Neutron detection

• Neutrons are neutral particles forming the nucleus together with protons. Discovered in 1932 by Chadwick (Fermi experiments in Via Panisperna!! Here around!!)

- No charge. Easily interacts with matter (Neutrons used as "probe" in matter).
- Neutrons do not exist free because decay after 13 min.
- Neutrons are produced by fission, by nuclear reactions. Neutrons cannot be accelerate, they loose energy when interacting with matter
- Neutrons detected using indirect methods n converted into something else in a converting medium (The latter not necessarily is the detector).
- Two broad class of detectors: 1- Active Detectors 2- Passive Detectors

Active detectors necessitate of H.V. to operate and produce electrical signals (pulses or current) that can be recorded for on-line/off-line analysis. Among the many types of available active neutron detectors, the most suitable can be: Fission chambers (FC) (^{235}U, ^{239}P, ^{238}U etc.), BF_3 and He-3 tube, ^{6}Li covered detectors (Si-diode or diamond), Scintillators (NE-213 or NE-422). Active gamma detectors: Scintillators, Ionization and/or Proportional chambers, Geiger-Muller (GM) tube. Due to the unpredictable intensity and type of the neutron emission (Burst(s)? Long lasting?), operation in Pulse mode seems more effective. NOTE: Active detectors are sensitive to E.M. noises [caution when operating under EM or MF. Shielding required (Aluminum, m-metal (Ni-Mo annealed)

Classic neutron detection options

As a result of these properties, detection approaches for neutrons fall into several major categories:[3]

- Absorptive reactions with prompt reactions - low energy neutrons are typically detected indirectly through absorption reactions. Typical absorber materials used have high cross sections for absorption of neutrons and include helium-3, lithium-6, boron-10, and uranium-235. Each of these reacts by emission of high energy ionized particles, the ionization track of which can be detected by a number of means. Commonly used reactions include ^{3}He(n,p) ^{3}H, ^{6}Li(n,α) ^{3}H, ^{10}B(n,α)^{7}Li and the fission of uranium.

- Activation processes - Neutrons may be detected by reacting with absorbers in a radiative capture, spallation or similar reaction, producing reaction products that

then decay at some later time, releasing beta particles or gammas. Selected materials
(e.g., indium, gold, rhodium, iron (^{56}Fe(n,p) ^{56}Mn), aluminum(^{27}Al(n,α)^{24}Na), niobium (^{93}Nb(n,2n) ^{92m}Nb), & silicon (^{28}Si(n,p) ^{28}Al)) have extremely large cross sections for the capture of neutrons within a very narrow band of energy. Use of multiple absorber samples allows characterization of the neutron energy spectrum. Activation also allows recreation of an historic neutron exposure (e.g., forensic recreation of neutron exposures during an accidental criticality).

- Elastic scattering reactions (also referred to as proton-recoil) - High energy neutrons are typically detected indirectly through elastic scattering reactions. Neutron collide with the nucleus of atoms in the detector, transferring energy to that nucleus and creating an ion, which is detected. Since the maximum transfer of energy occurs when the mass of the atom with which the neutron collides is comparable to the neutron mass, hydrogenous[4] materials are often the preferred medium for such detectors.

Types of neutron detectors

Gas proportional detectors

Gas proportional detectors can be adapted to detect neutrons. While neutrons do not typically cause ionization, the addition of a nuclide with high neutron cross-section allows the detector to respond to neutrons. Nuclides commonly used for this purpose are helium-3, lithium-6, boron-10 and uranium-235. Since these materials are most likely to react with thermal neutrons (i.e., neutrons that have slowed to equilibrium with their surroundings), they are typically surrounded bymoderating materials.

Further refinements are usually necessary to isolate the neutron signal from the effects of other types of radiation. Since the energy of a thermal neutron is relatively low, charged particle reaction is discrete (i.e., essentially monoenergetic) while other reactions such as gamma reactions will span a broad energy range, it is possible to discriminate among the sources.

As a class, gas ionization detectors measure the number (count rate), and not the energy of neutrons.

^{3}He gas-filled proportional detectors

An isotope of Helium, ^{3}He provides for an effective neutron detector material because ^{3}He reacts by absorbing thermal neutrons, producing a ^{1}H and ^{3}H ion. Its sensitivity to gamma rays is negligible, providing a very useful neutron detector. Unfortunately the supply of ^{3}He is limited to production as a byproduct from the decay of tritium (which has a 12.3 year half-life); tritium is produced either as part of weapons programs as a booster for nuclear weapons or as a byproduct of reactor operation.

BF_3 gas-filled proportional detectors

As elemental boron is not gaseous, neutron detectors containing boron may alternately use boron trifluoride (BF_3) enriched to 96% boron-10 (natural boron is 20%^{10}B, 80% ^{11}B). It should be noted that boron trifluoride is highly toxic.

Boron lined proportional detectors

Alternately, boron-lined gas-filled proportional counters react similarly to BF_3 gas-filled proportional detectors, with the exception that the walls are coated with ^{10}B. In this design, since the reaction takes place on the surface, only one of the two particles will escape into the proportional counter.

Scintillation neutron detectors

Scintillation neutron detectors include liquid organic scintillators, crystals, plastics, glass and scintillation fibers.

Neutron-sensitive scintillating glass fiber detectors

Scintillating ^{6}Li glass for neutron detection was first reported in the scientific literature in 1957 and key advances were made in the 1960s and 1970s. Scintillating fiber was demonstrated by Atkinson M. *et al.* in 1987 and major advances were made in the late 1980s and early 1990s at Pacific Northwest National Laboratory where it was developed as a classified technology. It was declassified in 1994 and first licensed by Oxford Instruments in 1997, followed by a transfer to Nucsafe in 1999. The fiber and fiber detectors are now manufactured and sold commercially by Nucsafe, Inc.

The scintillating glass fibers work by incorporating ^{6}Li and Ce^{3+} into the glass bulk composition. The ^{6}Li has a high cross-section for thermal neutron absorption through the ^{6}Li(n,α) reaction. Neutron absorption produces a tritium ion, an alpha particle, and kinetic energy. The alpha particle and triton interact with the glass matrix to produce ionization, which transfers energy to Ce^{3+} ions and results in the emission of photons with wavelength 390 nm - 600 nm as the excited state Ce^{3+}ions return to the ground state. The event results in a flash of light of several thousand photons for each neutron absorbed. A portion of the scintillation light propagates through the glass fiber, which acts as a waveguide. The fibers ends are optically coupled to a pair of photomultiplier tubes (PMTs) to detect photon bursts. The detectors can be used to detect both neutrons and gamma rays, which are typically distinguished using pulse-height discrimination. Substantial effort and progress in reducing fiber detector sensitivity to gamma radiation has been made. Original detectors suffered from false neutrons in a 0.02 mR gamma field. Design, process, and algorithm improvements now enable operation in gamma fields up to 20 mR/h (^{60}Co).

The scintillating fiber detectors have excellent sensitivity, they are rugged, and have fast timing (~60 ns) so that a large dynamic range in counting rates is possible. The detectors have the advantage that they can be formed into any desired shape, and can be made very large or very small for use in a variety of applications.Further, they do not rely on ^{3}He or any raw material that has limited availability, nor do they contain toxic or regulated materials. Their performance matches or exceeds that of ^{3}He tubes for gross neutron counting due to the higher density of neutron absorbing species in the solid glass compared to high-pressure gaseous^{3}He. Even though the thermal neutron cross section of ^{6}Li is low compared to ^{3}He (940 barns vs. 5330 barns), the atom density of ^{6}Li in the fiber is fifty times greater, resulting in an advantage in effective capture density ratio of approximately 10:1.

$LiCaAlF_6$

$LiCaAlF_6$ is a neutron sensitive inorganic scintillator crystal which like neutron-sensitive scintillating glass fiber detectors makes use of neutron capture by ^{6}Li. Unlike scintillating glass fiber detectors however the ^{6}Li is part of the crystalline structure of the scintillator giving it a naturally high ^{6}Li density. A doping agent is added to provide the crystal with its scintillating properties, two common doping agents are cesium and europium. Europium doped $LiCaAlF_6$ has the advantage over other materials that the number of optical photons produced per neutron capture is around 30.000 which is 5 times higher than for example in neutron-sensitive scintillating glass fibers.This property makes neutron photon discrimination easier. Due to its high ^{6}Li density this material is suitable for producing light weight compact neutron detectors, as a result $LiCaAlF_6$ has been used for neutron detection at high altitudes on balloon missions.The long decay time of Europium doped $LiCaAlF_6$ makes it less suitable for measurements in high radiation environments, the cesium doped variant has a shorter decay time but suffers from a lower light-yield.

Semiconductor neutron detectors

Semiconductors have been used for neutron detection.

Neutron activation detectors

Activation samples may be placed in a neutron field to characterize the energy spectrum and intensity of the neutrons. Activation reactions that have differing energy thresholds can be used including ^{56}Fe(n,p) ^{56}Mn, ^{27}Al(n,α)^{24}Na, ^{93}Nb(n,2n) ^{92m}Nb, & ^{28}Si(n,p)^{28}Al.

Fast neutron detectors

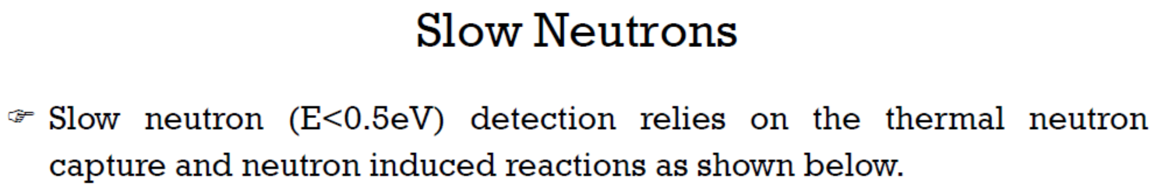
Fast neutrons are often detected by first moderating (slowing) them to thermal energies. However, during the slowing-down process the information on the original energy of the neutron, its direction of travel, and the time of emission is lost. For many applications, the detection of “fret” neutrons that retain this information is highly desirable.

Typical fast neutron detectors are liquid scintillators, 4-He based noble gas detectors and plastic detectors. Fast neutron detectors differentiate themselves from one another by their 1.) capability of neutron/gamma discrimination (through pulse shape discrimination) and 2.) sensitivity. The capability to distinguish between neutrons and gammas is excellent in noble gas based 4-He detectors due to their low electron density and excellent pulse shape discrimination property.

Detection of fast neutrons poses a range of special problems. A directional fast-neutron detector has been developed using multiple proton recoils in separated planes of plastic scintillator material. The paths of the recoil nuclei created by neutron collision are recorded; determination of the energy and momentum of two recoil nuclei allow calculation of the direction of travel and energy of the neutron that underwent elastic scattering with them.

Background noise

The main components of background noise in neutron detection are high-energy photons, which aren't easily eliminated by physical barriers. The other sources of noise, such as alpha and beta particles, can be eliminated by various shielding materials, such as lead, plastic, thermo-coal, etc. Thus, photons cause major interference in neutron detection, since it is uncertain if neutrons or photons are being detected by the neutron detector. Both register similar energies after scattering into the detector from the target or ambient light, and are thus hard to distinguish. Coincidence detection can also be used to discriminate real neutron events from photons and other radiation.



Slow Neutrons

- ☞ Slow neutron (E<0.5eV) detection relies on the thermal neutron capture and neutron induced reactions as shown below.

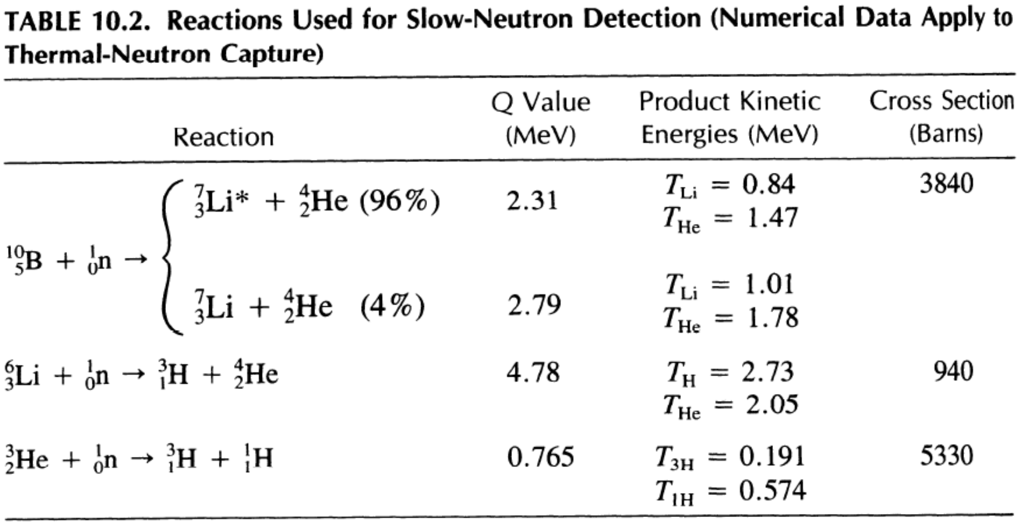


TABLE 10.2. Reactions Used for Slow-Neutron Detection (Numerical Data Apply to Thermal-Neutron Capture)

Reaction	Q Value (MeV)	Product Kinetic Energies (MeV)	Cross Section (Barns)
$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li^{*} + ^{4}_{2}He$ (96%)	2.31	$T_{Li} = 0.84$ $T_{He} = 1.47$	3840
$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + ^{4}_{2}He$ (4%)	2.79	$T_{Li} = 1.01$ $T_{He} = 1.78$	
$^{6}_{3}Li + ^{1}_{0}n \rightarrow ^{3}_{1}H + ^{4}_{2}He$	4.78	$T_{H} = 2.73$ $T_{He} = 2.05$	940
$^{3}_{2}He + ^{1}_{0}n \rightarrow ^{3}_{1}H + ^{1}_{1}H$	0.765	$T_{3H} = 0.191$ $T_{1H} = 0.574$	5330

Slow Neutrons

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

- ☞ Proportional counter with boron trifluoride (BF_3) gas (enriched in ^{10}B) is one of the most used slow neutron detector.
- ☞ BF_3 proportional counter can discriminate against gamma rays.

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

- ☞ Compared with $^{10}B(n,\alpha)$ reaction, $^{6}Li(n,\alpha)$ reaction has smaller cross section → lower efficiency, but greater Q-value → better discrimination against gamma ray background.
- ☞ LiI(Eu) scintillator is frequently used for slow neutron detection.

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

- ☞ Highest cross section → good efficiency.
- ☞ ^{3}He is a better counter gas and can be operated at higher pressure.
- ☞ Low Q-value → worse gamma discrimination.

Intermediate and Fast Neutrons

In general there are four groups of detection methods – **neutron moderation**, **nuclear reaction**, **elastic scattering** and **foil activation**.

Neutron Moderation

- ☞ Two types – long counter and moderating sphere enclosing a small thermal-neutron detector.

Intermediate and Fast Neutrons

Nuclear Reaction

- ☞ The $^{6}Li(n,\alpha)$ and $^{3}He(n,p)$ reactions are the only ones of major importance for neutron spectroscopy.

Intermediate and Fast Neutrons

Elastic Scattering

- ☞ A number of neutron detection instruments are based on elastic scattering alone, especially from hydrogen.
- ☞ One example is the proton-recoil telescope for measuring the energy of neutrons.