absence of excited states of the daughter nucleus, so that a single reaction energy corresponds to a given neutron energy and the total reaction energy from the capture of a neutron is high enough for the pulse not to be distorted by gamma-ray-induced electrons. As a detecting material, ^{3}He is used in gas-filled proportional counters and gas scintillators.

$^{6}Li(n,\alpha)T$

From its thermal value of 945 barns, the cross section for the $^{6}Li(n,\alpha)T$ reaction decreases with increasing neutron energy according to the 1/v law until it first exhibits a resonance in the region of 250 keV. This reaction is readily adaptable to the detection of slow neutrons; its high reaction energy of 4.78 MeV helps distinguish the reaction product recoils from gamma rays. At higher neutron energies the large resonance of the $^{6}Li(n,\alpha)$ cross section is widely used in ^{6}Li-loaded scintillators designed for the detection of fast neutrons. However, since lithium has no usable gaseous compounds, it is not as versatile as boron.

$^{14}N(n,p)^{14}C$

This reaction has a limited application to neutron detectors because of its low cross section and the competing $^{14}N(n,\alpha)^{11}B$ reaction at higher neutron energies. It is used primarily in the detection of neutrons with photographic plates in which nitrogen occurs naturally. In addition, ^{14}N is commonly included in a counter gas as a small impurity to provide an energy calibration point.

Fission Reactions

The large amount of energy released from fission makes it an efficient and convenient method to detect neutrons. Fission events are detected by the ionization produced by the fission fragments or by the detection of the fission fragment radioactivity. Because of their insensitivity to gamma rays or other reaction products, fission detectors are particularly suited to environments of high gamma-ray fluxes.

In general, fissionable material used in detectors can be divided into two categories: slow fissionable (^{233}U, ^{235}U, and ^{239}Pu), with thermal fission cross sections of a few hundred barns, and fast fissionable (^{231}Pa, ^{232}Th, ^{234}U, ^{236}U, ^{238}U, and ^{237}Np), whose fission thresholds occur above 0.4 MeV. One aspect that puts a limit on the use of fissionable materials in fission detectors is their natural alpha decay activity; if the alpha half-life is $<10^{6}$ yr, the material is difficult to use as a detector because of the alpha particle buildup during the average pulse. However, if the alpha activity does not exceed that of a 10^{6}-yr half-life, it is possible to set discriminating levels of the detectors high enough to eliminate detection of the alpha particles. The fissionable nuclides that fall into this category and require more care in their application as neutron detectors are ^{231}Pa, ^{233}U, ^{234}U, and ^{239}Pu. In general, because of the undesirable properties of their gaseous compounds, fission detectors use the metallic or oxide form of the fissionable materials.

Radiative Capture

This process, in which the capture of a neutron by a nucleus forms a compound nucleus that decays to its ground state by emitting one or more gamma rays, is used

for the detection of neutrons either by detecting the capture gamma rays or by observing the activity of the product nucleus. Radiative capture by heavier elements is well suited to the detection of slow neutrons because of the high value of the capture cross section at low energies and the relatively small probability of competing reactions, such as elastic scattering.

Detecting neutrons by observing the capture gamma rays has not found extensive use. The principal use of the radiative capture reaction in neutron detection has been in the observation of the unstable product nucleus and its activity. The choice of the capturing element is dictated by its cross section, the decay characteristics of the product nuclide, and its physical form. Detectors are usually foils or capsules, although other techniques, such as the manganese bath ($MnSO_4$ in solution) for the calibration of neutron sources, are also used. The elements most often used in radiative capture detectors are sodium, manganese, cobalt, cadmium, indium, iodine, and gold.

Another neutron detection technique based on radiative capture, frequently used to detect and estimate weak neutron sources, is the Szilard-Chalmers method (SZ34). This technique uses the energy of the recoiling product nucleus to break a chemical bond, thus separating the radioactive nuclei from the stable ones and enhancing the concentration of the detecting element.

Endoergic Reactions

In endoergic neutron-induced reactions, the kinetic energy of the reaction products is smaller than the kinetic energy of the initial particles by an amount equal to the reaction energy. These reactions have an energy threshold (determined by the minimum reaction energy) below which they are energetically impossible. Since these threshold energies are primarily in the fast energy region, endoergic neutron-induced reactions are specifically suited for the detection of fast neutrons.

In general, endoergic reactions emit either more than one neutron or a charged particle. Since the threshold of the reaction is usually chosen to be close to the energy of the neutron to be detected, the emitted charged particles have a low energy and are difficult to detect. Although it is possible to observe the ionization produced by the emitted charged particle, the method normally adopted is to measure the activity induced in the product nucleus.

Detector choice for endoergic reactions is similar to that for radiative capture. Decay half-life, emitted radiation, effective threshold, and magnitude of the reaction cross section determine the applicability of a nuclide to given detection criteria. Threshold detectors are normally foils or capsules that measure the induced activity after the exposure of the sample to the neutron environment.

In addition to the endoergic reactions that emit either more than one neutron or charged particles, inelastic scattering (e.g., (n, n') reactions), which leaves the excited nucleus in an isomeric state, has also been used as a threshold detector of fast neutrons.

NEUTRON DETECTOR TYPES

The development of specific neutron detector types has been dictated by the combined consideration of the neutronic and physical properties of neutron-sensitive materials and the desired performance of a particular detector. Although the principles are few, the number of applications is large. Neutron detectors can be classified as ionization chambers, proportional counters, semiconductor detectors, scintillation counters, and passive detectors. Of these, the first four are complex in their design and require ancillary electronic instrumentation. Passive detectors are simpler, smaller, and require analysis subsequent to the detection process.

Ionization chambers and proportional counters are gas detectors that depend on the ionization of a gas by a high energy charged particle. A third detector that is also a gas ionization detector is the Geiger-Müller counter. This detector, however, is not easily adapted to the direct detection of neutrons but is often used in the detection and measurement of gamma radiation induced by neutrons. The essential difference between the three types of gas ionization detectors is in the voltage applied between the two electrodes of the instrument, which determines the field strength in the filling gas.

Ionization Chambers

Ionization chambers, probably the most widely known and used particle detectors, usually consist of a gas-filled chamber containing a cathode and a collector anode, or plate. Most ionization chambers operate in the range of 200 to 4000 V, while high pressure chambers may require up to 20,000 V.

Ionization chambers work because a charged particle passing through a gas leaves in its wake a large number of ion pairs whose charge is collected and measured on the collector plate. In the specific application to neutron detection, the charged particles originate from neutron interactions either in the chamber gas itself or in a radiator located within the chamber. Depending on the neutron reactive element used, ionization chambers detect either fast or slow neutrons. Depending on their construction and associated electronics, they can also be used as either integrating chambers or pulse counters. The former measure the average ionization current produced by many events; the latter record the number and magnitude of individual ionization events.

Integrating ionization chambers have been used to measure the fast neutron flux by observing the direct current caused by recoil protons in a hydrogenous gas. The homogeneous ionization chamber is one such chamber; it was originally developed by Bretscher and French (BR44) and subsequently used by Larsson (LA54). This technique, however, has two inherent problems: losses in the chamber wall and the effect of background ionizing radiation.

To compensate for those protons that lose part of their energy outside the sensitive volume of the chamber, the chamber walls of some detectors have been coated with a hydrogenous material having a composition similar to that of the gas. Effectively,

there is no discontinuity in material at the gas boundary; to the neutrons the chamber appears to be an infinite volume of gas. The effect of gamma rays and other ionizing radiation has been suppressed by comparing the current from two identical chambers having the same sensitivity to ionizing radiation but filled and lined with hydrogenous material having different response to neutrons.

Pulsed ionization chambers are designed to detect individual ionization events originating either in the filling gas or caused by particles ejected from a radiator. Ionizing particles detected in an ionization chamber may be either recoiling nuclei or the charged products of nuclear reactions. In the pulsed mode of operating ionization chambers, there is a limit to the voltage that can be applied without introducing electrical noise. This limit sets a lower charged particle energy limit of ~100 keV. Another limitation of pulsed ionization chambers is the difficulty of recording particles having a long range in the ionization chamber gas.

In general, the use of the proton recoil mechanism in ionization chambers has been limited by the lack of internal gas amplification of the ionization produced by the recoiling proton and the resulting electronic amplification noise level. More commonly used in ionization chambers are reactions such as $^{10}B(n,\alpha)$ or fission in which the pulse height is large in comparison to the amplifier noise level or to pulses generated by gamma-ray-induced electrons.

Ionization chambers incorporating boron as the reactive element have been primarily of the boron-lined counter type (LO50, JA53, TA51, MA54, LA51, DU57, AB56). These counters do not exhibit as flat a response plateau as the gas-filled BF_3 counters (which operate more effectively as proportional chambers) because some of the alpha-particle energy is absorbed in the counter lining. However, their advantage is that the filling gas can be chosen for its counting qualities and the counter itself can be designed to operate at lower voltages than BF_3-filled tubes. Commercially available boron-lined chambers usually operate at ~600 V, while BF_3-filled counters require from 2000 to 4000 V.

The standard boron-lined chamber (type TQT) developed in England has been described by Jacques et al. (JA53). Taylor and Sharpe (TA51) have described its BF_3-filled counterpart (type TPA). Gamma-ray compensated boron-lined ionization chambers, which provide for electronic or mechanical control of the gamma-ray flux contribution, have been described by MacCreary and Bayard (MA54) and Duchene et al. (DU57), respectively.

One type of ionization chamber that is widely used in the detection of neutrons relies on the fission process. Such fission chambers, in which the fissionable material is either the chamber lining or a radiator, are very effective because of the high energy and short range of the fission fragments. However, for this same reason and because fissionable material is not available in gaseous form, such counters have a low detecting efficiency. To overcome this deficiency, several fission chambers have been designed to increase the density of fissionable material within the chamber: the spiral chamber

(RO49), the multiplate chambers (AL55, ER56), and the cylindrical chamber (AV54). The fissionable material used in fission chambers depends on the neutron energy to be measured.

Table 1 is a summary outline of ionization chambers.

Proportional Counters

A proportional counter is usually a cylindrical ionization chamber where one thin-wire electrode is kept at a positive potential with respect to an outer cylindrical electrode. These counters are employed widely in the detection of neutrons from a few keV to several MeV and are used to advantage in detecting fast neutrons in the presence of gamma rays.

Table 1. Ionization chambers.

Proton-recoil chambers
Homogeneous ionization chamber (BR44, LA54, RO49)
Boron-lined chambers
Standard chamber (JA53)
B_4C-lined chamber (LA51)
Compensated ionization chamber (MA54)
BF_3-filled chambers
Standard chamber (TA51)
Parallel-plate gamm-ray compensated chambers (JA53, MA54, DU57)
Fission chambers
Spiral-type chamber (RO49)
Multiplate chambers (AL55, ER56, HO54B)
Cylindrical chamber (AV54)
Gridded chamber (LA60)

Proportional counters differ from ionization chambers in that they operate at a higher voltage, so the ions released by the passage of energetic ionizing particles are multiplied by secondary ionization. Thus, for a given voltage, the multiplication is constant and the pulse size is proportional to the number of ion pairs produced and to the energy of the detected particle. The pulse size is greater than an equivalent pulse from an ionization chamber by a factor of 100 to 1000. This gas amplification has the advantage over electronic amplification because it eliminates electronic noise. The other advantage of a proportional counter over an ionization chamber is that the pulse height is independent of the radial position of the particle track.

Proportional counters applied to neutron detection make use of three techniques: observation of recoils in hydrogen, helium, gaseous hydrocarbons, or solid hydrogenous radiators; counting of alpha particles and ^{7}Li recoils from the $^{10}B(n,\alpha)^{7}Li$ reaction in BF_3-filled or boron-lined counters, and detection of protons and tritium recoils from the $^{3}He(n, p)T$ reaction in ^{3}He-filled counters.

Proton Recoil Proportional Counters

The proton recoil proportional counters primarily detect fast neutrons. Gas recoil counters filled with a hydrogeneous gas are effective in the energy range from

2 or 3 keV to 3 MeV. Since for a given neutron energy the most energetic recoils are those of hydrogen nuclei, hydrogen—both pure and in the form of hydrocarbons such as methane and propane—is the most useful filling. In some specialized applications, however, gases such as helium may be preferred (WA54). The early development of proportional counters filled with hydrogen and methane was done in England (SK52). A review of the early development of gas recoil techniques has been published by Rossi and Staub (RO49), and Ferguson gives a comprehensive treatment of gas recoil counters and their characteristics (FE60).

To increase the efficiency of gas-filled counters using proton recoil detection, thin hydrogeneous radiators of polyethylene or paraffin can be mounted in proportional counters, either as a lining of the inner wall chamber or in the form of separate radiators built into the chamber. An extension of this technique has led to the development of recoil telescope detectors. This type of detector consists of a hydrogenous radiator with two or more counters placed in tandem and operated in coincidence, or anti-coincidence, to detect the recoil protons. The advantage of this technique is its high degree of discrimination against background radiation; its disadvantage is its low efficiency. For a detailed review of recoil telescope detectors, see (JO60).

A proton recoil proportional counter specially designed for dosimetry applications, closely approximates the neutron dose response of human tissue and is gamma ray insensitive (HU51). It consists of two proton recoil radiators and uses a special gas mixture. Another proportional counter based on proton recoil detection was designed to minimize secondary scattering effects (PE56). This triple proportional counter eliminated the need for wall corrections, and the response spectrum to monoenergetic neutrons is in the form of a peak rather than a plateau. Another gas-filled counter, using anti-coincidence methods to eliminate wall effects, is described in (GI53).

BF_3-filled Proportional Counters

The BF_3-filled proportional counters have been the most widely used of all neutron counters. Although primarily designed for slow neutrons, the BF_3 counter has been adapted to fast neutron detection by surrounding it with a block of shaped neutron moderating material, such as paraffin or polyethylene. One such design, known as the Long Counter, is robust, insensitive to gamma rays, reasonably directional, and not sensitive to variations in the power supply (HA47, AL60B). It is a relatively efficient detector, and within the neutron energy range of 25 keV to 5 MeV the response of the Long Counter is flat to within about ±8%. Another design, for detecting a highly collimated neutron beam, combines the use of a large number of BF_3 counters in paraffin surrounding a centrally situated scatterer (LA52A). This detector achieves efficiencies of 20% for fast neutrons. To improve its efficiency in detecting slow neutrons, the BF_3 gas of proportional counters can be enriched in ^{10}B, increasing the sensitivity of the detector by about a factor of 5 over that of natural boron BF_3 gas. Nowadays most commercially available BF_3 counters contain enriched boron. One of

the important advantages of the BF_3 counter is that the alpha and ^7Li particles are not slowed down by the solid boron lining and, having the same energy, they therefore produce the same pulse heights for all slow neutrons.

Boron-lined Proportional Counters

The boron-lined proportional counters coated with enriched boron have been developed to provide a high sensitivity to thermal neutrons compared to the BF_3 proportional counter. They have the additional advantage of operating at higher temperatures. Proportional counters lined with ^{10}B are effectively used in high proton fields. Their sensitivity is proportional to the lining thickness, but self-absorption of the alpha particles prevents significant increases in sensitivity at the greater thicknesses. These counters are insensitive to gamma rays and are capable of neutron-sensitive operation in gamma-ray fields as high as 10^4 or 10^5 R/hr. Typically, they are filled with argon or CO_2. Their operating voltage is usually lower than that of the BF_3 or ^3He chambers, and they normally produce larger output pulses with shorter rise times.

^3He-filled Proportional Counters

The ^3He-filled proportional counters employ the $^3He(n, p)T$ reaction, which has a smooth response with no resonances over a wide range in the low neutron energy range. These counters, unlike BF_3-filled chambers, can be used effectively for neutron spectrometry. Very high sensitivity can be achieved by increasing gas pressure, which increase does not require much increase in operating voltage. For two reasons, many of the reactions near the counter wall do not contribute their full energy to the output pulse. First is the kinematics of the reaction, which produces two product particles emitted in different directions, and second is the relatively low stopping power of ^3He. The wall effect, however, has been minimized in all commercial ^3He detectors by increasing the counter diameter so that the proportion of events near the wall is small; also, an increase of the helium pressure or the addition of small amounts of a heavier gas improves the stopping power of the gas. Batchelor has developed a ^3He-filled proportional counter containing krypton and CO_2 that is useful in the region of 100 to 1000 keV (BA55). For a comprehensive review of ^3He neutron spectrometers, see (BA60).

Table 2 is summary of proportional counters.

Semiconductor Detectors

Semiconductor radiation detectors behave like gas ionization chambers except that the charge is carried by electrons and electron vacancies (holes) in a solid semiconducting material instead of by electrons and positive ions in a gas. Because of this similarity, this detector is often called a solid-state ionization chamber. Small in size and

with low operating voltage requirements, it provides excellent energy resolution for charged particles. For neutron detection, the semiconductor is coupled with conversion foils coated with neutron-sensitive materials that produce charged particles for detection.

The use of a solid as a detector is very attractive because the sensitive layer can be very thin and yet possess a high stopping power. Another advantage is the low energy necessary to produce a single hole electron pair. The intrinsically high response speed of the device results from the high mobility of the carriers in the electric field and the short distance between electrodes.

There are two classes of semiconductor detectors that can sustain a high electric field inside a solid without using high applied voltages. One type is a reverse-bias p-n junction. This device is made of high-resistivity p-type material into which a small amount of donor impurity such as phosphorus has been diffused. A second class is the surface barrier detector, which is usually made from high-resistivity n-type silicon. The nature and formation of the surface barrier is believed to arise from surface states whose existence is well-established for silicon and germanium.

Table 2. Proportional counters.

Proton recoil counters (AL57)
Hydrogen-filled (WI50)
Deuterium-filled (FE60)
Gaseous hydrocarbon-filled (SK52)
Hydrogenous radiator (HU51)
Helium-filled (WA54)
Recoil telescope detectors (JO60)
BF_3 counters
Enriched BF_3 counters (AB58)
Long Counter (HA47, AL60B)
Langsdorf counter (LA52A)
Multiple coincidence counters
Boron-lined counters
Argon/CO_2-filled counters
^{3}He-filled counters (BA60)
^{3}He/krypton-filled counter (BA55)
^{3}He/argon-filled counter (BL55B)

Both the ^{6}Li(n, α) and the ^{3}He(n, p) reactions have been applied to neutron detection by surface barrier detectors. One such ^{6}Li counter has been used primarily as a neutron spectrometer (AR64). Surface barrier counters using ^{3}He applied to the spectrometry of continuous neutron spectra have been developed by Dearnaley and Ferguson (DE62) and Love and Murray (LO61). Walter developed a fast-response fission detector which detects electrical pulses from carriers produced by the passage of fission fragments through germanium p-n junction semiconductor detectors (WA58).

Scintillation Counters

The scintillation counter is the most sensitive and versatile detector for many types of radiation. In addition to its efficiency, it has the considerable advantage of speed. The scintillation counter consists of a transparent scintillator optically coupled to a photomultiplier. The photomultiplier output is connected to electronic circuitry. When a neutron or other particle gives up its energy in the scintillator, it produces an excitation that generates a flash of light or scintillation. Some of these photons then

strike the photocathode of the multiplier and cause the release of photoelectrons. The photoelectrons are directed into the electrode structure of the photomultiplier, where their number is increased by a very large factor. The amplified electron current finally arrives at the collector plate where it produces a voltage pulse proportional to the light output of the scintillator.

Scintillators are attractive as neutron detectors because the range of charged particles from neutron interactions is small compared to the sensitive volume of the detector. In addition, scintillation detectors allow for a denser ionizing medium than gas ionization detectors, and they produce faster pulses that are particularly amenable to coincidence counting techniques.

To compensate for their high sensitivity to gamma rays, scintillation counters must include neutron reactive elements to enhance their response to neutrons. The reactions normally used to detect neutrons in scintillator materials are

- neutron scattering in hydrogenous materials, where the high energy recoil protons generate the scintiliation;
- exoergic charged particle reactions in ^{6}Li, ^{10}B, sulphur, and others, which release a considerable amount of energy in the form of charged particles that produce ionization in the scintillator medium; and
- radiative capture of neutrons in the cesium, iodine, cadmium, or gadolinium component of solid or liquid scintillators and observation of the prompt or delayed gamma-ray emission.

A variety of schemes to reduce the gamma-ray sensitivity of organic scintillators has been devised. Harding proposed using a layered mixture of scintillator and hydrogenous material (HA51). Hornyak (HO52) constructed a gamma-ray insensitive detector using a dispersion of ZnS in Lucite;* another proposed design consisted in embedding small pieces of plastic phosphor in Lucite or quartz (MC54). Numerous similar detectors consist of ZnS or KI suspension in paraffin, polystyrene, or other organic materials (FR50, EM54, SE54, BR54). In addition, either neutrons or gamma rays in mixed radiation fields can be discriminated by pulse shape analysis (BI60, KU71). A review of organic scintillation materials and an experimental comparison of these detectors was published by Koontz, Keepin, and Ashley (KO55).

In general, the versatility of the scintillator technique makes it adaptable to the detection of both slow and fast neutrons. Among the most sensitive scintillators are thallium-activated NaI [NaI(Tl)], europium-activated ^{6}LiI [$^{6}Li(Eu)$], ^{6}Li-loaded cerium-activated silicate glass, and ZnS crystals. The size of the detecting scintillator is critical in that it can significantly perturb the neutron field being measured. Except for this flux perturbation effect and self-shielding effects, the scintillator has negligible detection anisotropy. For more detailed descriptions of scintillation detectors, see

*Reference to a company or product name does not imply approval or recommendation by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

(MU60, BI60, SN69). Specific scintillators have been described in (GI67, BO67, GR63). Table 3 is a summary of commonly used scintillator materials.

Table 3. Commonly used scintillation detector materials.

Solid inorganic scintillators (MU60, BI60)
Europium-activated LiI [LiI(Eu)] (SC53, MU58, GI61, LE65, HO51)
Thallium-activated NaI [NaI(Tl)] (GR63)
Thallium-activated ^{10}B-loaded NaI (NE60)
Thallium-activated KI [KI(Tl)] (MU60)
Thallium-activated CsI [CsI(Tl)] (KN56, EN58, BA58, ST58)
Silver-activated ZnS [ZnS(Ag)], "Hornyak Button" (HO52, HO54A, KA49, KO55)
Polyethylene-moderated ZnS(Ag), "Egghead" Detector (MO52B)
ZnS/B_2O_3 glass mixture (GU55, AL52)
Boron-(^{10}B) and Lithium-(^{6}Li) loaded ZnS (SU56)
Cerium-activated borate glass (BO59)
Cerium-activated lithium-magnesium glass (BO59)
Liquid organic scintillators (MU60, BI60)
Xylene + p-terphenyl + dibiphenyloxazole (NE60)
Toluene + p-terphenyl (NE60)
Phenylcyclohexene + p-terphenyl + diphenyloxazole benzene (NE60)
Triethylbenzene + p-terphenyl (NE60)
Isopropylbiphenyl + p-terphenyl (NE60)
Boron-loaded toluene (BO57)
Cadmium-loaded triethylbenzene (DI56)
Gadolinium-loaded xylene [Pilot LS/Gd]
Cd or B-loaded liquid "total absorption spectrometer" (CL52, CO56)
Boron oxide or methylborate in terphenyl/toluene (DR51, TH53)
Organic crystals and plastics (BI60)
Anthracene (BR56, KA57, SA56)
Stilbene (SA56, SW57A, BO67, BR56, KA57)
Quaterphenyl (SA56)
Polystyrene + p-terphenyl (SW54B)
Polyvinyltoluene + p-terphenyl (SW54B)
Noble gases (HU60B)
^{4}He (EV71, MA72)
^{3}He/xenon mixture (NO58A)
Argon/nitrogen mixture (EG56)
Liquid noble gas (NO56B)

Passive Detectors

Passive detectors do not require auxiliary electronic equipment to amplify or analyze the detector signal at the time and place of detection. The analysis of the recorded detection is performed later, usually in a controlled environment. Passive detectors are small and simple, so they are adaptable to nonlaboratory situations. This review discusses foil detectors, particle track detectors, moderated activation detectors, and thermoluminescent detectors.

Foil Detectors

Foil detectors use three categories of neutron-sensitive materials, all of which have been used in neutron spectroscopy and for accurate neutron flux measurements over a wide energy range. In all cases the detecting foils are exposed to neutrons and the induced gamma, beta, or fission product activity is measured. The degree of activity produced depends on the intensity of the neutron flux, the duration of irradiation, and the half-life of the product nucleus. Measuring of the activity after irradiation, under controlled laboratory conditions, permits an accurate determination of the neutron flux.

The three categories of foil detectors are activation foil detectors, resonance foil detectors, and threshold foil detectors. Activation foil detectors, commonly referred to as 1/v detectors, depend on their high radiative capture cross sections and the smooth energy dependence of this cross section in the thermal and low energy range. They are often used to measure thermal flux. Because of its very large thermal cross section, indium is most widely used when high sensitivity is required. Cobalt, because of the 5.2-yr half-life of the product nucleus, is adaptable to integral measurements of the neutron flux over long exposure times. Gold is particularly well-suited for precision measurements up to 3 eV.

Table 4 is a list of isotopic radiative capture reactions amenable to thermal neutron activation detection, together with their nuclear characteristics. The isotopes most commonly used as activation detectors are underlined. Some of the listed isotopes are available only in a chemical form (e.g., an oxide) that reduces the macroscopic cross section shown. Since the total number of isotopes that can be activated by neutron irradiation is very large, we listed only those isotopes in which (1) the isotope in its natural state is nongaseous, (2) the product nucleus is gamma-emitting, (3) the half-life of the product nucleus is >1 min, and (4) the macroscopic activation cross section (equal to the microscopic activation cross section multiplied by the atomic density weighted by the natural abundance) is >0.01 cm^{-1}.

Resonance foil detectors, which like activation foil detectors use the radiative capture process, are suited to neutron detection in the intermediate energy range because of the existence of pronounced resonances in their radiative capture cross section. Resonance detectors can be used to measure the flux density of decelerating neutrons from the cadmium cut-off energy of 0.4 eV up to ~1 keV. Even though their

Table 4. Isotopic radiative capture reactions amenable to thermal neutron activation detection.

Isotope	Isotopic abundance (%)	2200 m/sec absorption cross section: Microscopic[a] (barns)	2200 m/sec absorption cross section: Macroscopic[b] (cm^{-1})	Product nucleus	Half-life of product nucleus[c]	Beta and gamma radiation emitted by product nucleus[c] (MeV)
^{23}Na	100.0	0.40 ± 0.03	0.01	^{24}Na	15 hr	β^-(1.4), γ(1.38, 2.75)
^{27}Al	100.0	0.232 ± 0.003	0.014	^{28}Al	2.31 min	β^-(2.85), γ(1.78)
^{39}K	93.1	2.2±0.2	0.027	^{40}K	1.28×10^9 yr	β^-(1.31), γ(1.46), β^+(0.483)
^{45}Sc	100.0	11.0 ± 4.0	0.113	$^{46m}Sc^*$	20 sec	γ(0.142)
	100.0	25.0 ± 2.0	0.256	^{46}Sc	83.8 d	β^-(1.48, 0.36), γ(0.89, 1.12)
^{51}V	99.8	4.8 ± 0.2	0.338	^{52}V	3.76 min	β^-(2.47, γ(1.434)
^{50}Cf	4.3	16.0 ± 0.5	0.049	^{51}Cr	27.8 d	γ(0.32)
^{55}Mn	100.0	13.3 ± 0.1	1.05	^{56}Mn	2.576 hr	β^-(2.85), γ(0.847, 1.811, 2.11)
^{59}Co	100.0	17.0 ± 2.0	1.55	$^{60m}Co^*$	10.5 min	β^-(1.55), γ(0.059, 1.33)
	100.0	19.9 ± 0.91	1.81	^{60}Co	5.26 yr	β^-(1.48, 0.314), γ(1.173, 1.332)
^{63}Cu	69.1	4.5 ± 0.2	0.263	^{64}Cu	12.9 hr	β^-(0.573), β^+(0.656), γ(0.511, 1.34)
^{65}Cu	30.9	2.3 ± 0.3	0.06	^{66}Cu	5.1 min	β^-(2.63), γ(1.039)
^{64}Zn	48.9	0.82 ± 0.01	0.026	^{65}Zn	243.6 d	β^+(0.327), γ(0.511, 1.115)
^{69}Ga	60.1	1.8 ± 0.4	0.056	^{70}Ga	21.1 min	β^-(1.65), γ(0.173, 1.040)
^{75}As	100.0	4.3 ± 0.10	0.199	^{76}As	26.5 hr	β^-(2.97), γ(0.559-2.10) many
^{79}Br	50.5	2.6 ± 0.2	0.027	$^{80m}Br^*$	4.4 hr	γ(0.037)
	50.5	8.6 ± 1.4	0.089	^{80}Br	17.6 min	β^-(2.0), β^+(0.87), γ(0.511, 0.618, 0.666)
^{81}Br	49.5	3.5 ± 0.5	0.036	^{82}Br	35.5 hr	β^-(0.444), γ(0.554-1.475) many
^{93}Nb	100.0	0.15 ± 0.1	0.0082	$^{94m}Nb^*$	6.26 min	β^-(2.1), γ(0.0415, 0.703, 0.872)
	100.0	1.15 ± 0.05	0.063	^{94}Nb	2.0×10^4 yr	β^-(2.06), γ(0.702, 0.871)
^{102}Ru	31.3	1.2 ± 0.3	0.027	^{103}Ru	39.6 d	β^-(0.22, 0.70), γ(0.50, 0.61)
^{103}Rh	100.0	11 ± 1	0.798	$^{104m}Rh^*$	4.4 min	β^-(0.5), γ(0.051-0.77) many
	100.0	139 ± 5	10.09	^{104}Rh	43 sec	β^-(2.44), γ(0.56, 1.24)
^{108}Pd	26.7	12.0 ± 2.0	0.206	^{109}Pd	13.47 hr	β^-(1.028), γ(0.088-0.6) many
^{107}Ag	51.4	35.0 ± 5.0	1.05	^{108}Ag	2.42 min	β^-(1.64), β^+(0.9), γ(0.434-0.632) many
^{109}Ag	48.6	4.2 ± 0.7	0.12	$^{110m}Ag^*$	253 d	β^-(1.5, 0.53, 0.087), γ(0.658-1.5) many
	48.6	89.0 ± 4.0	2.54	^{110}Ag	24.4 sec	β^-(2.87), γ(0.658)
^{114}Cd	28.9	0.36 ± 0.007	0.005	$^{115m}Cd^*$	43 d	β^-(1.62), γ(0.485, 0.935, 1.29)
	28.9	0.30 ± 0.015	0.004	^{115}Cd	53.5 hr	β^-(1.11), γ(0.23-0.53) many
^{113}In	4.2	56.0	0.090	$^{114m}In^*$	50 d	γ(0.192, 0.558, 0.724)
	4.2	2.0	0.003	^{114}In	72 sec	β^-(1.988), β^+(0.42), γ(1.299)
^{115}In	95.8	85.0 ± 10.0	3.12	$^{116m2}In^*$	2.16 sec	β^-(0.22), γ(0.164)
	95.8	72.0 ± 4.0	2.64	$^{116m1}In^*$	54 min	β^-(1.0), γ(0.138-2.111) many
	95.8	42.0 ± 4.0	1.54	^{116}In	14 sec	β^-(3.3), γ(0.434, 0.95, 1.293)
^{120}Sn	33.0	0.001 ± 0.001	0.012	$^{121m}Sn^*$	76 yr	β^-(0.42), γ(0.37)
	33.0	0.14 ± 0.03	0.002	^{121}Sn	27 hr	β^-(0.383), no γ
^{123}Sb	42.8	0.015 ± 0.004	0.002	$^{124m2}Sb^*$	21 min	β^-(0.035), γ(0.025)
	42.8	0.03 ± 0.008	0.004	$^{124m1}Sb^*$	93 sec	β^-(1.19), γ(0.505, 0.603, 0.644)
	42.8	3.4 ± 0.8	0.045	^{124}Sb	60.3 d	β^-(2.31), γ(0.603-2.008) many
^{127}I	100.0	6.2 ± 0.2	0.145	^{128}I	25.08 min	β^-(2.12), γ(0.441, 0.528, 0.743, 0.969)
^{133}Cs	100.0	2.6 ± 0.2	0.0153	$^{134m}Cs^*$	2.90 hr	β^-(0.55), γ(0.128)
	100.0	27.4 ± 1.5	0.232	^{134}Cs	2.05 yr	β^-(0.662), γ(0.57-1.365) many
^{139}La	99.9	8.8 ± 0.7	0.235	^{140}La	40.22 hr	β^-(2.175, 1.69, 1.36), γ(0.329-2.53) many
^{141}Pr	100.0	3.9 ± 0.5	0.108	^{142}Pr	19.2 hr	β^-(2.16), γ(1.57)
^{152}Sm	26.6	210 ± 10.0	1.725	^{153}Sm	46.8 hr	β^-(0.8), γ(0.07-0.64) many
^{154}Sm	22.5	5.5 ± 1.1	0.038	^{155}Sm	22 min	β^-(1.53), γ(0.104, 0.246)
^{151}Eu	47.8	3000 ± 200	29.7	$^{152m1}Eu$	9.2 hr	β^-(1.88), β^+(0.89), γ(0.073-1.41) many
	47.8	5000 ± 300	49.5	^{152}Eu	13 yr	β^-(0.22-1.46), β^+(0.47, 0.71), γ(0.122-1.53) many
^{158}Gd	24.9	3.5 ± 1.0	0.026	^{159}Gd	18 hr	β^-(0.95), γ(0.058, 0.363)
^{159}Tb	100.0	30 ± 10	0.946	^{160}Tb	73 d	β^-(1.74, 0.86), γ(0.087-1.272) many
^{164}Dy	28.2	2100 ± 400	18.77	$^{165m1}Dy^*$	75 sec	β^-(1.04, 0.89), γ(0.108, 0.152, 0.362, 0.514)
	28.2	500 ± 450	4.47	^{165}Dy	2.3 hr	β^-(1.29), γ(0.095-1.08) many
^{165}Ho	100.0	3.45 ± 0.35	0.11	$^{166m}Ho^*$	1200 yr	β^-(0.067), γ(0.08-1.43) many
	100.0	61.2 ± 2.0	1.96	^{166}Ho	26.9 hr	β^-(1.84), γ(0.081, 1.38, 1.528, 1.663)
^{170}Er	14.9	6.0 ± 1.0	0.029	^{171}Er	7.52 hr	β^-(1.49, 1.06), γ(0.112-0.96) many
^{169}Tm	100.0	115 ± 15	3.83	^{170}Tm	128.6 d	β^-(0.96), γ(0.084)
^{168}Yb	0.14	3200 ± 400	0.109	^{169}Yb	32 d	γ(0.008-0.336) many
^{174}Yb	31.8	65 ± 5	0.505	^{175}Yb	101 hr	β^-(0.466), γ(0.114, 0.283, 0.396)
^{176}Yb	12.7	5.5 ± 1.0	0.017	^{177}Yb	1.9 hr	β^-(1.40), γ(0.122, 0.151, 1.08, 1.241)
^{175}Lu	97.4	21 ± 3	0.684	$^{176m}Lu^*$	3.7 hr	β^-(1.31), γ(0.088)
^{176}Lu	2.6	7 ± 2	0.006	$^{177m}Lu^*$	155 d	γ(0.0716-0.466) many
	2.6	2050 ± 50	1.784	^{177}Lu	6.7 d	β^-(0.497), γ(0.113, 0.208)

Table 4. Continued.

Isotope	Isotopic abundance (%)	2200 m/sec absorption cross section: Microscopic[a] (barns)	2200 m/sec absorption cross section: Macroscopic[b] (cm^{-1})	Product nucleus	Half-life of product nucleus[c]	Beta and gamma radiation emitted by product nucleus[c] (MeV)
^{180}Hf	35.4	12.6 ± 7	0.198	^{181}Hf	42.4 d	β^-(0.41), γ(0.133, 0.346, 0.482) complex
^{181}Ta	100.0	0.01 ± 0.002	0.0007	$^{182m}Ta^*$	16.5 min	γ(0.147, 0.172, 0.184, 0.319, 0.356)
	100.0	22 ± 1	1.215	^{182}Ta	115 d	β^-(1.71, 0.522), γ(0.068-1.6) many
^{186}W	28.4	37 ± 2	0.664	^{187}W	24 hr	β^-(1.31, 0.63), γ(0.072-0.773) many
^{185}Re	37.1	110 ± 5	2.7	^{186}Re	90 hr	β^-(1.07), γ(0.137, 0.632, 0.768)
^{187}Re	62.9	2.0 ± 0.5	0.083	$^{188m}Re^*$	18.7 min	γ(0.0024-0.106)
	62.9	75 ± 4	3.125	^{188}Re	16.7 hr	β^-(2.12), γ(0.155-2.0) many
^{184}Os	0.02	<200.0	<0.256	^{185}Os	94 d	γ(0.646, 0.875) complex
^{190}Os	26.4	12 ± 6	0.225	^{191m}Os	13 hr	β^-(0.13), γ(0.0495-0.1887) many
	26.4	4 ± 2	0.075	^{191}Os	15 d	β^-(0.143), γ(0.129)
^{192}Os	41.0	1.6	0.047	^{193}Os	31 hr	β^-(1.13), γ(0.139-0.558) complex
^{191}Ir	37.3	610 ± 60	15.9	$^{192m1}Ir$	1.4 min	β^-(1.5), γ(0.058, 0.317, 0.612)
	37.3	300 ± 30	7.82	^{192}Ir	74 d	β^-(0.67), γ(0.296-0.612) many
^{193}Ir	61.5	110 ± 15	4.76	^{194}Ir	17.4 hr	β^-(2.24), γ(0.328-1.7) complex
^{196}Pt	25.4	0.9 ± 0.1	0.016	^{197}Pt	18 hr	β^-(0.67), γ(0.077, 0.191)
^{198}Pt	7.2	4.0 ± 0.5	0.0195	^{199}Pt	30 min	β^-(1.69), γ(0.075-0.96) many
^{197}Au	100.0	98.8 ± 0.3	5.83	^{198}Au	2.693 d	β^-(0.962), γ(0.412, 0.676, 1.088)
^{202}Hg	29.8	4.9 ± 0.2	0.059	^{203}Hg	46.57 d	β^-(0.214), γ(0.279)
^{232}Th	100.0	7.4 ± 0.1	0.217	^{233}Th	22.2 min	β^-(1.23), γ(0.029-0.895) many

[a] D. T. Goldman, National Bureau of Standards, Gaithersburg, Md., private communication.

[b] Macroscopic cross sections were calculated, taking the isotopic abundance into consideration.

[c] C. M. Lederer, J. M. Hollander, and I. Perlman, Table of Isotopes (John Wiley and Sons, New York) 6th ed.

* Partial activation to metastable state.

cross sections rise to high values at low energies, these materials can be made to respond as resonance detectors by using neutron absorbing cadmium or boron shields to make them insensitive to thermal neutrons. A judicious combination of resonance detectors and other foil detectors makes an effective spectrometer of high sensitivity over a wide energy range. A representative list of resonance reaction data, where the most commonly used isotopes are underlined, is given in Table 5; a comprehensive tabulation of resonance detectors and their characteristics has been published by Zijp (ZI65).

Threshold foil detectors offer a convenient means of measuring neutron flux density over a broad range of the fast neutron spectrum. By using a set of threshold detectors, it is possible to obtain an approximate energy dependence of the neutron flux density. Most of the available threshold detectors are based on endoergic and fission reactions that have a threshold in the MeV energy range. Table 6 is a list of commonly used threshold detectors. A comprehensive list, together with an analysis of the criteria for selecting an appropriate set of threshold detectors, has been published by Byerly (BY60). Grundl reviewed current techniques in the use of threshold detectors in studies of fission-neutron spectra (GR68). The application of the threshold activation technique to the determination of ^{235}U fission spectrum has been described by Fabry (FA67).

One widely used threshold detector system (HU56, RE58B) utilizes four fast neutron foil detectors and one thermal neutron foil detector to determine the spectrum

Table 5. Resonance reaction data (in order of increasing resonance energy)(MO70).

Isotope	Isotopic abundance (%)	Half-life of product nucleus	Main resonance energy (eV)	Representative infinite dilution resonance absorption data: Resonance integral (barns)	Cut-off energy (eV)	References
^{191}Ir	37.30	74.2 d	0.654/5.36	3500	~0.5	a
^{193}Ir	62.70	19.0 hr	1.303	1370	~0.5	a
^{103}Rh	100.00	4.4 min	1.257	656	~0.5	a
^{115}In	95.72	54.0 min	1.457	3480 ± 120	0.55	b
^{181}Ta	99.99	115.0 d	4.28	1558	~0.5	a
^{197}Au	100.00	2.7 d	4.906	1534 ± 40	0.5	c
^{109}Ag	48.65	253.0 d	5.20	1160	0.4	d
^{152}Sm	26.63	46.2 hr	8.01	>1750	~0.5	a
^{107}Ag	51.53	2.3 min	16.5	74	~0.5	a
^{186}W	28.40	24.0 hr	18.8	320	0.6	e
^{127}I	100.00	25.0 min	20.5	140	~0.5	a
^{74}Se	0.87	120.0 d	27.0	—	—	
^{75}As	100.00	26.5 hr	47.0	36.8	0.4	d
^{139}La	99.91	40.2 hr	73.5	11	~0.5	a
^{110}Cd	12.40	48.6 min	89.0	—	—	
^{198}Pt	7.21	30.0 min	95.0	69	~0.5	a
^{59}Co	100.00	5.26 yr	132.0	72.3 ± 5.0	0.5	b
^{65}Cu	30.91	5.1 min	227.0	2.3 ± 0.23	0.5	e
^{203}Tl	29.50	3.9 yr	238.0	129	~0.5	a
^{71}Ga	39.60	14.1 hr	295.0	15	~0.5	a
^{55}Mn	100.00	2.56 hr	337.0	15.6 ± 0.6	0.55	g
^{100}Mo	9.36	14.6 min	367.0	13	~0.5	a
^{98}Mo	23.78	67.0 hr	480.0			
^{63}Cu	69.09	12.8 hr	580.0	5.1 ± 0.15	0.5	f
^{80}Se	49.80	56.8 min	2000.0	—	—	
^{64}Zn	48.99	245.0 d	2750.0	2	~0.5	a
^{23}Na	100.00	15.0 hr	2850.0	0.3 ± 0.01	0.5	f

[a] R. A. Charpie, et al., Eds., Physics and Mathematics (McGraw-Hill Book Co., New York, 1956), Ch. 6.

[b] K. H. Beckhurts, et al., Nucl. Sci. Eng. 17, 329 (1963).

[c] F. J. Johnston, et al., J. Nucl. Energy A11, 95 (1960).

[d] R. L. Macklin and H. S. Pomerance, in Proc. Conf. on Peaceful Uses of Atomic Energy, Geneva, 1955 (United Nations, Geneva, 1955), vol. 5, p. 96.

[e] S. P. Harris, C. D. Muelhause, and G. E. Thomas, Phys. Rev. 79, 11 (1950).

[f] R. Dahlberg, K. Jirlow, and E. Johansson, Reactor Sci. Technol. 14, 33 (1961).

[g] F. Feiner, Knowles Atomic Power Laboratory, Rept. KAPL 2000-16 (1961).

Table 6. Threshold reactions applicable to the detection of fast neutrons.

Isotope	Reaction	Threshold energy (MeV)	Fission spectrum averaged cross section (mbarns)	Reference	Product nucleus	Product nucleus half-life
^{103}Rh	(n, n')	0.04	—[a]		^{103m}Rh	57.5 min
^{115}In	(n, n')	0.34	200 ± 8	1	^{115m}In	4.5 hr
^{16}O	(n, p)	10.24	0.014	2	^{16}N	7.2 sec
^{19}F	(n, p)	4.25	0.5	2	^{19}O	29.1 sec
^{23}Na	(n, p)	3.75	0.7	2	^{23}Ne	37.6 sec
^{24}Mg	(n, p)	4.93	1.62	3	^{24}Na	15.0 hr
^{25}Mg	(n, p)	3.17	2.0	2	^{25}Na	60.0 sec
^{27}Al	(n, p)	1.90	4.32 ± 0.2	1	^{27}Mg	9.46 min
^{28}Si	(n, p)	4.00	4.0	2	^{28}Al	2.31 min
^{29}Si	(n, p)	3.00	2.7	2	^{29}Al	6.6 min
^{31}P	(n, p)	0.73	30.5 ± 1.2	4	^{31}Si	2.6 sec
^{32}S	(n, p)	0.96	73 ± 3	1	^{32}P	14.28 d
^{35}Cl	(n, p)	(-0.62)[b]	16.0	2	^{35}S	87.9 d
^{37}Cl	(n, p)	4.18	0.24	2	^{37}S	5.07 min
^{46}Ti	(n, p)	1.62	13.0	3	^{46}Sc	83.9 d
^{54}Fe	(n, p)	(-0.09)[b]	89.0	3	^{54}Mn	303.0 d
^{56}Fe	(n, p)	2.97	1.15 ± 0.04	1	^{56}Mn	2.58 hr
^{58}Ni	(n, p)	(-0.40)[b]	120.0 ± 6.0	1	^{58}Co	71.3 d
^{9}Be	(n, α)	0.67	10.0	2	^{6}He	0.8 sec
^{11}B	(n, α)	7.24	0.085	2	^{8}Li	0.84 sec
^{19}F	(n, α)	1.60	4.5	2	^{16}N	7.2 sec
^{23}Na	(n, α)	4.03	0.4	2	^{20}F	11.5 sec
^{27}Al	(n, α)	3.25	0.78 ± 0.03	1	^{24}Na	15.0 hr
^{31}P	(n, α)	2.01	1.43	2	^{28}Al	2.31 min
^{34}S	(n, α)	1.37	3.0	2	^{31}Si	2.62 hr
^{35}Cl	(n, α)	(-0.94)[b]	3.0	2	^{32}P	14.28 d
^{51}V	(n, α)	2.09	0.08	2	^{48}Sc	1.83 d
^{12}C	(n, 2n)	20.28	(200)[c]		^{11}C	20.4 min
^{63}Cu	(n, 2n)	11.02	0.123 ± 0.009	5	^{62}Cu	9.76 min
^{58}Ni	(n, 2n)	12.41	(1100)[c]		^{57}Ni	36.0 hr
^{92}Mo	(n, 2n)	12.83	(1000)[c]		^{91}Mo	15.5 min
^{127}I	(n, 2n)	9.21	(1300)[c]		^{126}I	12.8 d
^{203}Tl	(n, 2n)	7.76	(1000)[c]		^{202}Tl	12.0 d
^{232}Th	(n, f)	1.25[d]	87.5 ± 3.5	1	Fission products	—
^{231}Pa	(n, f)	0.42[d]	—[a]		Fission products	—
^{234}U	(n, f)	0.26[d]	—[a]		Fission products	—
^{236}U	(n, f)	0.70[d]	—[a]		Fission products	—
^{238}U	(n, f)	1.25[d]	325 ± 19	5	Fission products	—
^{237}Np	(n, f)	0.32[d]	1365 ± 95	5	Fission products	—

[1] A. Fabry, et al., in Proc. IAEA Conf. on Nucl. Data for Reactors, Helsinki, 1970 (IAEA, Vienna, 1970), vol. 2, p. 535.

[2] D. J. Hughes, Pile Neutron Research (Addison-Wesley, 1953), p. 100.

[3] A. Fabry, private communication quoted in (IC69).

[4] J. M. Boldeman, J. Nucl. Energy A/B 18, 417 (1964).

[5] (GR68)

[a] No information available.

[b] Exoergic reaction: Q-value is given in parentheses. Effective threshold is in the MeV range.

[c] No fission-averaged cross section value available; value in parentheses is the average cross section near peak.

[d] Effective (extrapolated) threshold.

to acceptable accuracies. In this system, foils of ^{239}Pu (shielded with ^{10}B), ^{237}Np, ^{238}U, and ^{32}S are used as threshold detectors. The first three foils use the fission reaction and the last uses the $^{32}S(n, p)$ reaction.

Some of the advantages of threshold detectors are their insensitivity to gamma rays or thermal neutrons, their suitability for extremely high flux intensities, their ruggedness, and their independence of temperature, humidity, or pressure.

Particle Track Detectors

The nuclear emulsion (CH54, BE63B, HA63, BE66A) and fission track (BE66B, PR68) techniques use nuclear particle tracks to detect neutrons. They have an advantage over other passive detection techniques, because (1) the permanent track record left by the particles allows accurate range, angle, and ionization measurements to be made, and (2) greater discrimination is possible against backgrounds of scattered neutrons, electrons, and gamma rays. However, considerable labor is involved in reading the tracks.

The nuclear emulsion technique measures the flux and energy of incident neutrons by detecting reaction products in a photographic emulsion. It can be applied in three different ways: (1) observation of proton recoils that originate in the emulsion (RO53), (2) observation of reaction products originating in nuclides with which the emulsion was impregnated (KE50), and (3) observation of reaction products originating in an external radiator. The nuclear emulsion technique can be used in monodirectional beams or in multidirectional neutron fields, either as an integral neutron detector or as a spectrometer. A typical emulsion plate consists of a 1-cm^2 piece of emulsion, 600 μ thick, mounted on a glass plate. The tracks can be measured with a microscope of magnification 500. A 5 MeV proton track has a track length of ~180 μ, measurable with high accuracy; accuracy deteriorates considerably at proton energies below 500 keV, with 100 keV the approximate limit of measurement.

The photographic emulsion has the advantages that it is a very compact detector with excellent resolution and it provides a permanent record of the results, even in low neutron density fields. In addition, it does not perturb the local neutron spectrum, it requires no associated electronic equipment, and it allows for multiple simultaneous measurements (IC71). The disadvantage of the method is the laborious nature of the scanning process (IC69). Moreover, this method fails to detect effectively neutrons with energies between ~10 eV and 0.5 MeV (CO58, CH54). Protons must have an energy of 0.25 MeV, corresponding on the average to a neutron energy of 0.5 MeV, to generate a track at the limit of recognition.

At the upper end of the energy scale, systems with hydrogenous radiators can be used up to ~20 MeV (BE63). Although such detectors have a low gamma-ray sensitivity, gamma-ray doses of 1 to 10 rad will complicate interpretation, and higher gamma-ray intensities will usually make track counting impossible.

A comprehensive review of the nuclear emulsion technique is given by White (WH60).

Fission track detectors, which record fission events by fission fragment etching of glass, mica, or plastic, offer an attractive alternative to counting fission product gamma activity. This technique can detect both low energy neutrons (using ^{235}U or ^{239}Pu) and fast neutrons (using any of the fast fissionable elements, e.g., ^{238}U, ^{237}Np, or ^{232}Th). Fission track detectors can be made to give absolute values and are totally insensitive to gamma rays below the photofission threshold. Recent development of track registration techniques in glasses and plastics has opened a new possibility for fission (and alpha emitting) foil analysis (KE66). In this technique, thin fission foils are placed in close contact with a glass or plastic surface, allowing the fission fragments to intercept the surface; the glass or plastic is then etched to render the tracks visible under a microscope. The fission track detection technique is readily adaptable to longterm integrating measurements. In addition, (1) milligram rather than gram quantities of fissile material are sufficient, (2) the technique has very good sensitivity, (3) early recovery of samples is unnecessary as the tracks are permanent at normal temperature, and (4) complex and expensive electronics are not required (IC71).

Moderated Activation Detectors

Moderated activation detectors, commonly referred to as Bonner spheres, consist of a material susceptible to slow or intermediate neutron activation surrounded by a moderating or absorbing spherical shell. Various activating materials and moderating envelope thicknesses can be selected to allow neutron detection over a wide range of intermediate and fast neutron energies. These assemblies, although fairly large in size, are easy to use and can be made to have low gamma-ray sensitivity and to be insensitive to thermal neutrons. They are equally adaptable to pulsed and to uninterrupted neutron fields and, like all detectors of spherical design, they have a nondirectional response. Analysis of the results and determination of the measured spectrum requires extensive calculation, for which computer codes have been written.

Thermoluminescent Detectors

A detector can in principle be any solid material that, when irradiated, exhibits a property whose response to radiation is a function of the energy absorbed. Thermoluminescence is a physical property that has been applied to the detection of neutrons. Although mainly responsive to gamma and high level beta radiation, the thermoluminescence technique has been extended to detect thermal and slow neutrons by using the neutron absorbing properties of ^{6}Li and ^{10}B. Two devices that use this technique are the $CaF_2(Mn)$ thermoluminescent material, used in conjunction with ^{10}B and ^{6}Li films, and LiF, which can be enriched with ^{6}Li to varying degrees. The addition of ^{6}Li to LiF varies the thermal neutron detector response in mixed radiation fields. The

response to neutrons of higher energies follows the Li cross section energy dependence and is low. Thermoluminescent devices can be quite small, are rugged and compact, and have good energy storage properties (IC71).

Miscellaneous Detector Types

In addition to these major neutron detection techniques, there exist several miscellaneous detector types. They include neutron radiography, cloud chambers, and neutron thermopiles. Neutron radiography can be considered an extension of the nuclear emulsion technique. It is, however, primarily a qualitative method. In principle it is very similar to x-ray photography or radiography. As in the case of x rays, neutrons are scattered and absorbed differentially by the constituents of an item under investigation and can be recorded on a photographic plate. Neutron radiography is used principally with slow neutrons and takes advantage of the neutron absorptive properties of elements, which are more pronounced at lower energies. Since photographic plates are not sensitive to slow neutrons, they are normally used in conjunction with a converter that emits alpha particles, gamma rays, or beta rays upon absorption of neutron and changes neutron intensity into film blackening.

Cloud chambers are one of the oldest methods of detecting fast neutrons by the proton recoil method. The analysis of cloud chamber data is extremely time-consuming and tedious, so the use of other, more efficient detectors is preferred. However, cloud chambers are still used to record neutrons between 10 keV and 500 keV, an energy range in which it is difficult to measure the neutron spectrum with other detectors. Although cloud chambers are normally filled with hydrogen, the composition and the pressure of the cloud chamber gas can be varied to suit a particular experiment. Cloud chamber detectors have been used to study the fission neutron spectrum (BO52), the spectrum of a fast reactor (AN56), and the energy distribution D-D neutrons emitted from the Zeta controlled thermonuclear device (RO58).

Neutron thermopile detectors, or neutron thermometers, were designed primarily to monitor the neutron flux in the high-flux environment of a nuclear reactor. These instruments consist of a series of thermocouples whose junctions are coated with amorphous boron compound enriched with ^{10}B or ^{235}U. The ^{235}U coating, however, has the disadvantage of becoming radioactive after exposure to neutrons. The heat generated by the alpha particles from the $^{10}B(n,\alpha)$ reaction or by the fission products from the ^{235}U creates an electrical signal proportional to the neutron flux. Thermopiles of various construction are described in (JA50, LE51, WE57, GR57, LA52B, LA58A); a more extensive description of this type of detector is in (PR58).

There are a few other neutron detector types and techniques. Among these are the gas evolution technique (HA54 and HA56), the boron-lined spark chamber, (SA52, SW57B, LA58B, SA57), detection based on the variation in semiconducting properties (CA55), and the palladium film dosimeter, which is based on the change in electrical resistance (CH58).

APPLICATIONS OF NEUTRON DETECTING INSTRUMENTS

The use and application of specific neutron detecting instruments and the techniques used to determine the intensity and energy of neutrons encompasses practically the whole field of neutron physics.

Although no one instrument exists that can perform all neutron detection functions, many detectors and the principles on which they are based have been adapted to more than one type of detection. The five general categories of neutron detector applications are relative intensity measurements, total source strength measurements, flux measurements, neutron spectrometry, and neutron dosimetry.

Relative Intensity Measurements

The measurement of the relative neutron intensity, which is the least complex of neutron detection problems, consists of recording a number proportional to the number of neutrons incident on a neutron detector. Detectors used for such measurements are also referred to as neutron monitors.

Measurements of relative intensity are frequently performed in neutron physics experiments. The neutron intensity of the source must also be monitored in most experiments conducted with reactors or accelerators. Most neutron detectors can be used as neutron monitors; the type of detector to be used in a specific situation will depend on the experimental requirements and the energy range of the neutrons to be detected. In general, neutron monitors should have low sensitivity to gamma rays as well as a selective neutron energy and directional response. In some instances it is necessary to design special collimating and shielding assemblies to confine the monitored neutrons to specific energy and angular incidence.

Fission chambers and BF_3 proportional counters have been used extensively as monitors for both slow and fast neutrons. The Long Counter (HA47) is an example of such a detector. Used as a monitor as well as in other applications, it incorporates a BF_3 counter in a shaped paraffin block and has a nearly flat response between 20 keV and 5 MeV. Another monitor incorporates BF_3 proportional chambers in a highly efficient counter assembly (LA52A). More recently, two high efficiency neutron detectors consisting of arrays of ^3He proportional counters imbedded in polyethylene moderators have been developed (EA69). Hornyak's inorganic crystal scintillator, known as the Hornyak Button, consists of a mixture of ZnS and Lucite and is also used to measure the relative intensity of neutrons (HO52). Moyer developed a polyethylene moderated ZnS(Ag) scintillator, known as the Egghead, for the detection of fast neutrons (MO52B). Nuclear emulsions are seldom used as neutron monitors because of the tedious process of reading tracks; their use, however, has been effectively incorporated in a collimated detector assembly to measure angular distributions (RO55).

Total Source Strength Measurements

A basic problem in neutron physics is measuring the total number of neutrons emitted by a neutron source per unit time. In some cases it is desirable to compare a source of unknown intensity with a known standard source; in others it is necessary to determine the neutron source intensity on an absolute basis.

Most methods devised to measure neutron source strength depend on degrading the neutrons to low energies where they can be relatively easily detected. The slowing-down medium most commonly used is water or graphite. The energy-degraded neutrons are then absorbed by activation foils or in an absorber in solution, or they are detected by BF_3 counters located in the slowing-down medium. This latter method is applicable to both relative and absolute measurements; absolute measurements require accurate calibration of the foils and an absolute determination of their activity.

More accurate methods used in the measurement of absolute neutron source strengths, such as in the calibration of accelerator-generated neutrons for neutron physics measurements, are the associated particle and associated product methods. In neutron-yielding charged-particle reactions, such as the DD or DT reactions, a charged particle (^3He or ^4He) is emitted for each neutron produced. The associated particle method consists of measuring the total number of charged particles emitted and from this measurement obtaining the total neutron source strength (AL60). An example of the associated particle method for measuring neutrons between 100 and 500 keV with a ^6Li glass scintillator is described in (FO70).

The associated product method consists of a quantitative measurement of reaction product nuclei produced in a neutron-yielding reaction. One reaction that has been used in this method is the $^7Li(p, n)^7Be$ reaction. The amount of ^7Be formed is determined by measuring its radioactivity (TA48). Another reaction is the $^{19}F(\alpha, n)^{22}Na$ reaction in which the radioactive ^{22}Na product decays into stable ^{22}Ne. In this instance the measured volume of ^{22}Ne provides a quantitative measurement of the neutrons produced (LI55).

Neutron Flux Measurements

The measurement of the neutron flux consists of the determination of the number of neutrons within a given energy interval that pass per second through the surface of a sphere whose cross-sectional area is 1 cm^2. Since neutron detectors respond preferrentially in either the fast, the intermediate, or the slow energy ranges, the description of their application to neutron flux measurements is considered by energy range.

Fast Neutron Flux

The fast neutron flux is generally considered to comprise neutrons whose energies range from 200 keV to 20 MeV; this is the energy range in which most neutrons are produced. The fast neutron flux may originate from monoenergetic neutron sources

(e.g., accelerator-induced charged-particle reactions and isotopic sources) or from energy distributed sources (e.g., fission).

Because of the tendency of neutrons to degrade in energy upon scattering and to be absorbed in radiative capture reactions, the fast flux is usually accompanied by lower energy neutrons and may also have a strong gamma-ray background. Thus, a frequent problem in fast flux measurements is the need to discriminate gamma rays and lower energy neutrons.

Table 7 is a summary of neutron flux measurement methods in the energy region between 30 keV and 20 MeV.

The proton recoil method to detect fast neutrons has been used extensively to measure the fast flux. Proportional counters filled with hydrogen or other hydrogenous gases are well-suited to the detection of neutrons between 20 keV and 3 MeV. Proportional counter telescopes with hydrogenous film radiators extend the effectiveness of these detectors to neutrons having energies >3 MeV. The hydrogen-filled homogeneous ionization chamber, which measures the direct current from proton recoils, is another proton recoil method suitable for the measurement of the fast neutron flux.

An alternate application of the proton recoil method is the use of plastic or liquid scintillators that act both as radiator and counter. These scintillators can be used either independently or in conjunction with coincidence proton recoil proportional counters. Another proton recoil method is the measurement of proton tracks produced in nuclear emulsions.

The associated particle and associated product methods, also used to measure the total neutron source strength, can be used to measure the fast flux. Another technique, which has the advantage of isolating the fast neutron component of the flux, is measuring the activity induced in threshold detectors by endoergic or fast fission reactions (see Table 6). In addition the BF_3 counter moderated with paraffin, although basically a thermal neutron detector, has a high sensitivity, good gamma discrimination, and an energy response that is nearly flat between 25 keV and 5 MeV. It is also adaptable for relative measurements of the fast neutron flux.

Intermediate Neutron Flux

Intermediate energy neutrons range in energy between the cadmium cut-off energy of 0.4 eV and 200 keV. The neutrons that populate this energy range are primarily fast neutrons that have been degraded in energy as a result of inelastic scattering in a slowing-down medium. Because of the difficulties inherent in detecting neutrons in this energy range, intermediate energy neutrons are usually moderated to thermal energies where they can easily be absorbed by radiative capture or exoergic charge particle reactions.

Boron-loaded liquid organic scintillators, the so-called black detectors designed to absorb all neutrons below a maximum energy, have been used to detect intermediate

Table 7. Methods of fast neutron flux measurements (PE60).

ABSOLUTE OR PRIMARY METHODS

- Recoil Proton Method
  - Harwell proportional counter (SK52, AL55, AL57)
  - Counter telescopes (JO56, BA57)
  - Photographic plates (RO53, CR57)
    - External radiator (PE60)
    - Plate as radiator and detector (RO53)
    - 90° incidence (BA52)
  - Organic scintillation counters
  - Other proton recoil methods
    - Recoils from thin radiator (with proportional counter) (DI57)
    - Recoils from thick radiators (BA47)
    - Homogeneous ionization chamber (BR44, RO49, AL50, LA54)
    - Cloud chambers and bubble chambers
- Neutron Moderation Methods
  - Liquid moderators
    - Large liquid scintillators (Cd solution) (RE54, DI56)
    - $MnSO_4$ bath (AL60B, BA52, SN50, DE55)
    - Paraffin oil bath
  - Graphite assemblies (MA57, MA58, GR52)
  - 4π paraffin-shielded counters

RELATIVE OR SECONDARY METHODS

- Moderation Counters
  - Long counter (HA47, AL57)
  - Schardt's long counter
  - Langsdorf detector (LA57)
- Fission Detectors
  - Parallel plate counters (RO49, LA54)
  - Spiral and cylindrical counters (RO49)
  - Fast fission detectors
    - Fission fragments in organic scintillation (MI54)
    - Fast fission in noble gases (NO56A, AV57)
    - Fast fission in semiconductors (p, n junction) (WA58)
- $^3He(n, p)T$ Detectors (BA55)
- $^6Li(n, \alpha)T$ Detectors [$^6LiI(Eu)$ crystal] (MU58, MU57)
- $^{10}B(n, \alpha)^7Li$ Detectors
- Induced Activity Methods (TA48, BA52)

energy neutrons. The major difficulty of this technique is discriminating the gamma-ray background. Other instruments, consisting of polyethylene-enclosed scintillator detectors, have been designed to have a flat response over the intermediate energy range and excellent gamma discrimination.

Another method, which is often used to measure the intermediate neutron flux in and around reactors, is resonance activation. Materials normally applicable to such measurements (e.g., gold, tungsten, or molybdenum) have strong resonance of their radiative capture cross section and a decay half-life of their daughter product that is adaptable to foil counting techniques. The application of foil activation to the intermediate range, however, is considerably more complex than the activation detection of slow neutrons and is therefore used only where other detection techniques cannot be applied.

Slow Neutron Flux

The slow neutron flux covers a much wider range, both in energy and intensity, than the fast neutron flux. It is sometimes accompanied by higher energy neutrons and gamma rays that require discrimination.

In a nuclear reactor the slow neutron flux is composed of two components. The thermal or Maxwellian component, between 0 and 0.1 eV, has an energy spectrum in thermal equilibrium with the temperature of the reactor. The epithermal component consists of a continuous energy spectrum between 0.1 and 0.4 eV and has a dependence proportional to the neutron energy.

A wide variety of detectors is available to measure the slow neutron flux; the specific application of any one of these depends on the conditions of the experiment. A large fraction of these detectors use radiative capture, fission, and exoergic charged particle reactions.

A significant characteristic of some of these reactions is that their cross sections are inversely proportional to the neutron velocity, so detectors that use these reactions are called 1/v detectors. Since the flux (ϕ) in the epithermal energy range in a reactor is proportional to the neutron density (n) and the reaction velocity (v), i.e., $\phi = nv$, the reaction rate per atom of detecting material in a pure 1/v detector is independent of velocity (or energy) and proportional only to the total neutron density. If the slow flux is accompanied by a significant number of higher energy neutrons, the cadmium ratio method can be applied to discriminate neutrons having energies higher than the cadmium cut-off energy of 0.4 eV.

Reactions most commonly used in the measurement of the slow neutron flux are $^{10}B(n,\alpha)$, $^{6}Li(n,\alpha)$, $^{3}He(n,p)$, $Mn(n,\gamma)$, $Au(n,\gamma)$, and $^{235}U(n,f)$. The $^{10}B(n,\alpha)$ reaction is probably used most extensively. It is used in gas-filled proportional and ionization chambers both in gaseous (BF_3) and solid form. The ^{3}He gas proportional counter, similar to the BF_3 counter, is another commonly used thermal flux detector. Still another gas proportional counter to detect slow neutrons is the fission chamber, in

which ^{235}U or another fissionable material is coated on the counter walls. This detector is very efficient in this low energy range and can operate at temperatures as high as 700°C and in extreme gamma-ray fluxes.

Scintillation crystal detectors incorporating ^{6}Li, such as [$^{6}LiI(Eu)$], ^{6}Li-loaded cerium-activated silicate glass, and ^{6}Li-loaded ZnS, as well as activation crystals such as NaI(Tl), are also widely used to measure the slow neutron flux.

Two passive methods, which provide a time-integrated neutron-flux measurement, are foil activation and thermoluminescence detectors.

Neutron Spectrometry

Neutron spectrometry is an important branch of neutron physics that encompasses a number of techniques for analyzing the energy distribution or spectrum of neutrons. It presents probably the most difficult experimental problems among the neutron detection categories. Neutron spectrometers are generally required to determine energy spectra of neutrons to a high degree of efficiency and resolution.

Neutron spectrometry methods can be separated into two categories. One of these, applicable to continuous or uninterrupted neutron fields, requires neutron detection techniques that are specifically adaptable to neutron energy spectrum analysis. The other, normally used when neutrons can be produced in bursts or in very short time intervals, comprises time-of-flight and crystal spectrometer techniques that rely on the spatial segregation of neutrons of different energies and require no special energy discriminating neutron detection technique. Most crystal spectrometers, however, are steady state devices and are useful only up to energies in the eV range.

Although time-of-flight techniques have very high detection efficiencies and resolution over a wide energy range, their application is restricted primarily to experimental neutron physics laboratory conditions and will not be discussed in this report. More detailed descriptions of neutron time-of-flight techniques and their applications can be found in (CA63, AL60A, NE60).

Proton recoil and scintillation detectors are commonly used to measure fast reactor neutron spectra. Proton recoil proportional counters that require a collimated incident flux have been described (JO60, RE58A). Benjamin (BE63A) and Bennett (BE64, BE67) have devised proton recoil proportional counters that do not require a collimated incident neutron flux. Werle describes spectrum measurements of radioactive neutron sources in the 10 keV to 10 MeV energy region with proton recoil proportional counters and compares them with other methods (WE70).

High pressure ^{4}He scintillation detectors, recently developed by Matthews and Menlove (MA72), have been used to measure fast neutron distribution from fission reactions in assay samples. These detectors are characterized by high fast neutron detection efficiency relative to gas proportional counters, low gamma-ray sensitivity, very short pulse length, energy discrimination capability, and compactness (EV71).

Many of the neutron detection methods described in this report can be applied to neutron spectrometry; however, most neutron spectrometers are based on measurement of the proton recoil energy in elastic scattering, and determination of the energies of nuclear reaction products. Table 8 summarizes the major neutron spectrometry techniques and their performance and characteristics.

Neutron Dosimetry

The monitoring of neutron health hazards and studies of the biological effects of radiation center around the measurement of absorbed radiation dose. Generally, radiation dose is defined as the amount of energy deposited per unit mass in irradiated biological tissue. In the case of neutrons, this energy deposition is caused by nuclear reactions dependent on the energy of the incident neutrons. The relative biological effectiveness (RBE) of the neutron radiation dose therefore has a specific nonlinear energy dependence. As a result, neutron detecting instruments designed specifically to measure the neutron dose equivalent directly should ideally have an energy response proportional to the RBE of neutrons absorbed in tissue.

A summary of detectors and techniques that have been adapted or developed specifically as neutron dose-measuring instruments is given in Table 9.

Table 8. Properties of fast neutron spectrometers (CA63).

Type	Resolution	Efficiency	Useful energy range (MeV)	Method of recording and analyzing results	Remarks
Photographic plates [n-p scattering]	3% at 14 MeV (0.5 MeV constant half-width over fairly large range)	—	0.5-15	Measurement of recoil track length and three angles for each neutron counted	Suitable for simultaneous exposure at several angles. Analysis extremely laborious. Difficult to find high energy neutrons in low energy background. Poor intensity measurement.
Photographic plates with external radiator [n-p scattering]	2% at 14 MeV (0.3 MeV half-width)	Very low below 2 MeV	2-20	Measurement of recoil proton track lengths in emulsion	More accurate absolute and relative intensity measurements than with plates alone.
^{6}Li loaded plates [^{6}Li(n, t)^{4}He reaction]	0.2 MeV half-width	—	0-1.3	Range of α and t and angle between is measured for each ^{6}Li(n, t)^{4}He event	It is not necessary for incident neutrons to be collimated or to come from known direction.
^{3}He proportional counter [^{3}He(n, p)T reaction]	15% at 0.5 MeV 8% at 2.0 MeV	—	—	Pulse-height analysis	Background from slow neutron capture and ^{3}He recoils from high energy neutrons.
^{6}Li and ^{3}He solid state spectrometers	60% at 0.5 MeV 6% at 5.0 MeV	—	0.5-5.0	—	—
Low pressure cloud chamber [n-p recoils in H_2]	0.2 MeV half-width	—	0.5-3.5	Measurement of length and direction of recoil proton tracks from cloud chamber photographs	—
High pressure cloud chamber [n-p recoils in methane]	0.2 MeV half-width	—	2-8.5	—	—
Proportional counter telescope with radiator and absorbers	5% at 15 MeV	—	2.5-20	Integral range spectrum counted	—
Holt-Litherland triple ionization chamber. Time of arrival of ions from end of proton recoil track	5%	10^{-9}	5-25	Analysis of photographic record of oscillograph sweeps	Only part of energy range may be studied at any given chamber pressure (range of 5 MeV or less in neutron energies). Resolution is not affected by high gamma-ray backgrounds.
Single anthracene crystal	0.4 MeV	High	1-3	Multichannel pulse-height analysis giving integral spectrum	—
^{6}Li(Eu) crystal [^{6}Li(n, t)^{4}He reaction]	6% at 14 MeV	$\leq 10^{-3}$	1-20	Pulse-height analysis	No collimation required. For good resolution the crystal must be cooled to the temperature of liquid nitrogen.

Table 8. (Continued).

Type	Resolution	Efficiency	Useful energy range (MeV)	Method of recording and analyzing results	Remarks
Recoil telescope with radiator. Collimated n-p recoils passing through two proportional counters into NaI crystal	6% at 14 MeV	3×10^{-9} at 14 MeV	2-20	Pulses from NaI crystal in coincidence with proportional counters are analyzed on multichannel analyzer.	
Scintillation counter telescope. Proton recoils from anthracene passing through proportional counter into NaI crystal	6%	6×10^{-8} at 20 MeV	5-25	NaI and anthracene pulse heights simultaneously recorded when in coincidence with proportional counter. Spectrum analyzed from film record.	Also used with anthracene as second crystal.
Scintillation counter spectrometer. Measurement of recoil proton energy and detection of recoil neutron at specific angle	20-28%	Very low	2-15	Pulse-height analysis of pulses from scintillator that are in coincidence with detected recoil neutron.	—

Table 9. Dose equivalent neutron detectors (IC71).

Detector	Description	Sensitivity or working range	Energy range response	Comments	References
Proportional counter with cylindrical moderator	BF_3 thermal neutron proportional counter in a cylindrical hydrogenous moderator	2.5 cps/ mrem/hr	Thermal to 15 MeV	Commercially available; commonly referred to as SNOOPY. Gives direct dose measurement independent of neutron energy. Slight directional response produces maximum 10% sensitivity variation. Suitable for pulsed neutron measurement. Portable model weighs 8.5 kg. Not affected by gamma exposure rates <200 R/hr (^{60}Co).	AN64, BL64, LE64
Scintillator or proportional counter with spherical moderators	$^{6}LiI(Eu)$, ^{10}B-loaded plastic phosphor or BF_3 proportional counter as thermal neutron detector in spherical hydrogenous moderator	1.5 to 15 cps/ mrem/hr	0.01 eV to 50 MeV (depending on sphere diameter)	Commercially available. Referred to as Bonner sphere. Gives direct measurement independent of neutron energy. Nondirectional response. Multisphere system yields spectrum information. Weight ranges from 5 to 40 kg. Gamma sensitivity depends on type of thermal detector, by discriminator against dose rates <100 R/hr.	HA62, NA67 LE67, BR60
Recoil type proportional counter	Proportional counter lined with cylindrical hydrogenous radiator and filled with hydrogenous gas	Approximately 0.1 cps/ mrem/hr	0.1 MeV to 14 MeV	Commercially available. Fast neutron instrument with response independent of neutron energy for direct measurement of maximum dose equivalent. Will tolerate gamma/fast neutron dose ratios of 200:1 and thermal/fast neutron dose rate ratios of 100:1.	HU54, HU60A
Tissue equivalent spherical proportional counter	Spherical tissue equivalent proportional counter filled with tissue equivalent gas at low pressure (few mm Hg). Pulse counter.	>20 μrem/hr	0.2 MeV to 14 MeV	Pulse counting instrument specially designed for the absolute measurement of fast neutron absorbed dose. Interpretation of results involves complex analysis. Requires multichannel analyzer. Nondirectional response. Moderate weight and size.	HU54
Ion recombination ionization chamber	Tissue equivalent parallel plate ion chamber with tissue equivalent gas at pressures up to 6 atm.	no information	fast neutrons	Method under development primarily for the measurement of fast neutrons and mixed radiations. Potentially suited for mixed radiation dosimetry near high energy accelerators.	ZI63, SU63
Liquid ionization chamber	Very small ion chamber using n-pentane, n-hexane or iso-octane as the liquid dielectric.	>15 mrem/hr	fast neutrons	Method under development for measurement of dose equivalent of fast neutrons and mixed radiations. Appoximately tissue equivalent. Long time period required to accumulate results. Requires large polarizing voltages.	RO56, RO63, LA63

Table 9. (Continued).

Detector	Description	Sensitivity or working range	Energy range response	Comments	References
Plastic phosphor scintillation counter	Plastic phosphor sandwiched between two slabs of polyvinyltoluene. Pulse counter.	>20 μrem/hr	0.4 MeV to 14 MeV	Instrument used with a multichannel analyzer for the measurement of absolute proton recoil tissue dose in air from fast neutrons. Lightweight and small size. Suitable for radiobiological research but analysis or results is complex. Nondirectional response. Moderate gamma sensitivity.	WI52, WI57
Fission track detectors	Fission threshold detectors mounted on plastic, mica or glass. Tracks are observed by selective etching.	>10 μrem (thermal neutrons)	thermal to 10 MeV	Method is completely insensitive to gamma rays. By choice of suitable fissionable materials will yield approximate spectrum. Potentially suitable for radiological protection monitoring. Simple readout. Longterm stability.	BE66B, PR68
Threshold detectors	Threshold detector foils of ^{239}Pu, ^{237}Np, ^{238}U, and ^{32}S are used for fast neutron fluence measurement above respective thresholds. Gold and gold plus cadmium are used for thermal neutron measurements.	>100 rem	low MeV range	Accuracy for fission spectra ±15% limited by finite threshold slope. Gross uncertainty where neutrons of energies greater than several MeV are present. Suitable for criticality and high dose rates. Negligible gamma response.	HU56, RE58B, MO62, RO65
Solid state spectrometer	High resolution spectrometry of reaction products from thin layers of $^{6}Li(n,\alpha)$ and $^{3}He(n,p)$ sandwiched between silicon diodes. Pulses are summed to give energy spectrum.	>100 rem/hr	For ^{6}Li: 0.7 to 3.0 MeV For ^{3}He: 0.3 to 7.0 MeV	Accurate flux and energy measurement. Instrument subject to thermal neutron interference and to (n, p) and (n,α) background in silicon, which can be reduced by coincidence techniques. Good gamma discrimination.	LO61, AR64, DE62
Nuclear emulsions	Packaged photographic emulsions. Recoil proton tracks are counted per unit area of film.	>20 mrem	0.5 MeV to 20 MeV	Valid for neutron detection over fast energy range. Subject to fading losses due to humidity, temperature, and emulsion type. Not applicable in gamma doses >10 rad because of fogging. Tedious measurement. Gives permanent record. No electronics required.	CH54, BE63B, HA63, BE66A

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APPENDIX A
COMMERCIALLY AVAILABLE NEUTRON DETECTORS AND THEIR CHARACTERISTICS

Tables A-1 through A-4 contain a representative list of currently marketed neutron detectors. The characteristics included in these tables have been extracted from specifications of the following manufacturers:

20th Century Electronics Ltd., Centronics Works, England.
(U.S. distributorship: Bailey Instruments, Inc., New Jersey)

Eberline Instrument Corporation, Santa Fe, New Mexico

The Harshaw Chemical Company, Cleveland, Ohio

Kaman Nuclear, Colorado Springs, Colorado

LND, Inc., Oceanside, New York

Ludlum Measurements, Inc., Sweetwater, Texas

N. Wood Counter Laboratory, Inc., Chicago, Illinois

Ortec, Inc., Oak Ridge, Tennessee

Reuter Stokes, Cleveland, Ohio

Texas Nuclear Corp., Austin, Texas

Victoreen Instrument Division, Cleveland, Ohio

The tables include only complete detector assemblies. Detector materials such as scintillators, activation and fission foils, thermoluminescent compounds and emulsions, most of which constitute primary components of certain types of detectors, have not been included.

Table A-1. Commercially available ionization chambers.

Type	Manufacturer and model or serial number	Size range	Operating voltage (V)	Operating temperature (°C)	Gas fill pressure range (atm)	Sensitivity	Detection range
BF_3 filled (96% ^{10}B) uncompensated ionization chamber	Reuter Stokes (RSN-337)	3.25 × 14.5 in.	1000-1400	<300	1	3×10^{-13} A/nv (thermal)	10^{10} nv (thermal)
Portable BF_3 filled paraffin moderated fast/slow neutron counter	Ludlum (Model 15)	9.75 × 3.5 × 7 in.	500-2400	—	—	no information	thermal and fast neutrons
96% ^{10}B lined, He filled compensated ionization chamber	Centronics (Type D.C. 12)	3.5 in. diam 31 in. long	1000	550	2	2.75×10^{-14} A/nv (thermal)	$<7.5 \times 10^{10}$ nv (thermal)
^{10}B lined ionization chambers	Reuter Stokes (RSN-17A/326/330/251/327)	1 - 3 in. diam 5 - 32 in. long	800-900	150-200	—	4-35 cps/nv (thermal)	3×10^4 - 2.5×10^5 nv (thermal)
92% ^{10}B lined, 95% A, 5% N filled ionization chamber	Reuter Stokes (RSN-229A)	1 × 36 in.	800	300	1	1.1×10^{-14} A/nv (thermal)	10^4 - 10^{11} nv (thermal)
Gamma-compensated 92% ^{10}B lined, N filled ionization chamber	Reuter Stokes (RSN-234A-M1)	1.5 × 14 in.	800	300	1	10^{-14} A/nv (thermal)	10^4 - 10^{11} nv (thermal)
^{10}B lined ionization chambers	Reuter Stokes (RSN-15A/304/325/332/306)	3 in. diam 18 - 145 in. long	100-1000	150/300	—	4.4×10^{-14} to 2×10^{-13} A/nv (thermal)	10^3 - 10^{10} nv (thermal)
93% ^{235}U fission ionization chamber	Reuter Stokes (RSN-314A)	3 × 13 in.	200-800	300	—	1.5×10^{-13} A/nv (thermal)	10^3 - 10^{10} nv (thermal)
^{235}U fission ionization chambers	Reuter Stokes (RSN-186S-M2 and 216S-M5)	0.25 or 0.125 in. diam cable up to 200 ft long	20-150	<340	—	3×10^{-17} A/nv (thermal)	10^8 - 10^{14} nv (thermal)
Cylindrical A and CO_2 filled fission chamber	LND (Series 30771)	1 × 10 in.	500	200	—	1.2×10^{-1} to 1.2×10^{-3}	3 decades
Cylindrical A/CH_4 filled, ^{235}U or ^{238}U fission chamber	LND (Series 3077)	1 × 8 in.	200-800	—	1	1 count/10^{13} neutrons to 1 count/10^8 neutrons	6 decades thermal (with ^{235}U) or fast (with ^{238}U)
Miniature ^{235}U fission chamber	LND (Series 3075)	0.25 in. diam	200-500	—	—	1 count/10^{13} neutrons to 1 count/10^8 neutrons	Thermal neutron

Table A-1. (Continued).

Type	Manufacturer and model or serial number	Size range	Operating voltage (V)	Operating temperature (°C)	Gas fill pressure range (atm)	Sensitivity	Detection range
Parallel plate, A/CH_4 filled ^{235}U fission chamber	LND (Series 3000, 3050)	4 - 6 in. diam 0.75 in. thick	50-500	—	—	1 count/10^3 neutrons to 1 count/10^{14} neutrons depending on specification	Thermal neutron
Parallel plate pulse fission chambers (A and 2% N filled) Fissile coatings in the form of oxides of any one of following isotopes: ^{232}Th, ^{233}U, ^{235}U, ^{237}Np, ^{238}U, and ^{239}Pu	Centronics (PFC 16A)	2 - 6 in. diam 0.75 in. thick	250-500	80	—	1.1×10^{-3} cps/nv	9×10^3 - 9×10^7 nv
93% ^{235}U (in form of U_3O_8) coated, A filled, pulse fission chamber	Centronics (PFC 16B)	1 in. diam 4 - 12 in. long	200-400	550	6.8	10^{-2} cps/nv (2×10^{-14} A/nv)	10^{11} nv

Table A-2. Commercially available proportional counters.

Type	Manufacturer and model or serial number	Size range	Operating voltage (V)	Operating temperature (°C)	Gas fill pressure range (atm)	Sensitivity	Detection range
BF_3 filled (96% ^{10}B) or depleted BF_3 (11% ^{10}B) proportional counter	N. Wood (Model G)	From 0.25 × 0.25 in. to 2 × 38 in.	1100-2300	—	<1	~5 cps/nv	—
BF_3 filled proportional counters	Centronics	1 - 2 in. diam	2400-4000	100	0.26-0.92	From ~0.01 cps/nv to 169 cps/nv depending on specifications	thermal neutrons
Miniature enriched BF_3 filled proportional counters	Centronics (Series 5EB/6)	0.25 × 6.75 in.	900-1100	80	0.53	0.015 cps/nv	3.3×10^3 - 6×10^6 nv (thermal)
Cylindrical and quadrilateral BF_3 filled proportional counters	LND	0.5 - 2 in. diam 6 - 52 in. long	1100-3000	-50 to 100	0.2-1.8	—	—
BF_3 filled proportional counters (96% ^{10}B)	Reuter Stokes (RSN-7A/7S/44/ 177S-M7/320-M2/ 108S-MG)	1 or 2 in. diam 5 - 14 in. long	2500-3500	-80 to 100 (depending on specifications)	0.7-1.2	1-30 cps/nv (thermal)	10^{-3} - 10^{-5} nv (thermal)
BF_3 filled proportional counter (enriched or depleted B)	Harshaw (Model series B3, B6, B12, and B14)	1 or 2 in. diam	1700-3400	-40 to 150	0.16-2.2	2-60 cps/nv	thermal neutrons
Ultrasensitive BF_3 (96% ^{10}B) proportional counter	Harshaw (Model B4-72S)	6 in. diam 72 in. long	2800	—	0.26	1775 cps/nv	—
Portable BF_3 proportional counter with cadmium shielded paraffin moderator	Eberline (PNC-4)	9 × 4 × 12 in.	1300-1800	-40 to 140	—	3×10^{-3} to 1 cps/nv from 10^3 eV-10^2 eV 0.3-1 cps/nv from 0.2-18 MeV	0.01-10^3 eV and 0.2-18 MeV
Spherical portable BF_3 dosimeter in cadmium loaded polyethylene sphere	Eberline (PNR-4 and NRD-1)	9 in. diam	1600-2000	-40 to 140	—	—	Dose response from thermal to 10 MeV
^3He filled proportional counter (with 20% Kr)	Centronics	1 - 2 in. diam 8 - 16 in. long	—	<200	2-4	14-16 cps/nv (thermal)	thermal neutrons
^3He filled cylindrical proportional counters	Texas Nuclear (Series 9300 Texlium)	1/4 - 2 in. diam 4 - 12 in. long	800-1400	-70 to 200	1-10	—	thermal neutrons

Table 2-A. (Continued).

Type	Manufacturer and model or serial number	Size range	Operating voltage (V)	Operating temperature (°C)	Gas fill pressure range (atm)	Sensitivity	Detection range
^{3}He filled cylindrical and quadrilateral proportional counters	LND	0.3 - 2 in. diam 5 - 23 in. long	1000-4800	-50 to 100	4-20	—	thermal neutrons
^{3}He filled cylindrical proportional counters	Reuter Stokes	0.3 - 1 in. diam 5 - 52 in. long	2000-3000	<100-150	4-40	0.1-19 cps/nv (thermal)	10^{-3} to 5×10^4 nv (thermal)
^{3}He filled cylindrical proportional counters	Harshaw (Series H3)	0.25 - 4 in. diam 1 - 24 in. long	400-2000	<175	1-40	—	thermal and fast neutrons
B (>90% ^{10}B) lined A/CO_2 filled pulsed proportional counter	Centronics (PN12EB)	1 in. diam 9 in. long	800	<220	0.5	3 cps/nv (thermal)	3 to 3×10^4 nv (thermal)
B (92% ^{10}B) lined A/CO_2 filled proportional counters	Reuter Stokes (RSN-127A/ RSN-250)	1 in. diam 8 in. long	2000	<200	0.26	1 cps/nv (thermal	10^{-2} to 10^5 nv (thermal)
92% ^{10}B lined porportional counter	Harshaw (B10-4A and B10-14S)	1 in. diam 4 or 14.5 in. long	700-2000	-40 to 200	0.26	—	—
B lined proportional counter with 1 in. thick polyethylene moderator and 1/32 in. Cd shield	Victoreen (Type 488A)	—	—	—	—	—	thermal and fast neutrons
U_3O_8 (93% ^{235}U) coated, A/CH_4 filled proportional counter	Reuter Stokes (RSN-312-M4)	3 × 3 × 1 in.	300-700	150	1	10^{-4} cps/nv (thermal)	10^3 - 10^9 nv (thermal)
U (93% ^{235}U) lined A/N filled proportional counters	Reuter Stokes (RSN-34A-M1)	1 in. diam 8 in. long	200-800	300	1	0.1 cps/nv (thermal)	10^{-1} - 10^6 nv (thermal)
H-filled proton recoil spherical proportional counter	Centronics (Model SP2)	1 - 2 in. diam <6.5 in. long	1500-4400	<200	1-10	50 cps/nv 10^{-3} to 5×10^{-3} cps/nv (fast)	thermal - 1.25 MeV
H filled proton recoil spherical counter	LND (Series 270 and 281)	1.7 in. diam	1500-3200	-50 to 75	1-4	5×10^{-3} cps/nv (fast)	fast neutrons
Hurst-type polyethylene lined, A/CH_4 filled proton recoil proportional counter	LND (Series 280)	2 in. diam 6.75 - 21 in. long	1400	0-50	5.7	—	0.1 - 15 MeV

Table A-3. Commercially available scintillation detectors.

Type	Manufacturer and model or serial number	Size range	Operating voltage (V)	Gas fill pressure range (atm)	Sensitivity	Detection range
ZnS(Ag) loaded crystal proton recoil scintillation detector	Ludlum (Model 42-2)	2.25 in. diam 7.5 in. long	900	—	0.25 cps/nv (5 MeV neutrons)	fast neutrons
Scintillation probe assembly with different crystals: -Natural B with ZnS(Ag) -Enriched B with ZnS(Ag) -96% enriched ^{6}Li with ZnS(Ag) -ZnS(Ag) dispersed in clear plastic	Eberline (Model SPA-2)	2 in. diam 8 in. long	900-1200	—	—	slow or fast neutrons
ZnS(Ag) dispersed in B glass thermal scintillation detector	Ludlum (Model 42-1)	2in. diam 7 in. long	900	—	1 cps/nv	1/v for thermal neutrons
Portable polyethylene moderated, 8 X 4 cm ^{6}LiI crystal, scintillation dosimeter	Kaman (Model Δ-300)	10 in. sphere	120	—	5 cps/μrem/hr	thermal and fast— 0-14 MeV
Portable polyethylene moderated, 4 X 4 cm ^{6}LiI crystal scintillation dosimeter	Ludlum (Model 42-4)	12 in. sphere	900	—	~1 cps/mrem/hr	thermal - 12 MeV
Multiple Bonner sphere polyethylene moderated 4 X 4 cm ^{6}LiI crystal neutron spectrometer	Ludlum (Model 42-5)	Spheres range from 2 to 12 in.	900	—	—	thermal and fast neutrons
High pressure ^{3}He gas scintillation detector intense neutron beam	LND (Series 800)	1.25 in. diam 1.5 in. long	—	238	—	thermal neutrons

Table A-4. Commercially available miscellaneous detectors.

Type	Manufacturer and model or serial number	Size range	Operating temperature (°C)	Gas fill pressure range (atm)	Sensitivity	Detection range
Semiconductor neutron spectrometer system. (Two surface barrier detectors in a face-to-face or sandwich geometry with neutron sensitive material: ^{3}He or ^{6}LiF)	Ortec (System 525)	1.4 in. diam 4 in. long (detector head)	—	^{3}He at 5 atm	—	—
Self-powered neutron detectors:	Reuter Stokes	0.0625 in. diam 4 in. sensitive length	—	—	—	—
Co			<500	—	1.6×10^{-22} A/nv	10^{15} nv
Cd			<250	—	1.5×10^{-21} A/nv	5×10^{14} nv
Rh			<500	—	1.2×10^{-20} A/nv	10^{15} nv
V			<500	—	1.0×10^{-21} A/nv	10^{15} nv
Neutron thermopile	Nuclear Instruments and Chemical Corp. (Model 3782)	0.5 in. diam 6.5 in. long	—	—	5×10^{-12} mV/nv	linear between 10^{7} and 10^{12} nv

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