Steven M. Grimes. "Neutron Measurement."

Neutron Measurement

Steven M. Grimes
Ohio University

68.1 Detector Types
Detectors Based on Elastic Scattering • Detectors Based on Capture Reactions • Detectors Based on Fission • Counters Based on Inelastic Scattering • Detectors Based on (n,p) or (n,α) Reactions
68.2 Efficiency Calculations
68.3 Summary

Neutrons have characteristics that make them of particular importance in technology and research. Since they are uncharged, they are able to enter the nucleus at very low energy. Furthermore, the lack of energy losses through ionization permits deep penetration into materials.

This latter characteristic makes detection of neutrons more complicated than detecting protons or alpha particles. The energy of these charged particles can easily be determined by detecting them in ionization chambers, proportional counters, or scintillators, and ultraprecise measurements can also utilize the steering effect of magnetic fields. Detection efficiencies approach 100%. Neutrons, on the other hand, are not directly detected by these detectors and some means of converting the neutron through a nuclear reaction to a charged particle or gamma ray must be used.

Nuclear reactions occur when neutrons interact with nuclei (including protons). When a neutron interacts with a nucleus, the following processes are possible:

1. Elastic scattering occurs if the neutron simply changes its direction without giving the nucleus any intrinsic excitation energy. The transfer of energy is analogous to that in a collision of two billiard balls and is governed by the laws of mechanics.
2. Capture reactions are those in which the neutron is absorbed by the nucleus to form a heavier nucleus. In this case, the energy released comes in the form of one or more gamma rays.
3. Fission occurs in many cases if a heavy nucleus (mass $> A = 230$) is struck by a neutron. The nucleus divides into two smaller nuclei with a huge energy release ($E > 100$ MeV, where 1 MeV = 10^6 eV = 1.6×10^{-13} J).
4. Inelastic scattering occurs if a neutron transfers energy to the target nucleus and leaves it in an excited state. This energy is usually emitted in the form of a gamma ray, although in some cases positron-electron emission occurs, and in many cases, a number of low-energy gamma rays are emitted rather than one higher-energy gamma ray.
5. (n,z) reactions can also occur, where the neutron is absorbed by the nucleus and a charged particle (usually a proton or alpha particle) is emitted.

Each of these processes could, in principle, be used to detect neutrons. Unfortunately, in many cases, one cannot ensure that only one type of reaction occurs and even when this condition is met, the resulting pulse spectrum does not always allow determination of the energy of the neutron.

68.1 Detector Types

Detectors Based on Elastic Scattering

Detectors based on elastic scattering are attractive because the elastic scattering cross-section is large (usually about half of the total interaction cross-section). A fundamental problem with elastic scattering is that the recoil energy as a fraction of the incident energy ranges from 0 (at 0° scattering angle) to $4A/(A + 1)^2$ (for 180° scattering angle), where A is the mass number of the target. For $A = 1$ (hydrogen), this recoil energy ranges from 0% to 100%, but for even as light a target as carbon ($A = 12$), the maximum energy of recoil is less than 30%. The fact that a continuous range of energies is produced even from a monoenergetic neutron beam makes the efficiency difficult to calculate, since it depends on accurate knowledge of the cutoff threshold of the electronics. The same feature complicates determining the energy distribution of neutrons when a range of energies is present.

Hydrogen-containing counters are nonetheless frequently used in neutron physics. Below about 500 keV, the pulse height is usually too small to be useful, but above this energy this type of counter is effective. Proportional counters or ion chambers filled with methane can be used in situations where fast timing is not required. Hydrogen-containing scintillators have poorer energy resolution but better timing information and are available in large volumes. Scintillators are subject to a threshold but can be made highly efficient ($\epsilon > 50\%$) if the volume is sufficiently large. For either proportional counters or scintillators, gamma rays can produce background pulses through the Compton effect, but some liquid scintillators have the capability of identifying the two types of pulses produced by neutrons and gamma rays, respectively, allowing discrimination against gamma rays. The excellent timing characteristics of scintillators have resulted in extensive use of these detectors for time-of-flight spectrometers. In these spectrometers, the energy of the neutron is deduced by timing the neutron over a measured flight path. For typical flight paths ($L < 10$ m), a precision of a few nanoseconds is required.

The fundamental limitation of counters of this type is that the pulse height in the detector is not uniquely related to the neutron energy. If the detector is not used in a time-of-flight spectrometer, the energy of the neutron cannot be deduced. A related problem is that the efficiency is determined by an electronic cutoff, which is difficult to determine accurately. Finally, detectors that include the entire angular distribution do not have directional sensitivity.

All of these drawbacks can be removed if only a limited portion of the angular range is sampled. This is the case in a recoil counter telescope. The spectrometer consists of a polyethylene radiator at one end of an evacuated cylinder. Near the other end are either one or, more typically, two detectors. Neutrons enter the telescope from the end holding the radiator. A small fraction of them produce recoil protons at small angles to the beam. A two-detector system is arranged so that the particles traverse both. Requiring a coincidence in pulses reduces backgrounds. These detectors register protons scattered by the neutron beam at angles near 0° to the original beam. The recoil energy of such protons is $E_n \cos^2 \theta$, where E_n is the neutron energy and θ is the angle of recoil. This implies that for a telescope which subtends an angle θ around 0°, the energy range of recoil protons will be E_n to $E_n \cos^2 \theta$. It can be shown that the average energy is simply $(½)\ E_n\ (1 + \cos^2 \theta)$. Obviously, as θ becomes small, the proton energy reflects the neutron energy. The smaller θ becomes, however, the lower the efficiency of the telescope. Typical telescopes of this type have efficiencies of 10^{-5} to 10^{-6}. It is obvious that only neutrons arriving along the axis will give protons of the right energy. Neutrons coming from the backward hemisphere will not be able to produce protons that traverse the spectrometer. The drawback of a low efficiency is partly compensated by the fact that the efficiency can be accurately calculated and the fact that the energy spectrum can be deduced.

Detectors Based on Capture Reactions

Capture reactions have small cross-sections at energies above 1 MeV. At lower energies, the cross-section typically varies as $1/\sqrt{E}$, so it can be very large at low energies. Further, the capture process is exoergic, typically yielding about 7 MeV. This energy is usually divided among two to four gamma rays. The efficiency of gamma-ray detectors is usually much less than 100% and detecting the gamma rays in coincidence requires large solid angles. It is essentially impossible to use the capture process to determine the energy of individual neutrons in a flux of neutrons of varying energies.

An alternative use of the capture process is in a passive detector. A foil of the appropriate material can be placed at the location where the flux is to be determined. The target must be one that produces a radioactive residual nucleus when a neutron is captured. Thus, ^{28}Si would not be appropriate, since ^{29}Si is stable, but ^{27}Al would be a possibility, since ^{28}Al is radioactive. After the measurement is complete, the foil is removed and placed in a counting area. A detector then counts the beta particles or gamma rays emitted. Of particular importance is the choice of target to ensure an appropriate halflife. A very short halflife would allow the decay of the radioactive nuclei before they could be counted, while a very long halflife (>1 month) might require an excessive length of time to be counted.

The complicated energy dependence of the capture cross-section makes use of the capture process mostly useful for relative measurements. If two measurements are made of spectra with the same relative distribution of neutrons with energy, a measurement of the ratio of activities will give the ratio of neutron intensities. An important advantage to this technique is that small foils can be used, allowing the determination of the flux in a small volume. Other radiation, such as gamma rays, usually does not interfere in such a measurement. An important disadvantage is that the flux is not obtained until after the counting is completed; this might be as long as a month after the measurement. An additional disadvantage has already been mentioned. If the relative energy dependence of the two spectra is not the same, the relative ratio of neutrons will not be correct.

Detectors Based On Fission

The fission process is relatively unique, since an energy release of over 100 MeV occurs even when the incoming neutron has an energy below 1 eV. Fission cross-sections for gamma rays are small, so most of the pulses will be due to neutrons. There are two types of fission targets. Those with even proton number (Z) and even neutron number (N) have an energy threshold for fission. The cross-section for fission is normally negligible below 2 to 3 MeV. Other targets for which either N or Z or both are odd have no threshold energy. These isotopes (e.g., ^{235}U) normally have a low energy cross-section dependence of $1/\sqrt{E}$, giving a very large efficiency for neutrons below 100 keV. Fission detectors are designed either for $E_n > 2$ MeV (in which case ^{238}U would be an appropriate choice) or for the entire energy range, in which case the efficiency is highest at low energies.

Fission foils must be fairly thin to allow the escape of the fission fragments into the counting volume. This typically results in low efficiencies ($<10^{-6}$). Fission chambers also require the license to possess radioactive isotopes. The energy release in the fission process is so large that the pulse height in the counter cannot be used to infer the neutron energy. Reasonably good timing information ($\Delta t < 5$ ns) allows the use of fission chambers in time-of-flight spectrometers.

Counters Based on Inelastic Scattering

Inelastic scattering results in a transfer of energy from the neutron to the target nucleus through excitation of an excited energy state. This will then result in the production of one or more gamma rays. Gamma rays can be detected in germanium detectors with good energy resolution. Unfortunately, the efficiency of a spectrometer utilizing a germanium detector and inelastic scattering is quite small. This technique is being examined as a possible approach to identifying contraband materials in luggage, since both the neutrons and the gamma rays they produce are highly penetrating.

Although most gamma ray decays occur rapidly ($<10^{-6}$ s), some gamma-ray decays are inhibited by angular momentum coupling and have halflives longer than 1 s. These could be used in a detector based on inelastic scattering just as the capture reaction is used. Two nuclei with such states are ^{89}Y and ^{103}Rh. Unlike the capture reaction, such isomeric transitions will not be effective in detecting low-energy neutrons, since there is a threshold for populating such states (approximately equal to the energy of excitation, ignoring recoil effects).

Detectors Based on (n,p) or (n,α) Reactions

Detectors utilizing (n,p) or (n,α) reactions can be passive, in which a final product nucleus is radioactive, or active, in which a proton or alpha is detected. For a discussion of the passive type, see Section 68.2. Direct detection of the charged particle can occur in a proportional counter or a scintillator. As in the case of fission, many (n,p) and (n,α) reactions have an energy threshold, which prevents their occurring until this energy is exceeded. Others have no threshold (they are exoergic) and have low energy cross-sections that vary as $1/\sqrt{E}$. These targets and the reactions that occur are:

1. ^{3}He(n,p)^{3}H
2. ^{6}Li(n,α)^{3}H
3. ^{10}B(n,α)^{7}Li

Reaction (1) is often utilized in a proportional counter filled with ^{3}He. The second reaction can be used in a scintillator made of glass which has a loading of up to 9% ^{6}Li. For reaction (3), the gas BF_3 can be used in a proportional counter.

Each of these reactions is particularly effective in detecting neutrons below 1 MeV and especially thermal neutrons ($E \sim 0.025$ eV). Few charged particles are produced by neutrons at these energies from the counter housing or glass constituents, so the spectra are characterized by minimal interference from other materials. A common problem is that the low-energy neutrons that one seeks to measure are accompanied by a flux of thermal neutrons, which one does not wish to measure. In this case, the counter efficiency will be so high for the thermal neutrons that they may swamp the events one wishes to detect. An obvious solution to this problem is to use a thin layer of cadmium or boron to shield the detector, since these materials have very high thermal absorption cross-sections. Each of these reactions is much less effective at energies above 10 MeV, since backgrounds due to charged particles in the housing or in the glass can be comparably large. Although counters utilizing these reactions can be approximately 100% efficient at thermal energies, they are often less than 5% efficient at energies above 3 MeV.

There is an interest in having a counter that can detect neutrons with virtually constant efficiency independent of energy. A counter that approximately meets this characteristic is the long counter. This counter consists of a BF_3-filled proportional counter embedded in a polyethylene moderating cylinder. Those neutrons directly incident on the BF_3 chamber with very low energies will be detected with approximately 100% efficiency, while neutrons with $E_n > 1$ MeV will be detected with much smaller efficiency (<10%). By surrounding the BF_3 counter with polyethylene, the higher energy neutrons can be slowed down and the net efficiency increased, although some may be captured in the polyethylene. Very low energy neutrons will be more likely to be captured in the polyethylene, so the detection efficiency for these neutron energies is reduced. Study of the detailed energy dependence of the efficiency of such counters has resulted in a design that has certain cavities cut in the shielding on the side from which the neutrons enter. This allows some of the lower energy neutrons a shorter path to the counter. The fact that neutrons are detected after moderation means that the counter cannot give precise timing information, nor can it be used to determine neutron energy spectra. It also cannot determine the neutron flux over a small cross-sectional area but gives an average over 40 to 100 cm^2. It also will have a slightly different efficiency for neutrons coming from different directions. A sample design is shown in Figure 68.1. Note that since the counting element needs only to have an efficiency that rises sharply at low energy, a long counter can be designed using a ^{3}He ion chamber instead of a BF_3 tube.

Other (n,z) reactions do not have positive Q values (are not exoergic). These have thresholds and, in fact, usually have small cross-sections for a few MeV beyond the threshold. An example is ^{27}Al(n,α)^{24}Na. This reaction cannot occur for neutrons of less than 3 MeV and has a very small cross-section below 4.5 MeV. It does lead to a radioactive final nucleus and can be used as a passive detector. Unlike the detectors based on (n,γ) reaction, it will not detect low energy neutrons.

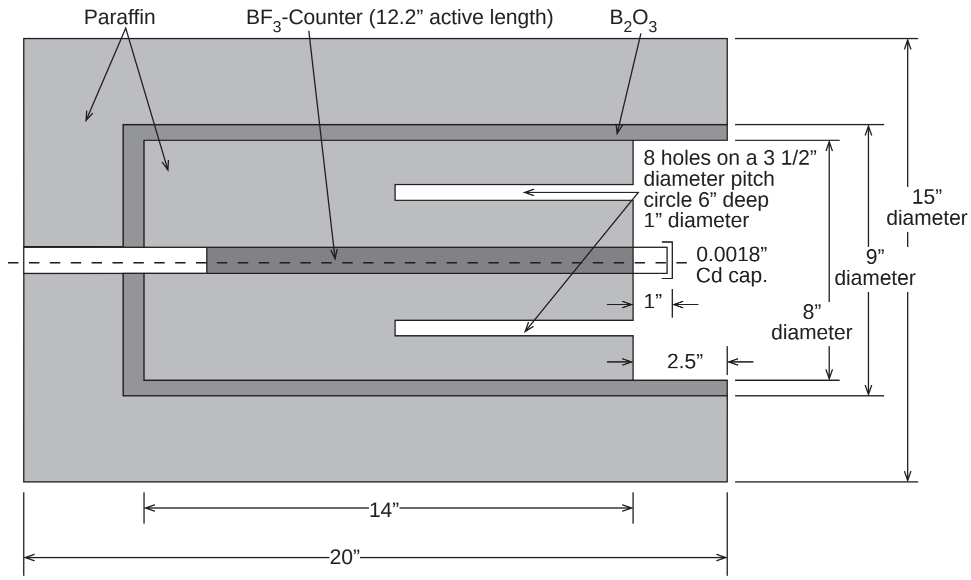

FIGURE 68.1 Cross-section of a typical long counter (described in M.H. McTaggart, AWRE NR/A1/59 (1958)). Neutrons incident from the right are scattered by the paraffin, causing them to lose energy. The BF_3 counter is efficient primarily for neutrons below 1 keV. The holes and the B_2O sections balance the efficiency as a function of energy.

An alternative reaction that can be used in a passive detector is the (n,2n) reaction. This typically has a threshold of about 8 MeV but has a large cross-section once the threshold is exceeded. Note that just as is found for (n,γ) or (n,z) reactions, not all nuclei reached in (n,2n) reactions are unstable.

68.2 Efficiency Calculations

Detectors based on np scattering have an efficiency that depends on the n-p elastic cross-section. For a proportional counter or scintillator, an approximate expression for the efficiency is

$$\epsilon = \left(1 - e^{-n\sigma_H L}\right)\left(1 - \frac{B}{E_n}\right) \tag{68.1}$$

This expression involves the parameters n, the number of hydrogen atoms per cm^3; σ_H, the n-p elastic cross-section; B, the electronic cutoff (in energy equivalent units); and E_n, the neutron energy. This expression ignores multiple scattering, so it would not include pulses produced by two scattering events in succession. It also does not include carbon interactions. For energies below 4.4 MeV, carbon interactions are almost entirely elastic and do not result in absorption or pulses large enough to detect. Particularly at energies above 10 MeV, carbon interactions not only remove neutrons from the beam but also, through (n,α) or (n,3α) events, can produce pulses that can be detected. Calculating the efficiency in this energy range can be done with Monte Carlo codes, but the efficiency will depend on knowledge of the ^{12}C (n,α) and ^{12}C(n,3α) cross-sections as well as the relation between alpha pulse heights and proton pulse heights as a function of energy.

Recoil telescopes have an efficiency which has the form:

$$\epsilon = \frac{n\sigma\left(0°\right)L\,A}{d^2} \tag{68.2}$$

Here, n is the number of hydrogen atoms per cubic centimeter, $\sigma(0°)$ is the n-p elastic-cross section at 0° (in units of cm^2/steradian), L is the thickness of the radiator, A is the area of the detector, and d is the distance between radiator and detector. Note this assumes that $n\sigma L \ll 1$ and that θ is small. A corrected version based on the assumption that the n-p cross-section is isotropic in the center of mass has:

$$\sigma(0°) = \frac{\sigma_{np}}{\pi} \tag{68.3}$$

where σ_{np} is the total elastic cross section and, if θ is not sufficiently small, $\sigma(0°)$ is replaced by:

$$\frac{\sigma_{np}}{2\pi}\left(1+\cos\theta\right) \tag{68.4}$$

Note that the efficiency can be increased by increasing L or A or reducing d. All of these changes degrade the energy resolution.

Efficiency of passive detectors is a function of many variables. The total activity of a sample after being struck by N_n neutrons will be:

$$n\sigma L\, N_n\, \frac{\tau}{T}\left[1-e^{-\frac{T}{\tau}}\right] \tag{68.5}$$

where n is the number of atoms per cm^3, σ is the appropriate cross-section (e.g., for n, γ), L is the thickness of the foil, T is the time over which the irradiation took place, and τ is the average lifetime of the radioactive nuclei produced. This expression assumes that $n\sigma L \ll 1$ and that the source strength was uniform over the time T.

If the counter has an area A, is at a distance d from the activated foil, has an efficiency ϵ_r, and measures the activity from a time t_1 after the bombardment to a time t_2, the efficiency ϵ_n will be

$$\epsilon_n = \left(n\sigma L\right)\frac{\tau}{\mathrm{T}}\left(1-e^{\frac{T}{\tau}}\right)\left(\frac{A\,\epsilon_r}{4\pi d^2}\right)\left(e^{-\frac{t_1}{\tau}} - e^{-\frac{t_2}{\tau}}\right) \tag{68.6}$$

Each of the factors in parenthesis is less than one, so the typical efficiency of such a monitor is 10^{-4} to 10^{-6}.

Fission chambers have an efficiency of:

$$\epsilon_n = n\sigma_f\, L \tag{68.7}$$

where n is the number of atoms per cm^3 in the foil, σ_f is the fission cross-section, and L is the thickness of the foil. At low energies, σ_f may be large enough so that the above expression is greater than 0.1. In that case,

$$\epsilon_n = \left(1-e^{-n\sigma L}\right)\frac{\sigma_f}{\sigma} \tag{68.8}$$

where σ is the total cross-section for neutrons.

The efficiency for a lithium- or boron-containing scintillator is:

$$\epsilon_n = \left(1 - e^{-(n_1\sigma_1 + n_2\sigma_2)L}\right)\left(\frac{n_1\sigma_1}{n_1\sigma_1 + n_2\sigma_2}\right) \quad (68.9)$$

n_1 is the density of lithium or boron atoms per cm^3, σ_1 is the (n,α) cross-section, n_2 is the density of atoms other than lithium or boron in the scintillator, and σ_2 is the average absorption cross-section for these atoms. If $(n_1\sigma_1 + n_2\sigma_2)\, L \ll 1$, this becomes:

$$\epsilon_n = n_1\sigma_1 L \quad (68.10)$$

Note that in each case where a term of the form $(1 - e^{-n\sigma L})$ appears, the average of this quantity is not $(1 - e^{-n<\sigma>L})$ if σ has energy fluctuations over an energy bin that are substantial. Here, $<\sigma>$ is the average cross-section over the energy bin. This limit is particularly important at low energies, where isolated resonances cause large fluctuations in σ and where the limit of small $n\sigma L$ may not be appropriate. In this case, the expression for the efficiency should be evaluated separately for individual energies in the bin and the resultant efficiencies averaged.

68.3 Summary

A summary of the features of various counters is presented in Table 68.1. More exhaustive treatment of the subject of neutron detectors can be found in References 1 and 2. Table 68.2 lists some suppliers of neutron detectors.

TABLE 68.1 Characteristics of Various Neutron Detectors

Detector Type	Gives Energy Spectrum	Small Size	Directional Information	Insensitive to Gamma Rays	Detects Neutrons Below 500 keV	Timing Information	High Efficiency
Hydrogen-containing counters							
Proportional counter	No	Yes	No	Somewhat	No	No	Yes
Scintillator	No[a]	Yes	No	Liquid Scintillator Can Reject Gamma Rays	No	Yes	Yes
Proton recoil telescope	Yes	Yes	Yes	Yes	No	Yes	No
Passive (n,γ) detector	No	Yes (smaller than others)	No	Yes	Yes	No	No
Fission detector	No[a]	Yes	No	Yes	Yes	Yes	No
Passive inelastic-scattering detector	No	Yes	No	No	No	No	No
Detectors based on (n,z) reactions							
Passive detector	No	Yes	No	Yes	Yes	No	No
Scintillator (lithium glass)	No[a]	Yes	No	No	Yes	Yes	Yes
Long counter	No	No	No	Yes	Yes	No	Yes

[a] Can give energy information when used in time-of-flight spectrometer.
[b] Timing information is considered to be available if the time is determined to within less than 10^{-6} s.
[c] High efficiency means ≥ 1%.

TABLE 68.2 Commercial Suppliers of Neutron Detectors

Supplier	Product
BICRON 12345 Kinsman Road Newbury, OH 44065 Tel: (216) 564-2251 Fax: (216) 564-8847	Plastic scintillators Liquid scintillators with pulse shape discrimination Assemblies, phototubes
EG&G ORTEC 100 Midland Road Oak Ridge, TN 37831-0895 Tel: (423) 482-4411 Fax: (423) 483-0396	He-3 detector and electronics Li-6 detector and electronics
NE Technology, Inc. Princeton Corporate Plaza 1 Dee Park Drive, Suite L Mamouth Junction, NJ 08852 Tel: (908) 329-1177 Fax: (908) 329-2221 Email: netec@delphi.com	Plastic scintillators Liquid scintillators with pulse shape discrimination Assemblies, phototubes
Reuter Stokes 8499 Darrow Road Twinsburg, OH 44087 Tel: (216) 425-3755 Fax: (216) 425-4045	He-3 proportional counters Fission chambers
REXON 24500 Highland Point Beachwood, OH 44122 Tel: (216) 292-7373 Fax: (216) 292-7714	Plastic scintillators Liquid scintillators with pulse shape discrimination Assemblies, phototubes
N. Wood Counter Laboratory, Inc. P.O. Box 509 Chesterton, IN 46304 Tel: (219) 926-3571 Fax: (219) 926-3571	Boron triflouride gas tubes

Defining Terms

Ionization chamber: A detector that collects the charge produced by ionization as a charged particle passes through the chamber.

Proportional counter: A detector that collects the charge produced by ionization with linear amplification as a charged particle passes through the chamber.

Scintillator: A detector that converts ionization energy to a short light pulse.

Compton effect: A process by which a gamma ray scatters from an electron on an atom. As a result, the electron is given a recoil velocity, producing ionization and yielding a pulse in an ionization chamber or proportional counter.

Isomeric transaction: A gamma ray decay of a nucleus in which the rate of decay is greatly slowed by restriction imposed by angular momentum coupling.

Time-of-flight spectrometer: A detection device for neutrons in which a neutron detector is placed a known distance from the neutron source and the energy of the neutron is deduced from the time the neutron takes to traverse this path.

Q value: A parameter expressing whether a nuclear reaction leads to a final state of higher final mass ($Q < 0$) or of lower final mass ($Q > 0$) than the initial state. Elastic scattering reactions have $Q = 0$.

Efficiency: The efficiency of a neutron detector is its probability of detecting a neutron incident on the detector. Efficiency is obviously a number between 0 and 1 and generally depends on neutron energy.

References

1. J.B. Marion and J.L. Fowler (eds.), *Fast Neutron Physics, Part I*, Interscience Publishers (New York, 1960).
2. G.F. Knoll, *Radiation Detection and Measurement*, John Wiley & Sons (New York, 1979).