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Position-sensitive detection of slow neutrons -
survey of fundamental principles*

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ABSTRACT

This paper sets forth the fundamental principles governing the development of position-sensitive detection systems for slow neutrons. Since neutrons are only weakly interacting with most materials, it is not generally practical to detect slow neutrons directly. Therefore all practical slow neutron detection mechanisms depend on the use of nuclear reactions to "convert" the neutron to one or more charged particles, followed by the subsequent detection of the charged particles. The different conversion reactions which can be used are discussed, along with the relative merits of each. This is followed with a discussion of the various methods of charged particle detection, how these lend themselves to position-sensitive encoding, and the means of position encoding which can be applied in each case. Detector performance characteristics which may be of importance to the end user are discussed and related to these various detection and position-encoding mechanisms.

1. INTRODUCTION

The use of position-sensitive detectors (PSDs) for the detection of slow neutrons has become widespread. Such detectors are now at the heart of many different types of neutron scattering instrumentation, both at reactors and at pulsed neutron sources, and have found their way into other applications as well. It is the intent of this paper to summarize the general principles which are important in the design/selection of a neutron PSD for specific applications. An excellent review of PSD principles has been provided by Convert and Forsyth,¹ and the book by Knoll² provides a detailed analysis of many aspects of the various types of detectors used. This paper draws heavily from both of these sources. It is not the intent here to provide a complete review of neutron PSDs now in operation. The recent survey of McElhaney and Vandermolen³ presents a fairly complete picture of the two-dimensional PSDs currently in operation or under development, and reviews of the detectors and detector developments at several major neutron scattering facilities have also appeared recently.⁴⁻⁶ These sources should be consulted for details of specific detectors and for a more detailed bibliography.

The discussion of neutron PSDs falls naturally into two parts: the detection of the neutron, and the encoding of the position of this detection. These are discussed separately below, and some of the advantages and disadvantages of each technique are indicated in each of these sections.

2. PRINCIPLES OF NEUTRON DETECTION

2.1 Conversion to charged particles

All radiation detectors depend on the collection of charge for their operation. Since neutrons are uncharged, neutrons must be made to produce charged particles if they are to be detected. This can be done either by the utilization of specific nuclear reactions, or else by the ionization of the detector material in direct collisions with the neutrons. "Slow" neutrons do not have sufficient energy to make this latter method of charge production a realistic option, so detectors for slow neutrons must rely exclusively on nuclear reactions. The reactions most commonly used for the detection of slow neutrons are

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The energies specified appear as kinetic energy of the reaction products. The cross-sections (specified in barns where 1 barn = 10^{-24} cm^2) for these reactions⁷ are listed in Table I. Several other nuclei have large energy-dependent resonance cross-sections for slow neutrons,⁸ but with the exception of ${}^{177}\text{Hf}$, which produces appreciable numbers of conversion electrons, most of these other reactions produce only energetic γ -rays and so are much more difficult to use in PSDs. Nevertheless, because of the energy dependence of the absorptions, some of these resonance reactions may be useful in some specific applications.⁹

TABLE I - Cross-sections for Useful Nuclear Reactions

Nucleus	% Natural Abundance	Cross-section at 25.3 meV
${}^3\text{He}$	0.00014	5333 barns
${}^6\text{Li}$	7.5	940
${}^{10}\text{B}$	19.8	3837
${}^{155}\text{Gd}$	14.80	60900
${}^{157}\text{Gd}$	15.65	254000
nat Gd		48890
${}^{235}\text{U}$	0.720	583 ^a
${}^{239}\text{Pu}$		748 ^a

^a Fission only.

Figure 1. Energy dependence of the cross-sections for reactions important in slow-neutron detection.

The efficiency for the absorption of a neutron is given by

$$\epsilon_a = 1 - e^{-N\sigma t} \quad (7)$$

where N is the number density of the absorbing nuclei in the detection medium, t is the thickness of this medium in the direction of the neutron path, and σ is the absorption cross-section of the nuclei being used for the conversion process. For a gas, $N = 2.69 \times 10^{19} nP$, where N is in cm^{-3} , P is the pressure of the absorbing gas (in atm) and n is the number of absorbing nuclei per molecule in the absorbing gas. For solids or liquids N is typically $\sim 10^{22} \text{ cm}^{-3}$. In general, the cross-sections for these reactions depend on the energy of the neutron. Figure 1 shows the energy dependence of the cross-sections for the reactions listed in Eqs. (1-6). (Curves shown for ${}^{235}\text{U}$ and ${}^{239}\text{Pu}$ are fission cross-sections only. Cross-sections for Gd, U, and Pu have a large number of additional resonances in the range above 10 eV.) The absorption cross-sections of ${}^3\text{He}$, ${}^6\text{Li}$, and ${}^{10}\text{B}$ vary inversely with the neutron velocity, that is

$$\sigma \propto 1/v \propto 1/E^{1/2} \quad (8)$$

This leads to a detector efficiency which varies smoothly and in a known manner as a function of neutron energy, a feature which is very useful for some detector applications. As can be seen from Fig. 1, the cross-sections for the other reactions show much more complex energy-dependent structures.

2.2 Gas-filled detectors

Either ^3He or $^{10}\text{BF}_3$ can be used as a neutron-sensitive gas. (Either natural BF_3 or isotopically enriched BF_3 can be used.) There are no suitable gases containing any of the other nuclei noted above. The $^3\text{He}(n,p)$ reaction produces a proton with 0.573 MeV of kinetic energy and a ^3H ion (triton) with 0.191 MeV of kinetic energy. Similarly, the predominant $^{10}\text{B}(n,\alpha)$ reaction produces ^4He (α particle) and ^7Li ions with 1.464 MeV and 0.836 MeV of kinetic energy respectively. The proton and triton (or the α particle and ^7Li ion) rush apart in opposite directions with their paths randomly oriented about the site of the absorption event. These energetic charged particles collide with the gas molecules with sufficient energy to ionize them, losing some of their energy in the process. By the time these initial charged particles have lost all their energy they have left in their wakes clouds of electrons and positive ions. Since the energy lost in producing an electron-ion pair is typically 30-35 eV in most gases,² this means that ~20,000 (~70,000) primary electron-ion pairs are produced when a neutron is absorbed in ^3He ($^{10}\text{BF}_3$) gas. The range of the 0.191 MeV triton is about half that of the 0.573 MeV proton for typical gaseous media,¹⁰ so the center of electron charge in the ionizations produced by the proton and triton will be displaced from the position of the absorption event by an amount Δx_c along the direction of the proton path. Integration of the ionization along each of the track lengths shows this center-of-charge displacement to be ~0.33 times the range R_p of the proton.¹¹ Figure 2 shows typical distributions of these primary charge clouds in the case of a BF_3 detector, indicating that in this case Δx_c is ~0.25 times the range R_α of the α particle. The intrinsic spatial resolution Δx_g of the detector fill gas is given by the fwhm of the angular average of the projection of this charge centroid displacement, or roughly

$$\Delta x_g \approx 1.4 \Delta x_c \approx \begin{matrix} 0.46 R_p & ^3\text{He}(n,p) \text{ reaction} \\ 0.35 R_\alpha & ^{10}\text{B}(n,\alpha) \text{ reaction} \end{matrix} \quad (9)$$

The range of a 0.573 MeV proton in ^3He at 1 atm is nearly 6 cm, so a "stopping gas" must always be added to the ^3He to provide good position resolution of the event. Typically used stopping gases include Ar, Xe, CF_4 , and C_3H_8 . Table II shows approximate ranges calculated from the tabulated data¹⁰ for the 0.573 MeV proton from the ^3He reaction and of the 1.464 MeV α particle from the ^{10}B reaction in a number of gases. These values are in good agreement with other calculations.^{11,12} Ranges will vary inversely with the pressure of the gas, so Eq. (9) and Table II can be used to estimate the intrinsic spatial resolution in a gas detector due to the gas stopping power at any reasonable gas partial pressure in each of these cases. Table II indicates that BF_3 has nearly the same stopping power as the best stopping gases, so the only use for an additional stopping gas in a $^{10}\text{BF}_3$ detector would be to permit independent adjustment of the detector resolution and efficiency.

Figure 2. Distribution of primary charges produced in stopping the ^7Li and α particles from the $^{10}\text{B}(n,\alpha)$ reaction in BF_3 gas at 1 atm.

TABLE II - Particle ranges in gases at 1 atm and 20°C

Material	$^3\text{He}(n,p)$ proton range	$^{10}\text{B}(n,\alpha)$ α particle range
He	58 mm	49 mm
Ar	11.2	9.2
Xe	6.7	5.6
CO_2	6.7	5.5
CH_4	10.3	8.6
CF_4	3.6	3.0
C_3H_8	4.2	3.4
BF_3	4.6	3.8

The electric field in the detection chamber causes these primary electrons to drift relatively rapidly toward the anode and the positive ions to drift relatively slowly (because of their greater mass) toward the cathode. As they drift, the electrons and ions suffer frequent collisions with the molecules of the gas. If the electric field is weak, the electrons will not achieve sufficient energy between collisions to ionize the gas molecules. In this case, the "ionization" regime, the total charge reaching the anode

is just that of the primary electrons. As the electric field is increased, eventually the point is reached where an electron can be sufficiently accelerated between collisions to ionize a gas molecule during a collision. The "secondary" electrons resulting from such ionizations also drift toward the anode, so a "gas multiplication" of the total charge occurs. The regime where such localized gas multiplication occurs is known as the "proportional" counting regime, since the total charge reaching the anode is proportional to the number of initial primary electrons and hence to the total energy deposited in the event. For practical reasons, the electric field geometry in a proportional counter is usually arranged so that gas multiplication occurs only as an "avalanche" within a small region near the anode (for example, by making the anode out of fine wire). Gas multiplication factors of a few hundred can be readily achieved, and multiplication factors up to a few thousand are possible,² so the pulses from a proportional counter typically have much greater amplitudes than do those from an ionization chamber. This makes them much less susceptible to noise in the processing electronics. For a given detector geometry the gas multiplication factor increases approximately exponentially with the applied voltage,² so very stable high voltage supplies are required for proportional counters. As the electric fields are increased to still greater values, one eventually reaches the Geiger-Mueller regime in which the avalanche from a single neutron absorption fills the entire detector. Since the discharge is no longer localized, this operating regime cannot be used for PSDs except when the PSD is an array of discrete non-position-sensitive detectors. The proportional mode of operation is usually the choice for PSDs because of its superior signal/noise characteristics. However, in very intense neutron beams ionization mode operation may offer some advantages, since the high density of ions and electrons produced in proportional counters can lead to chemical degradation of the detector fill gas or of the detector electrodes under these conditions.

The partial pressure of the ^3He or $^{10}\text{BF}_3$ gas can be adjusted to provide the desired neutron absorption efficiency. For example, for a detector with a 2 cm thick active volume, Eq. (7) and Table I indicate that the pressure of ^3He must be 3.66 atm to achieve a detection efficiency of 65% for 25 meV neutrons. For the same detector geometry, the pressure of $^{10}\text{BF}_3$ would have to be 5.09 atm to achieve the same efficiency. Pressures up to 10-20 atm can be used for ^3He detectors, while detectors containing BF_3 are usually restricted to a much lower pressure range because the electronegativity of this gas leads to appreciable recombination and/or chemical activity at higher pressures. An advantage of BF_3 is the much greater number of primary electron-ion pairs produced per absorbed neutron. However, when detectors are operated in the proportional mode this advantage becomes much less significant, since gas gains can usually be adjusted to provide the desired total charge per event simply by adjusting the operating potential of the detector. An advantage of ^3He is its chemical inertness, which allows much greater pressures to be used.

The distribution of amplitudes of the pulses resulting from slow-neutron events in a detector is quite important in determining how effective amplitude-discrimination will be in rejecting undesired events such as γ -rays, fast neutrons, or noise. If both of the charged particles from each of the neutron absorption events deposit all of their energy in the gas, the amplitude (pulse-height) distribution of the resulting pulses will be peaked about a value corresponding to this energy (more precisely, to the number of primary electron-ion pairs produced per absorbed neutron). From the numbers quoted above, the statistical variation in the number of primary electron-ion pairs should be less than 2%. However, in proportional counters the statistical fluctuations in the gas multiplication for each primary electron also contribute to the variation in pulse height, and in most cases are the dominant effect. If the gas multiplication is large, the large numbers of slowly-drifting ions will also have a pronounced effect on the spread in pulse amplitudes. Thus for a typical proportional counter the peak in the pulse-height spectrum has a fwhm nearer 10-15% or even more.² In practical detector geometries many of the neutron absorptions occur close to one of the detector walls, so that in some cases one of the resulting charged particles will strike the wall before giving up all its energy to the gas. Such an event will result in fewer primary electrons in the gas, with a corresponding reduction in the resulting pulse amplitude. Because of such "wall effects" the actual pulse-height distribution from a gas ionization chamber or proportional counter will have a "tail" which extends to much lower amplitudes than that of the full-energy peak. Figure 3a shows a typical pulse-height spectrum for a ^3He detector, with shoulders corresponding to either the proton or the triton striking the wall. Details of actual pulse-height spectra will depend on specific detector geometries, materials, and operating conditions.

Gamma rays interact with materials primarily by the photoelectric effect, Compton scattering, or pair production, with the interaction probability increasing strongly with the atomic number Z of the material. Figure 4 shows γ -ray cross-sections for some typical detector gases.¹³ High-energy γ -rays lose energy primarily by Compton scattering or pair production, and require many interactions in order to lose all their energy. For most detector geometries, the relatively low densities of the gases in the detector make it likely that such a γ -ray will escape from the detector active volume before it has deposited more than a fraction of its total energy. Thus the pulse height from a γ -ray interacting in the detector will usually be much smaller than the main pulse-height peak from slow neutron absorption, permitting the γ -ray pulse to be rejected by pulse-height discrimination.

Figure 3. Typical pulse-height spectra. a) ^3He proportional counter; b) ^6Li -glass scintillator + photomultiplier. Fast neutron spectra would be similar to the γ -ray spectra shown.

Figure 4. Total γ -ray cross-sections for several materials important in slow-neutron detectors. Rough magnitudes of cross-sections for other materials can be estimated by interpolating according to the atomic number Z .

A useful lower pulse-height discrimination level is indicated in Fig. 3a. Fast neutrons can also produce measurable counts in a ^3He or $^{10}\text{BF}_3$ detector when they are absorbed by the detector gas or scattered from light nuclei in this gas. Figure 1 shows the cross-section for neutron absorption by ^3He or ^{10}B at high energies. Typical scattering cross-sections for high-energy neutrons are a few barns. For neutrons scattering from H atoms, kinematics allows any energy up to the full neutron energy to be transferred to the H atom, which can cause this atom as well as many of its neighbors to become ionized. For other materials, the maximum energy which can be transferred per collision is much smaller, and since the gas density is relatively low and the scattering cross-section is small it becomes unlikely that the neutron can deposit all of its energy in the gas before escaping from the detector. Thus if the detector is to be operated in a fast-neutron background it is important to use only non-hydrogenous gases in the detector so the fast-neutron events can be eliminated from the data by the use of pulse-height discrimination.

The intrinsic gas resolution Δx_g of Eq. (9) provides a fundamental limit on the spatial resolution of a gas detector. Other factors in the gas amplification process and the position encoding can also contribute to the resolution, but the resolution can never be made better than Δx_g . Because of the long drift time of the ions in a gas detector, both the position resolution and the pulse-height spectrum of such a detector can be severely degraded at high data rates due to the build up of a "space charge" in the detector. This effect is much more pronounced if the gas multiplication is large. These space charge effects provide a fundamental limit on the maximum instantaneous data rates at which a gas detector can be used. The high pressure required to achieve good efficiency and good spatial resolution in a gas detector requires a bulky container, which may be a problem in some applications. Also the thickness of the active volume required to achieve good efficiency can lead to a worsening of the resolution near the edges of the PSD due to parallax. Major advantages of gas detectors include their extremely low intrinsic backgrounds and the fact that with proper choices of materials very good rejection of γ -rays and fast neutrons can be achieved. The technology is well developed and a number of different geometries of gas PSDs for neutrons are available commercially, which is also an advantage in many cases.

2.3 Scintillation detectors

Instead of just ionizing the atoms in the material, some of the charged-particle energy can be used to raise electrons in the material to excited states. These electrons can decay back to the ground state by the emission of electromagnetic radiation (light) or vibrational energy (heat), or by a combination of these. If this decay involves the prompt emission of a photon of light, this is referred to as scintillation. In order for a scintillator to be useful as a particle detector, a number of such prompt photons must be emitted whenever the particle of interest interacts with the material. Furthermore, the scintillation material must be relatively transparent to its own emitted radiation, as otherwise the light will be unable to escape the material before being absorbed. If the scintillator is to be useful as a neutron detector, it must be possible to incorporate significant numbers of one of the neutron-sensitive nuclei discussed above into the scintillating medium, either by using a scintillating compound which contains the nuclei of interest, or else by an intimate mixture of a scintillating compound with a compound containing the neutron-sensitive nuclei. The use of mixtures should allow a much greater flexibility in the choice of compounds, but in practice it is difficult to match the indices of refraction of the compounds so that such mixtures are usually not very transparent to their own scintillation light. Since ^3He forms no solid compounds, scintillation detectors for slow neutrons must contain either ^6Li or ^{10}B , or one of the other nuclei such as Gd listed above. The greater energy produced by the ^6Li reaction leads to much greater light production in ^6Li -based scintillators than in ^{10}B -based scintillators, so scintillators based on ^{10}B are not in common use for the detection of slow neutrons. Useful scintillators for slow neutron detectors have been made from crystalline inorganic salts (usually with a small amount of an "activating" impurity to provide the necessary electronic states to produce good scintillating properties), ^6Li -containing glasses, or from some organic liquids or solids doped with Gd. However, only small amounts (~0.5% by weight) of Gd can be added to the organic scintillators without significant reduction in the light output, so such scintillators must be made quite thick to have appreciable efficiency for the absorption of neutrons. Table III summarizes some of the data for scintillating materials which have been found to be most useful for slow neutron detectors.^{2,14}

TABLE III - Some Useful Scintillators for Neutron Detection

Material ^a	Density of Absorbing Nuclei	Scintillation Efficiency ^b	Photon Wavelength	Photons per Neutron
Li glass(Ce) ^c	$1.75 \times 10^{22} \text{ cm}^{-3}$	0.45%	395 nm	~7000
LiI(Eu)	1.83×10^{22}	2.8%	470	~51000
ZnS(Ag)-LiF ^d	1.18×10^{22}	10.8%	450	~160000

^a Activating ion is shown in parentheses.

^b Fraction of nuclear reaction energy converted to useful photons.

^c Values are representative of the commercially available glasses NE905, NE908, and NE912 (Nuclear Enterprises, Ltd.).

^d Powdered crystal mixture in a plastic binder, similar to NE422 or NE426 (Nuclear Enterprises, Ltd.).

Once the light has been produced in the scintillator, it must be detected by a light-sensitive device such as a photomultiplier tube, photo-diode, channel-plate amplifier, photographic film, *etc.* The scintillator can either be directly optically coupled to the light-detecting device, or can be coupled through light guides or optical fibers or even via a system of lenses or mirrors. This leads to a number of different possible light-detection geometries, and many options for encoding the positions of events in such detectors. From Table III, each neutron absorption results in the emission of ~7,000-160,000 photons, depending on the type of scintillator used. The statistical uncertainty in numbers of this size is only a percent or less. However, only a fraction of these photons are collected in the photomultiplier or other light-sensitive device, and the quantum efficiency of a typical photocathode is ~20%, so the number of photoelectrons produced may be only 500-2000. Nonuniformities in the scintillator, statistical fluctuations in the photomultiplier amplification process, *etc.*, can cause additional uncertainties. As a result, the fwhm spread in pulse amplitudes from a scintillation detector for slow neutrons is typically 10-20%. These statistical uncertainties in the production and detection of the photons are also a major factor in the spatial resolution of scintillation PSDs.

The densities of the materials in Table III are roughly two orders of magnitude greater than the densities of the gases in proportional counters. As a consequence, the initial charged particle tracks are only a few microns long, and so do not make an important contribution to the spatial resolution in scintillation detectors. The fact that these primary particle paths are very short

also means that "wall effects" should provide little distortion of the pulse-height spectrum. Also because of the high density, a thin sheet of scintillator can provide a very high efficiency for the absorption of slow neutrons, and the use of such a thin active volume effectively eliminates parallax problems in position-sensitive detection. On the negative side, the high density of atoms makes it possible for γ -rays or fast neutrons to deposit appreciable fractions of their energy within the scintillator volume, making it difficult to provide complete pulse-height discrimination against such unwanted radiation (see Fig. 3b). Cross-sections for γ -rays in scintillators can be determined from the data in Ref. 13. The γ -ray sensitivity can be reduced by making the scintillating material as thin as possible, consistent with the requirements of detection efficiency, and a number of innovative geometries based on this principle have been developed in order to minimize this sensitivity to γ radiation in scintillation detectors. Table III shows that ZnS(Ag)-LiF scintillators produce more than ten times as much light per neutron as do the Li-glass scintillators. The corresponding increase in the pulse height from slow-neutron events should make it much easier to discriminate against γ -rays, and this has been shown to be the case in some detectors recently made with this material.¹⁵

Photomultiplier tubes typically have significant counting rates even in the absence of any incident light. This dark counting rate can usually be decreased by cooling the tubes, and can be discriminated against to some extent by pulse-height discrimination. Even better discrimination against such random counting can be obtained by observing the same scintillation event by more than one photomultiplier tube (by skillful use of light guides or optical fibers for coupling), and requiring coincidence between the tubes before registering the event. This technique is routinely applied in some of the position-encoding configurations used for scintillator-based neutron PSDs.

Major advantages of scintillation detectors include their relatively low cost, very small intrinsic spatial resolution due to the charged-particle ranges, ability to achieve high efficiency in a thin active volume, and easy adaptability to a variety of geometries. Scintillation detectors can make use of a number of optical components developed for other applications in order to achieve their position encoding, and this minimizes the amount of development required. Very good spatial resolution is possible if the scintillator has a large light output per neutron and if care is taken in the optical system. The scintillation event is quite fast in some types of scintillators, so the scintillator itself usually does not limit the maximum data rates for such detectors. Disadvantages include the likelihood of intrinsic background due to radioactive contaminants in some types of scintillators (particularly Li-glass), and the relatively poor discrimination against γ -rays and fast neutrons found in many cases.

2.4 Solid-state detectors

Although most scintillating materials are also solids, the term "solid-state detector" has traditionally been reserved for detectors based on the deposition of the particle energy in a semiconductor to form electron-hole pairs. Since the energy to form such pairs in a typical semiconductor is of the order of 3 eV,² the number of pairs formed when the entire energy of one of the neutron-absorption reactions is deposited is $\sim 800,000$ - $1,600,000$. In analogy with the analyses above, this would lead to a peak in the pulse-height distribution with a fwhm of ~ 0.2 - 0.3% . Other noise contributions can worsen this pulse-height resolution somewhat, but since the collection of charges in a semiconductor is relatively direct, fwhm pulse-height resolutions better than 0.5% are common. This much better energy resolution is the reason solid-state detectors have long been preferred for precision charged particle and γ -ray spectroscopy. For slow neutron detectors, however, the energy deposited bears no relation to the incident energy of the neutron, so this improved energy resolution is only useful in discriminating against noise or other radiation. Semiconductor detectors are generally fabricated as diodes with the depletion layer in the diode forming the active region of the detector. The thickness of this layer can be adjusted by varying the bias voltage on the diode, with thicknesses up to several mm being possible in very-high-purity Si or Ge or in Li-compensated Si or Ge. In most solid-state diode detectors the primary electrons and holes are collected with no amplification, analogous to the gas ionization chamber. The much greater number of charges produced per neutron in solid-state detectors means that the resulting pulses are much larger, so the additional amplification is not so important as in the gas-detector case.

In order to use a solid-state detector for the detection of neutrons, it is necessary to incorporate neutron-sensitive nuclei into or near the active region of the semiconductor device. These nuclei must be present in sufficient quantities to provide the desired efficiency for detection. Both B and Li are commonly used as dopants in Si detectors, but are generally present in concentrations of only $\sim 10^{17} \text{ cm}^{-3}$. Thus even if isotopically enriched B or Li were used as the dopant, the absorption efficiency for 25 meV neutrons in a 2 mm thickness of such doped semiconductor would be only 2×10^{-5} for ^6Li or 8×10^{-5} for ^{10}B . If the active region of the semiconductor device is near the surface (as in surface-barrier detectors), then somewhat higher efficiencies can be obtained by coating the surface of the device with a compound containing the absorbing nuclei. However, since the maximum useful thickness of such a coating is roughly the path length of the charged-particle reaction products in the coating

material (see the discussion of foil detection below), the maximum efficiency possible in this manner is also fairly small. Thus the successful adaptation of semiconductor detectors to the direct detection of slow neutrons awaits the development of other semiconductor materials or other device geometries which can incorporate relatively large amounts of B or Li (or other neutron-sensitive nuclei) and still maintain useful semiconducting device properties. (For example, BP is a semiconductor containing a very high density of B atoms, which is just beginning to receive serious study.¹⁶⁾

If an appropriate material can be found, then as in the case of scintillators, the high density in solid-state detectors means that in principle an efficient neutron detector could be made quite thin. Also, the ranges of the primary charged particles will be short, so position resolution can potentially be very good. However, as in the case of scintillators, this high density means that the detector would also have appreciable sensitivity to γ -rays and fast neutrons, although the good pulse-height resolution may help to discriminate between such unwanted radiation and the slow neutron events of interest. The relatively direct conversion from a neutron absorption to an electronic pulse in a semiconductor detector, as compared with the multi-stage conversion required with a scintillation detector, makes it possible to fabricate very small solid-state detectors. Semiconductor processing techniques should also make it possible to fabricate PSDs with very good position resolution and in a wide variety of geometries, and may even make it possible to fabricate the signal processing electronics on the same chip which contains the detector active area. Thus although at present solid-state detectors are not generally useful for slow neutrons, these potential advantages make it important to continue to pursue the development of solid-state detectors for this purpose.

2.5 Foil detectors

Neutron detectors can also be made by using a neutron-insensitive medium as the charged-particle detector, and placing a thin layer of a compound containing the neutron-absorbing nuclei on one or more of the faces of this detection medium. Figure 5 shows schematically the transmission and backscattering geometries for such a "foil"-based detector. A common example of this type of detector is the fission chamber, which is usually made as a standard ionization counter with a fissile material such as UO_2 deposited inside one or more of the walls. Another common example is the use of Gd foils in direct contact with photographic film to provide a simple and useful neutron PSD. As noted above, a neutron-absorbing compound can also be coated on the surface of a standard solid-state detector to make a neutron detector.

Figure 5. Foil detection geometries. a) Transmission geometry. The neutron beam is shown in normal incidence (solid line) or alternatively in oblique incidence at angle α (dashed line). b) Backscattering geometry in normal incidence.

Unfortunately, when the neutron-sensitive material is a solid film, the density of this material is so high that the path lengths of the charged particles in the film are very short. Thus regardless of the thickness of this film, only those charged particles produced within a thin layer near the interface between the film and the detecting medium have a chance of actually being detected. From the solid-angle considerations suggested in Fig. 5, the probability a charged particle will escape into the detection medium is $\sim (1 - (t-x)/R)/2$ in the transmission geometry and $\sim (1 - x/R)/2$ in backscattering geometry, where R is the range of the charged particle. Considering only the longer-range particle from the reaction, the neutron detection efficiency for neutrons incident normal to the foil surface is then given approximately by

$$\begin{aligned}
 e &= \{(1 + 1/N\sigma R)(1 - e^{-N\sigma t}) - t/R\}/2 & t < R & \text{transmission} \\
 &= e^{-N\sigma t} \{e^{N\sigma R}/N\sigma R - 1 - 1/N\sigma R\}/2 & t > R &
 \end{aligned} \tag{10}$$

$$\begin{aligned}
e &= \{(1 - 1/N\sigma R)(1 - e^{-N\sigma t}) + (t/R)e^{-N\sigma t}\}/2 & t < R & \text{backscattering} \\
&= \{(1 - 1/N\sigma R)(1 - e^{-N\sigma R}) + (t/R)e^{-N\sigma R}\}/2 & t > R &
\end{aligned}
\quad (11)$$

where N and σ are the atomic density and cross-section of the neutron absorbers in the foil. The maximum detection efficiency is obtained in each of these cases at an optimum foil thickness t_{opt} given by

$$t_{\text{opt}} = \ln(1 + N\sigma R)/N\sigma \quad \text{transmission} \quad (12)$$

$$t_{\text{opt}} \geq R \quad \text{backscattering} \quad (13)$$

For a nuclear reaction such as the ^{157}Gd reaction which produces conversion electrons with a range of energies, the maximum neutron detection efficiency varies in a more complex manner with foil thickness. In transmission geometry there is an optimum foil thickness, but in back-scattering geometry the detection efficiency continues to increase slowly as the foil thickness is increased. Table IV gives values calculated for particle ranges,¹⁰ and for optimum foil thicknesses and maximum neutron-detection efficiencies based on Eqs. (10-13) for foils made of elemental Li, B, Gd, or U. If compounds containing these elements are used instead, maximum efficiencies will be somewhat reduced. Operation of the detector at an oblique angle α to the beam, shown as an alternative in Fig. 5a, permits a longer neutron trajectory through the absorbing material without affecting the collection of the charged particles. The detection efficiency is then increased over the values given by Eqs. (10-13) roughly by a factor of $1/\cos\alpha$. (More accurate expressions can be easily derived.) More complicated geometries making use of this principle (such as corrugated surfaces, *etc.*) can also be devised.

TABLE IV - Optimum Thicknesses and Detection Efficiencies for Neutron-Absorbing Foils

Material ^a	Density of Absorbing Nuclei	Charged Particle	Energy	Range	Optimum Thickness ^b	Maximum Detection Efficiency for 25 meV neutrons ^b
^6Li	$4.63 \times 10^{22} \text{ cm}^{-3}$	^3H	2.737 MeV	120 μm	97 μm	~10%
^{10}B	13.04×10^{22}	^4He	1.464	3.8	3.5	~4%
^{157}Gd	3.03×10^{22}	e^-	<0.182	varied	~4 ^c	~20% ^c
^{235}U	4.80×10^{22}	fission	~100	~8	7.9	~0.6%

^a Isotopically enriched foil of the atom in elemental form.

^b Transmission geometry, foil normal to the beam.

^c Foil thickness and detection efficiency from reference 1.

A significant problem with foil detection is that usually only one of the charged particles is detected, and this particle can lose varying amounts of its energy before entering the charged-particle detector. Thus the pulse-height spectrum will be very broad, with appreciable numbers of pulses having very small amplitudes. This makes pulse-height discrimination against fast neutrons or γ -rays quite difficult unless discriminator levels are set to eliminate a large fraction of the slow neutron events which would otherwise be detected. The low efficiency is also a significant disadvantage for many applications. A major advantage of foil detectors is their simplicity.

3. METHODS OF POSITION ENCODING

As was made clear in the preceeding section, the problem of neutron detection is always transformed by the use of nuclear reactions to a problem in the detection of specific charged particles. Over the years a wide variety of methods have been devised for obtaining one- or two-dimensional position information from charged-particle detectors, and neutron PSDs have been constructed using many of these different techniques. Several good reviews provide details about specific implementations of charged-particle or neutron PSD encoding,^{1,3-6} and other specific implementations will be discussed later in these proceedings. Thus the present discussion will focus on some general features of these encoding methods rather than providing a comprehensive review of specific detectors.

All the various types of position encoding so far developed can be grouped roughly into three broad categories: arrays of individually-processed discrete detection elements, encoding based on weighted networks of passive electrical components connecting the detection elements, and techniques which provide time-integrated images of the detected neutron events. (Some detection systems successfully combine elements of the first two categories, as for example the use of an array of discrete one-dimensional PSDs to make in effect a two-dimensional PSD.^{17,18}) Detectors in the first two categories can be used for neutron time-of-flight (TOF) measurements or for real-time measurements as well as being useful for steady-state measurements. However, in the third category all the short-time-scale information about the neutron events is averaged out, so the techniques are restricted to steady-state measurements or to real-time measurements involving processes with relatively long time constants. These three categories of position encoding are discussed separately below.

3.1 Discrete element

The most straightforward way to make a PSD is to arrange a number of discrete detectors in an array. Discrete gas proportional counters are widely available commercially. They are usually cylindrical, although detectors with elliptical cross-sections are available for some applications, and the neutron-sensitive fill gas is usually ^3He . These detectors come in a wide variety of diameters and lengths. If each detector has its own signal-processing electronics, then the spatial location of the neutron giving rise to a signal is immediately identified as being within the volume of the corresponding detector. Such detector arrays are in use on many neutron scattering instruments. In a similar manner, arrays of discrete scintillator elements can be used to provide position sensitivity. However, the scintillators do not require the bulky containers necessary to hold the high pressure gas, and so can be made much smaller and placed closer together than can the gas detectors. Elaborate schemes of fiber-optic encoding and multiple-coincidence techniques have been developed to allow a large number of discrete scintillators to be encoded with relatively few photomultiplier tubes.^{19,20}

Figure 6. Schematic representation of a portion of one cathode plane in a MWPC. In a two-dimensional detector, a second plane of orthogonal cathode strips might lie above the anode plane. In the coincidence technique the X position is taken to be that of the X cathode strip having the signal of highest amplitude, so in the case shown X would be encoded as X_2 . Similar encoding of the orthogonal cathode strips, or of the pulses on the anode wires, would determine the Y position of the event.

The multi-wire proportional counter (MWPC) is a natural extension of the discrete-gas-detector array. In this case, multiple electrodes are enclosed within a single gas chamber. Subgroups of electrodes function in effect as discrete detectors within this volume, but in this case there are no walls between the individual "detectors" so the individual detector elements are contiguous with no dead space between them. This type of construction also permits the individual detector elements to be quite small, so good spatial resolution is possible. Use of crossed electrode arrays and coincidence techniques minimizes the number of individual signals required for two-dimensional position encoding.²¹ Figure 6 shows a schematic representation of a portion of one cathode plane of such a detector and illustrates the coincidence technique for position location. Recent development²² of a microstrip plate to replace the usual multi-wire anode plane should greatly reduce space-charge effects and lead to gas-based neutron PSDs with higher counting rates and better spatial resolution than has previously been available in MWPC detectors. In some of the recently developed position-sensitive photomultipliers the position is read out via an array of separate anodes,²³ making the encoding very much like that in a MWPC.

Discrete detectors and MWPCs with coincidence encoding require very little signal processing to determine the position of the neutron, and so can operate at relatively high data rates. However, the position resolution of such arrays is limited to the size of the individual detection elements. Resolution can be considerably improved if the charge (or the scintillation light) from each neutron-detection event is distributed over several of the detection elements, as indicated in Fig. 6. This cannot be done for arrays of discrete gas detectors, but is easily achieved in MWPCs. A similar situation is found in the Anger camera detector,²⁴ which relies on the use of a scintillator and a position-encoding scheme based on the distribution of the scintillation light in an array of photomultipliers. In these latter cases, it is possible to locate the centroid of the charge-producing event with a precision many times smaller than the size of the individual detector elements. The centroid $\langle X \rangle$ can be determined by digitizing the signal amplitude from each detector element (or each photomultiplier) and then performing the calculation

$$\langle X \rangle = (\sum X_k Q_k) / (\sum Q_k) \quad (14)$$

Since this requires many channels of analog-to-digital conversion electronics (a separate channel for each cathode strip or each photomultiplier), the more common approach is to solve Eq. (14) at least in part using analog techniques. This approach is used in the neutron Anger detector,²⁵ and factors affecting the position resolution of such a system and a comparison with other centroid-finding methods have been discussed in some detail.²⁶ A convolution technique for centroid location has also been applied to neutron MWPCs.²⁷

A major advantage of discrete detectors or MWPCs is the fact that signals from each detection element can be processed individually, thus making possible quite high overall data rates. (Some of this speed may be lost if centroid-finding is employed to improve the resolution.) A significant disadvantage, however, is the relatively high cost involved in the construction of such detectors and in the provision of a large number of channels of signal-processing electronics.

3.2 Weighted network

If the multiple electrodes in a MWPC are connected internally with delay lines rather than being independently fed out of the gas chamber, then the electrode which is the source of a given event can be identified by comparing the times t_A and t_B of the resulting pulses at the two ends of the delay line. Furthermore, if the charge is distributed over more than one electrode as in Fig. 6, this technique can determine the centroid of the charge distribution, thus potentially improving the resolution over that available from an individual electrode. Figure 7a shows this schematically. The position in this case is

$$\langle X \rangle = [(t_A - t_B) / \Delta t_{\max} + 1] / 2 \quad (15)$$

where $\langle X \rangle$ varies from 0 to 1 and $\Delta t_{\max} = |t_A - t_B|_{X=0}$ is the maximum timing difference. Several PSDs have been based on this scheme,^{28,29} but some drawbacks³⁰ have precluded the general use of delay-line encoding for neutron PSDs.

Figure 7. Examples of weighted-network encoding. a) Delay-line encoding. b) Resistive encoding. c) Distributed RC-line encoding. For a) the position of the charge centroid is given by Eq. (15), while for b) and c) the position of the charge centroid is given by either Eq. (15) or Eq. (16), depending on the type of signal-processing used.

The electrodes can instead be linked by resistance elements, as indicated in Fig. 7b. If the charge from the event is collected in charge-sensitive preamplifiers, then it divides according to the resistive network, so the position centroid in this charge-division method is (with $\langle X \rangle$ again ranging from 0 to 1)

$$\langle X \rangle = Q_B / (Q_A + Q_B) \quad (16)$$

Alternatively, use can be made of the intrinsic resistance and capacitance of a single electrode, as shown in Fig. 7c. When a neutron event causes charge to be deposited over a small portion of this electrode, this charge will proceed to diffuse to the ends of the electrode according to the diffusion equations for such a distributed RC line. In this case the position can also be determined by charge-division as in Eq. (16), using charge-sensitive preamplifiers at the ends of the electrode. The diffusion of charge in this RC line also leads to differences in the rates at which the charge is accumulated at the two electrode ends, and with suitable pulse-shaping and timing circuits this difference in rates can be used to identify the position of the centroid of the original charge-deposition according to Eq. (15). This technique is usually referred to as rise-time encoding. A number of successful proportional counter PSDs for neutrons have been based on either charge-division^{17,18,30} or rise-time^{31,32} encoding, using signals from the cathodes or anodes or both. Some of the earliest discussions of the charge-division and rise-time methods of encoding were related to semiconductor detectors rather than to gas PSDs,³³ and a number of the scintillator-based detectors incorporate similar weighted networks as part of the readout system. Some neutron detectors have been built using a microchannel plate to detect and amplify the scintillation signal coupled with a resistive anode to read out the position of the electron cascade, so this becomes a special case of charge-division encoding.^{34,35} Resistively-coupled multi-wire anodes are used for the same purpose in some position-sensitive photomultipliers,³⁶ and a successful neutron detector using such a device coupled to a neutron-sensitive scintillator has recently been reported.³⁷

Such weighted network encoding schemes have the advantage of simplicity and the associated large saving in cost. However because of the extensive signal processing required, problems associated with dead-time or with pulse pile-up resulting in position encoding errors usually limit these techniques to relatively low data rate applications. Significant nonlinearities can result in some of these types of network encoding unless the external electronics are carefully impedance-matched to the detector network.³⁸⁻⁴⁰ Considerable care must also be taken to optimize the preamplifiers and pulse-shaping electronics in order to maximize the signal/noise ratio to achieve the best possible position resolution,^{33,39-41} and even then the signal processing electronics are usually the factor which limits the position resolution achievable.

3.3 Time-integrated image

Instead of coupling a scintillator to a pulse-readout device such as a photomultiplier or microchannel plate, it can be coupled to a position-sensitive intensity-integrating device such as a solid-state charge-coupled device (CCD), a television camera, or even to photographic film. A lens demagnification system with or without an image intensifier has been used to image a large scintillator screen onto a much smaller CCD in recent X-ray⁴² and neutron⁴³ detectors. Alternatively, the image (intensified or not) from a scintillator can be focused on the photocathode of a television camera tube, where it can be read out and digitally accumulated at a standard TV rastering frequency and resolution (525 or 625 lines/frame, 30 or 25 frames/sec, typically encoded as 512 x 512 picture elements),⁴⁴ or it can be integrated directly in the camera tube (typically a silicon-intensified-target tube) and then read out and digitized at a slower scan rate.⁴⁵ Several neutron detectors^{46,47} and a number of X-ray detectors have been based on this TV approach.

Photographic films do not usually contain any of the neutron-sensitive nuclei discussed here. However a photographic film can be used to detect the light produced in a neutron-sensitive scintillator screen or can be used in conjunction with a neutron-sensitive foil such as Gd to detect the charged reaction products directly. Again, because of the high density of the photographic emulsion, path lengths of the charged particles from the nuclear reactions are quite short, allowing extremely good spatial resolution to be achieved with photographic film. The best spatial resolution (down to ~20 μm) is achieved with good quality film in contact with a Gd foil enriched in ¹⁵⁷Gd, although resolution of 0.5 mm or better can be achieved with a standard neutron polaroid camera using a scintillator screen made of ZnS(Ag)-⁶LiF.⁴⁸ The optical densities on the photographic films can be digitized with optical scanners and can be calibrated to provide accurate integrated intensity information.^{49,50}

These integrating detectors have essentially no data rate limitations, and can be very simple to construct and operate. A disadvantage is that they provide little or no time information and so cannot be used in TOF applications or in some types of real-time measurements.

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