­­Neutron detectors

Neutron sources

Neutrons are particles with zero net charge. They appear in laboratories from …, airplane highs due to …, nuclear reactors, nuclear weapons and more. The last years there has been a growth of fields dealing with neutrons: storage of nuclear waste, search for illicit trafficking and hidden nuclear materials, and increased awareness in aviator hights(?).

The He-3 gas counter widely used, but there is a shortage of He-3. Motivation for developing alternative neutron detection methods. Gd- up and coming? Increased focus on Gd?

Neutrions are ahdronic particles contituing three quarks whos charge sum equals zero. In other words the neutron has no charge and does not interact through electromagnetic forces. IT does, owever interact with the hadronic force, which is strong, but has a very short range (10^-15m). Because it doesn’t interact with matter through electromagnetic force it does not ionize matter. It does however ionize indirectly. Neutrons may interact through hadorinc processes, which produce otherparticles (of charge) such as electrons and protons, and these are directly ionizing particles. Neutrons must therefor first be converted into otherparticles to be detected. This is done us­­ing a convertermaterial. The converte material may be gad, liwuid or solid.

The most common neutron detector is the gas proportional counter (?). A widely used convertermaterial is He-3 which brings many good qualities such as high count rate, fast countrate(?), A gas chamber is only a counter and does not give information about energy deposition.

Information about neutron energy is difficult to track and is still being developed?? (find any ref?)

The most common use of neutron detectors are counters. Active counters are gas, solid-state and scintillators.

Gas detectors (1/4) (particles of interest?, pros and cons? Set up? Most popular design? Cost? Efficiency?)

Scintillation (1/4)

Solid state (2/4)

There are many diffrent types of neutron detectors and the requirements for each is depedent on their field of use. For instance, in dosimetry a high persistion energy resolution and spatial resolution is required to give an accurate treatmentplan. On the other hand, energy deposition is not of interest in fields where only the activity of neutron flux is of intterest, such as in nuclear reactor monitoring to reulate neutrons bombarding fissile material.

The use of detect

Gas

Solid state

Scintillators

Requirements

Speed

Efficiency

Energy deposition

Spatial resolution

Convertermaterial

He-3

Gd

B-10

Li-6

??

Active

Passive

Examples

Nuclear Weapsons

Illicit trafficking and hidden nuclear materials

Radiation safety

Nuclear reactors

Nuclear storage

Neutron sources

Neutrons

Zero net charge

Indirecyly ionizing

Strongly penetrating radiation

Nuclear reaction

Reaction products

Q-value

Thermal energy

Neutron energy

Reaction cross section

What are neutrons?

**FOREWORD(?)**

This thesis focuses on semiconductor neutron detectors, an active neutron detection method. For this reason a brief introduction is given for passive detectors followed by a more extensive description of active detectors. Furthermore, a separate section/chapter is dedicated to semiconductors in addition to its mention in this section.

**WHY DETECT NEUTRONS?**

* There are many fields(?) in physics dealing with neutrons in which detecting neutrons is essential(?).(3 examples why. There are plenty more, but no need to list them all)
* The following exemplify the vast scope of neutron detection application.
* Nuclear Reactors (read more about this)
  + Are dependent on neutron detection to regulate and monitor oporations???
  + Neutron induced reactions, U-235.
  + Produce two/three neutrons
  + Cascade of reactions, exponential growth of neutrons(?)
  + If incident neutron flux too high, cascade escalates out of hand and it can have lethal consequences(?) .
  + E.g. Hiroshima?
  + Monitoring neutron flux allows us to keep reactor in stable conditions and calibrate neutron flux as needed to *prevent* *accidents*/ *maintain controll*.
  + Reference?
* Nuclear weapons (read more)
  + Contain traces of unstable radionuclides?
  + Many nuclear materials produces alpha, beta, gamma and neutrons. The first three are easy to shield, neutrons less so.
  + Neutron detection methods are therefore beneficial in the search of illicit trafficking of nuclear and other radiative materials.
  + neutron detection is an essential part of a comprehensive nuclear security program to prevent nuclear proliferation and possible construction of nuclear devices.
  + E.g. Plutonium (?)
  + Reference?
* Due to the development of new fields dealing with neutrons, for instance neutron spallation sources, neutron detection has become increasingly important
  + ESS??
  + What do they do
  + Why do they want/ is it important for them to track neutrons?
* Neutron imaging (ref. M Strobl 2019)
* Moreover, the detection of neutrons has allowed for the development of neutron imaging, a technique complementary to x-rays and other types radiation. Unlike x-rays, neutron attenuation does not depend on the atomic number of the penetrated material. Imaging with neutrons can therefor reveal structural information unattainable by x-rays. For instance, blood vs bones (synonyms for neutron imaging)
* A neutron imaging is a non-invasive analyzing tool and has been of great benefit to fields like biology, geography archeology, to name a few.
* The scope of neutron detection applications is wide. These are just a few examples and it would be difficult to summarize them all. (ref. to reviews of neutron detections applications?)

**NEUTRONS**

* Have Zero net charge
* Are penetrating particles (penetrating radiation)
* Interact with hadronic force
* Have a short interaction range (10^-15m)
* Do not interact electromagnetically
* Are Indirectly ionizing (non-ionizing)
* Allow for non-destructing and non-invasive(?) imaging instruments

**BASIC NEUTRON INTERACTION** (new chapter?)

* Summary of neutron interaction with matter
* Reaction depends highly on neutron energy
* Scatter and nuclear reactions
* *The neutrons intrinsic characteristics (causes it to react differently with matter than charged particles) and therefor set different requirements for a detectors.*

**HOW TO DETECT NEUTRONS? (write after types of detectors)**

* Most (all?) particle detectors are based on ionization (NO NOT SCINTILLATORS?) to produce a signal. An incoming particle strikes the detectors sensitive volume and by electromagnetic forces creates signal generating charge carriers (electrons).
* Neutrons have zero net charge and does not interact electromagnetically with material, they cannot not ionize material directly.
* Neutrons can, however, be converted to charged particles which in turn (?) activate a signal in the detector.
* Neutron detection relies on reaction products of neutron conversion as neutron indicators.
* Because of this necessity of conversion, neutron detection is more difficult and complex than photon or charged particle detection.

**CONVERTER MATERIALS**

* Must attribute high neutron abos. Prob?
* General properties of neutron converters
  + High Q-value so that production particles have high kinetic energy and are thus easier to detect, high cross section
* Popular materials are He-3 Li-6, B-10 and Gd-157/155, due to their high Q-value and/or high cross section.
* Neutron capture: Reaction equation, Q-value, cross section, cost, availability, abundancy
* He-3
  + Q-value: 0.764 MeV
  + Reaction equations:
  + Thermal Cross-section: 5330 barns
    - higher than B-10
    - Falls off 1/v
  + Abundancy: 0.000138% ([\*](https://physics.nist.gov/PhysRefData/Handbook/Tables/heliumtable1.htm))
  + Availability:
    - most commonly used,
    - After 9.11 increased demand in security against smuggled nuclear and radiological material
    - Caused a worldwide shortage and dramatic increase in cost. ([\*](https://fas.org/sgp/crs/misc/R41419.pdf))
    - Request to He-3 proportional counter alternatives has become a prominent topic of research in contemporary nuclear instrumentation (“”)
* Li-6
  + Q-value: 4.78 MeV
  + Reaction equations:
  + Thermal Cross-section: 940 barns
    - Less than B-10
    - Greater Q than B
    - Resonance region >100keV
    - Falls off 1/v
  + Abundancy: 7.50% ([\*](https://physics.nist.gov/PhysRefData/Handbook/Tables/lithiumtable1.htm))
  + Availability:
    - widely available in separate forms, but no usable gaseous compounds
    - not as versatile as boron (more research)
* B-10
  + Q-value:
    - 2.792 MeV (ground state)
    - 2.310 MeV (excited state)
  + Reaction equations:
  + Thermal Cross-section: 3840 barn
    - Drops 1/v (neutron velocity)
  + Abundancy: 19.9% ([\*](https://physics.nist.gov/PhysRefData/Handbook/Tables/borontable1.htm))
  + Availability:
    - Occurs in a variety of forms, very versatile
    - very accessible (“readily available”) (more research)
* Gd-157 (Gd-155)
  + Q-value: 7.9 MeV (8.5 MeV)
  + Reaction equations:
  + Thermal Cross-section: 255,000 barns (60900 barns)
    - Highest of all stable isotopes (ref! I know I have one)
    - Resonance at 31.4 meV (26.8 meV)
  + Abundancy: 15.7% (14.8%)
  + Availability: cost not overly prohibited?
  + Gamma ray background more problematic than for capture materials.
  + Historically used as neutron poison in nuclear reactors
  + Composites of neutron shielding alloys for nuclear reactor safety and fissile material storage
* Gadolinium (another chapter): short summary

**TYPES OF NEUTRON DETECTORS?**

* There are many different methods for detecting neutrons. They can be grouped into two categories: active and passive.
* Passive methods yield information after irradiation is complete.
* In contrast, active methods monitor neutron presence in real time.
* Examples of **passive detectors** are: thermoluminescent, etched-track, and nuclear-emulsion detectors
* Passive detectors do not need a power supply, do not experience any electromagnetic interference and respond well to high-energy radiations. For these reasons, passive detectors are commonly used in areas involving high-energy dosimetry.
* Nuclear track emulsion is the oldest method of neutron personal dosimetry. ([\*](https://watermark.silverchair.com/nch129.pdf?token=AQECAHi208BE49Ooan9kkhW_Ercy7Dm3ZL_9Cf3qfKAc485ysgAAApIwggKOBgkqhkiG9w0BBwagggJ_MIICewIBADCCAnQGCSqGSIb3DQEHATAeBglghkgBZQMEAS4wEQQMmjOgYv5S7D7kdhETAgEQgIICRbTB5j39f9ufWccHJM0DDGB1k7UuRgKZQRlBdKhbpBgB8Xs9hz6Y0uw4iV7-IMFBvsYbM_yM5OcllScoEIHVDsmN8J51lBXAGE3hjX_E8OAHq-7S79rnPndj3jD2uuw56FLqEGbYby2tA0x1Te1bjRftELelKcUKYrRQobCoLaJLwGWrcOfZgyMQ-hWO_wKAlxvL7cKuV7MygjcPjbWVUVwHNRjWPkx9xMGrVc_RPKR48__vi1laCF5_4HHxXQgEraqOSw_3eaFGOWqTtUFeJKBagkqHCakGd9xYTcU5EZFjOW7fSEnT9Zs7LFD3-IZy5mhSU3wT2arZ4RR4VTwoyjFfa7rlXLBjAZ-EfNGah1h6WOwQYTm5POUge6SDun5aUSXiW07G3UOY2DTwcB9Z_4720Q6pWVuStJUQy-GjIhXUqNNZemXkOPGwaAy2O6fC4oyBtU4xR1Syviodw-LywtVqq2i2-UQ4Ph4zfz0c5ZskCBXmDCLNDJt5JioY7aoRoNQKWkYqYsh3HgM-C3-o7HJFDIUL4xKysyY78pfW9b3wQAjob8_uQrfO8IjC5G3225ULuHIrjph8xWCd8-7WSNxXqeQ2j3Sc6MMvIioISJBjNXA1n_MxHx4ZsgL1Po6Cy-ec5KHFh2nPyxRyQKyNECKf-vDxgf0W9WuRI4WrHuIvVtuLqq4F8J0kSC5ZPvV3qaso07tofTcMF4GoA8BOSmVT2xmHghlalLnAqiVAyn45ce6sCxQB6SuA5s6UhN6THOJa6Jfx))
* The most important **active methods** are those using gaseous detectors, scintillators and semiconductor detectors.
* Active neutron detection methods have a wide range of applications like tracking movement of water in plants, providing compositional information on metallic cultural artifacts, and determining the structure of crystalline solids (Kilde: Advances in neutron radiography and tomography). + other examples than just imaging
* A relatively new development is active personal dosimeters (APD). Even though they compete with passive methods, there is still progress to be made with respect to energy-dependency.

Form

* Basic principle
* As a neutron detector
  + examples
* Application
* Pros/cons

**GAS-FILLED DETECTORS**

* Basic principle?
  + Ionization of the gas, Creation of ion pairs by high energy charged particles
  + Charged collected and measured by the collector plate
* Types: ionization chambter, proportional counters, geigermuller
  + Geigermuller not easily adaptbale to direct detection of neutrons, butoften used to measure gamma radiation induced by neutrons. (?)
  + Differe in operational voltage.
  + Increasig voltage increases sensitivity, can also cause higher signal to noise ratio,
* Nobel gases well suited for counting gases
* Most important counting gass: He-3, BF\_3
* He-3 is most commonly used in proportional counters.
* BF\_3 smaller pulse high than He-3 but better gamma discrimination. Detection efficiency of BF\_3 proportional counters can be increased with enriched boron.
* He-3 coslty and scars, BF\_3 is toxic and corrosive
  + Pros: high Q-value such that charged particles exceed detection thresholds, good detection efficiency (up to 90%)
  + Cons.: Shortage of He-3 (and expensive?) (find ref)
* Cons: bulky and expensive to use

**SCINTILLATORS**

* Basic principle? (doped scintillator material, photomultiplier tube to enhance the signal
* Of various types are seen as an alternative to gaseous detectors.
* Are sensitive to amount of energy deposited
* Pros: easy to operate, cheap, robust, fast (can be used for time of flight measurements)
* Cons: prone to radiation damage (?), problems w/ magnetic fields(?), poor neutron-gamma separation, aging effects
* Application: used in neutron imaging, spacious, CCD cannot lie in neutron path, therefor semiconductors are better.

**SEMICONDUCTORS (+ chapter)**

* Basic principle:
  + Ionization of active volume.
  + Generation of charge carriers (information carriers) analogous to electron ion pair in gas-filled detectors.
  + Produce more information carries and thus have a greater energy resolution.
* Practically available in 1960 (Ref. Glenn Knoll(nødvendig å ha med?))
* The primary semiconductor material is silicon. Such detectors operate sufficiently in room temperature, while detectors based on germanium need cooling to minimize thermally generated current leakage (explain what this is or mention in section with semiconductor?).
* Its compact size is preferable in medical imaging, above the bulky scintillator, however, the limitation thereof is negative in applications requiring large detector surfaces. / Are compact and small in size, one of the reasons making them more desirable than large, bulky gas-filled detectors.
* Pros: compact, lightweight, less expensive to fabricate, operates at lower voltages
* Cons: ?

Scintiallators (#2)

* A scintillator consist of x main components: a scintillating material, a photomultiplier tube and electronic readout system (?)
* Scintilating materials possess lightemitting characteristics. The light produced by a scitilator strikes a ?? causing photoelectric effect to take place. Photo electrons are emitted on the opposite side of ??, inside the photomuliplier tube.
* A photomultiplier tubes job is to increase the number of electrons inside the tube. The basic photonmuliplier tube is ?? shaped and a votlage is applied between each end. Along the tube are anodes/cathods/diodes(?) Photoelectrons from the ?? are accelerated by the applied electroc field towards the first ??. Once again, the photoelectric prosecco takes place and creates more electrons. Typically one electron yields ?? new electrons. The bundle of old and newly created photoelectrons accelerate towards the next ?? and yet again the electron population increases. This electron multiplication process contunies all the way down the tube until the end is reach where the cathod collect the electrons and produces an electronical signal. A typical photomultiplier tube can magnification of ??! Usually there is no need to futher amplify the signal after this.
* Electrical read out system collect the amplified electron signal and generates a pulse signal.
* There two types of scintillators, organic and inorganic. Because of theyr structural composition energy is released differelty.
* In organic scintillatros are different
* Inorganic scintillators consist of larger molecules. Where the excitation of a molecule then leads to the production of light. However, not all of the particles energy is guaranteed to translate into photoemission. Molecules may release energy through other channels such as vibrational or thermal energy.
* Conclusion? Not as effective? Pros and cons? Relevant?
* In contrast to organics types of
* Incomming charged particles interact with the scintillation material

Neutron detectors

* Boron lines proportional counter
* BF\_3 filled proportional counter
* LI scintillator
* He-3 filled proportional counter(?)

New structure build up arguemtns to be able to describe state of the art neutron detectors

* Basic principles of particle detectors
  + Gas
    - Counters: def.
    - Ionization, prop and geiger
  + Scint
  + semi
* Neutron reactions:
  + Energy
  + cross section and Q-value
  + Reactions used in neutron detection
* State of the art neutron detectors
  + ??

In principle any particle detector can be turned into a neutron detector. Therefor a breif introduction to the most common particle detectors is in place.

Gas

Scint

Semi

These detectors are initially oblivious to non-ionizing radiation such as neutrons. However, by incorporating a **converter material** to the design it allows for indirect detection thereof.

To ensure good quality neutron signals the conversion material must meet certain standards. First and foremost, it is essential that the material possesses a high probability of neutron interaction. The ideal situation would be 100% neutron detection, no neutrons going unseen. Nevertheless, this is usually not the case since some neutrons pass through the conversion material unaffected or react in other non-signal generating ways. High neutron reaction probability is therefore an essential characteristic of the conversion material to ensure a high detection efficiency.

Another …. Q-value