X-Ray & Slow Neutron Detectors

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This document has been published in

Manuel Angst, Thomas Brückel, Dieter Richter, Reiner Zorn (Eds.):
Scattering Methods for Condensed Matter Research: Towards Novel Applications at Future Sources
Lecture Notes of the 43rd IFF Spring School 2012
Schriften des Forschungszentrums Jülich / Reihe Schlüsseltechnologien / Key Technologies, Vol. 33
JCNS, PGI, ICS, IAS
Forschungszentrum Jülich GmbH, JCNS, PGI, ICS, IAS, 2012
ISBN: 978-3-89336-759-7

C 5 X-Ray & Slow Neutron Detectors

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Contents

Lecture Notes of the 43rd IFF Spring School "Scattering Methods for Condensed Matter Research: Towards Novel Applications at Future Sources" (Forschungszentrum Jülich, 2012).

1 Introduction

This lecture is about radiation detectors, which are used for the detection of X-rays and slow neutrons. After a short review of the relevant interactions of X-rays and neutrons with matter, the basic operating principles of these detectors and their specifics for X-ray and slow neutron detection will be described. However, neither all details of these detectors nor their application in different research area can be covered within this lecture. The books, listed in the references serve for this purpose. While references [1]-[3] give a comprehensive introduction and overview of the different types of radiation detectors, references [4] and [5] are specialized to semiconductor and scintillation detectors.

2 X-Ray and Slow Neutron Interactions with Matter

The common detection principle of radiation detectors is based on the ionization of the detector material, which gives rise to an electrical signal to be measured by signal processing electronics. As the ionization is due to the interaction of the particle radiation with matter, these interactions need to be known for an understanding of the radiation detectors. The following section gives a brief review of the interactions of X-ray and neutron radiation with matter, which are relevant for radiation detectors.

2.1 The interactions of X-Ray and Gamma-Radiation

For radiation detectors, there are three important interactions of X-rays or gammas with matter (see Fig. 1).

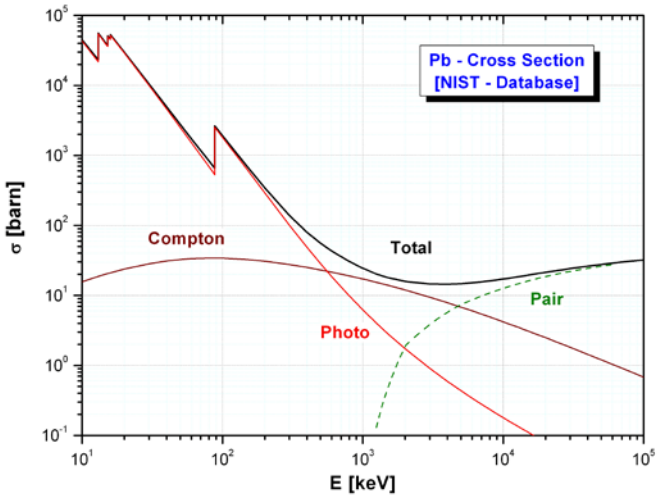

Fig. 1: Cross sections of the important interactions of X-ray and gamma radiation with matter, giving lead as example.

At X-ray energies up to about 100 keV, the photoelectric effect is dominant. There, an incident photon is absorbed by an atom and an electron is ejected. Due to energy and momentum conservation, the atom takes a part of the photon momentum. Thus, always the possible strongest bound electrons absorb the photon. As a result of the de-excitation of the

atom, a characteristic fluorescense photon or, especially at higher Z, Auger electrons are emitted. The higher the X-ray energy becomes, the electron appears to be less bounded for the photon. Therefore, there is a strong decrease of the cross section with increasing energies and a competitive effect, the Compton scattering, becomes important up to energies of 5 MeV. Compton scattering is incoherent scattering on a quasi-free electron of an atom accompanied by an energy and momentum transfer from the photon to the electron. At energies above 1.02 MeV, a third process called pair production gets relevant. Pair production is the process of creation of an e^+/e^--pair, mostly in the field of the nucleus. As the e+ is not stable in matter, it annihilates after stopping into two 0.51 MeV photons.

2.2 Converter Materials for Slow Neutrons

Slow neutrons are understood to have energies of up to some 100 meV. As neutrons don't have an electrical charge, they cannot produce ionisation by electromagnetic interactions. Furthermore, slow neutrons don't have the energy to built such ionization by collisions. Thus, the only method to detect slow neutrons is by nuclear reactions, where the neutron is captured by the nucleus following secondary particles with high energies, which are able to ionize the detector material. So, neutrons need to be 'converted' to some secondary particles which are able to be detected.

The most important nuclear capture reactions for neutron detection are based on the following isotopes:

$$
\begin{array}{lcll}
^{10}B + n & \rightarrow & ^{7}Li + \alpha + 2.78\ MeV \quad (6\%) & \\
 & \rightarrow & ^{7}Li^{*} + \alpha + 2.31\ MeV \quad (94\%) & \rightarrow \quad ^{7}Li + \alpha + \gamma\ (0{,}48\ MeV) \\
^{6}Li + n & \rightarrow & ^{3}H + \alpha + 4.78\ MeV & \\
^{3}He + n & \rightarrow & ^{3}H + p + 0.764\ MeV & \\
^{155}Gd + n & \rightarrow & ^{156}Gd^{*}\ (8.54\ MeV) & \rightarrow \quad ^{156}Gd + \gamma\text{'s} + \text{ce's} \\
^{157}Gd + n & \rightarrow & ^{158}Gd^{*}\ (7.94\ MeV) & \rightarrow \quad ^{158}Gd + \gamma\text{'s} + \text{ce's}
\end{array}
$$

The capture cross sections of these isotopes for different energies are shown in Fig. 2. It is not only sufficient to offer a high cross section for neutron capture, but the secondary particles should also deposit sufficient energy for the detection. A large amount of ionization favours the discrimination against gamma-radiation.

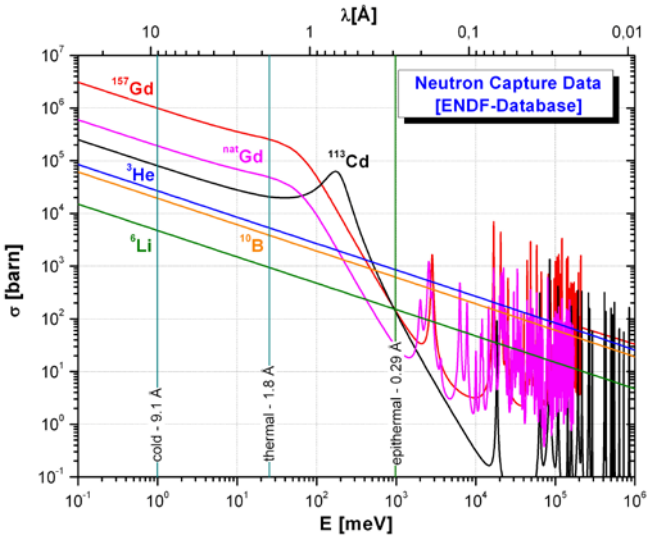

Fig. 2: Capture cross sections of the most important isotopes that are used as converter materials for slow neutrons. ^{113}Cd is also shown for comparison, because it is often used as shielding material.

3 Gaseous Detectors

The principle of operation for gaseous detectors is based on the ionization of gas by particle radiation within an electric field. The ions and electrons are moving to the electrodes by the electric field and induce a signal which can be detected by detector electronics. X-rays create this ionization by photoeffect, Compton-scattering or pair production. Neutrons create this ionization by nuclear reactions.

There are different operation regions for gaseous detectors in dependence of the applied electric field (voltage). The different regions are shown in Fig. 3.

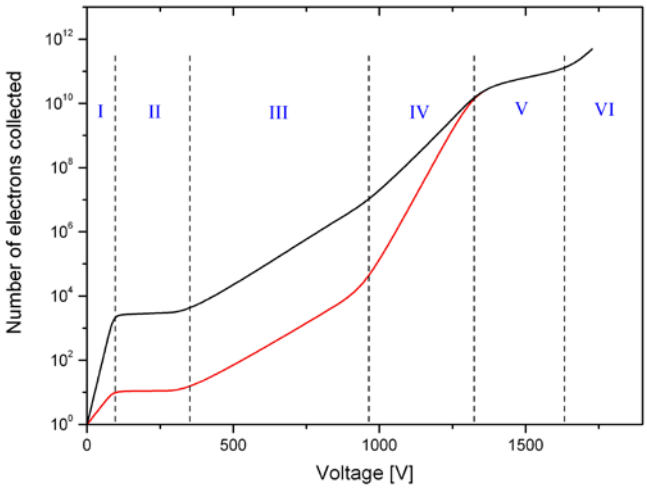

Fig. 3: Number of electrons collected per incident photon, illustrated for two different primary ionisations (e.g. two different photon energies)

Region I is called the recombination region. Here, the electric field is so low, that ion pairs partly recombine. The result is, that only a part of the charge carriers contribute to the pulse height of the detector. In region II, the ionisation region, all primary charge carriers are accumulated, within some range independent of the applied voltage. By rising the electric field in region III, further ionisation is produced by collision of the charge carriers. The gain of this amplification rises exponentially (avalanche), but the curves of different primary ionization are almost proportional to each other. In region IV the amplification gets more independent of the primary ionization. The proportionality between different primary ionizations is limited. Region V is called the Geiger-region. There is a number of charges collected, independent of the primary ionization. In region VI the electric field is so high, that discharges occur.

3.1 Ionization chamber

The ionization chamber is the simplest gaseous detector, which utilizes region II in the description above. An ionization chamber consists of a gas-filled parallel plate capacitor. In case of ionization by incident radiation, the electrons and ions are drifting separately to the anode and cathode. During this process a current is produced, which could be measured as a voltage signal.

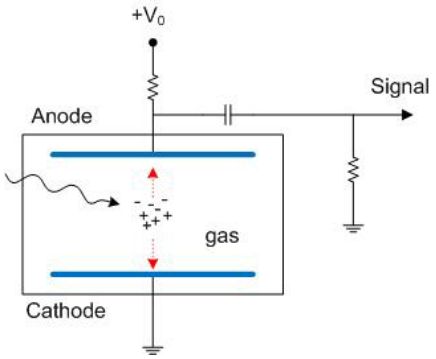

Fig. 4: Sketch of the operating principle of an ionization chamber.

The currents that need to be measured with ionization chambers are usually extremely small. If we assume that there are 1000 electron tracks per second in the gas volume and that each track is 2 cm long, the corresponding current is about 18 x 10^{-15} A. This ionization current causes a voltage drop over a resistor, which can be measured with a sensitive voltmeter (DC electrometer). The values of the resistors used are typically between 10^{9} Ω and 10^{12} Ω. Without adequate precautions by usage of guard rings the leakage current in the system could be much larger that the ionization currents one wants to measure.

Today, battery operated portable ionization chambers are commonly used as radiation monitoring instruments to measure gamma ray exposure. Then, the total charge pulse corresponding to one electron trajectory of a few centimeters long corresponds to only a few 100 electron charges. However, an ionization chamber can also be used to measure the concentration of air-borne alpha emitters (e.g. in smoke detectors). An alpha particle of 3.38 MeV will produce about 10^{5} electron–ion pairs in air. This is still a very small electrical pulse, but large enough to be observed with suitable low noise electronics.

3.2 Proportional Counter

Proportional counters work in the region with proportional charge multiplication (region II). Such detectors are made of a conductive cylinder with a thin wire in its centre. While the tube is at ground potential, a large positive voltage is applied to the anode wire.

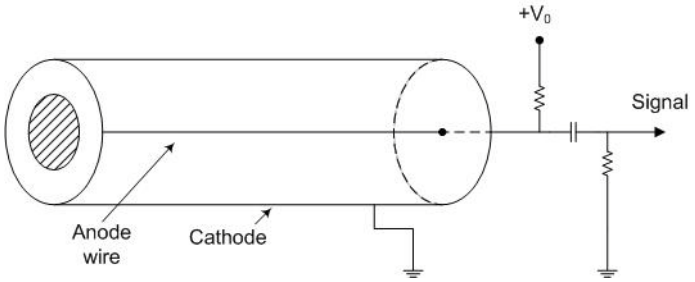

Fig. 5: Basic construction of a proportional counter tube.

The electric field for such a configuration shows a 1/r dependence. At large r the field is relatively weak, but becomes very high close to the surface of the wire. If ions and electrons are created in the cylindrical volume, they will simply drift towards their respective electrodes. But, if the electrons are very close to the wire, they are heavily accelerated by the high electric field, which leads to further ionization and finally to a charge avalanche. Regardless of where the ionizing event occurs, all multiplication takes place in a small region around the anode. The electrons of the avalanche are collected very quickly (~1ns) while the positive ions begin drifting towards the cathode. This ion drift is mainly responsible for the pulse signal on the anode wire.

The choice of filling gas is determined by several factors. High gain at low voltages, good proportionality and high rate capability are favorable properties. These conditions are generally achieved by gas mixtures rather than by pure gases.

Proportional counters are suitable for the detection of X-rays. The interaction probability of X-rays in argon drops to a very low value above 20 keV. With krypton or xenon, sizeable detection efficiencies up to100 keV can be obtained. For X-rays of the order of 10 keV, the photoelectron can be fully contained in the gas and the counter signal will be proportional to the energy of the X-ray. The energy resolution that can be obtained depends on the number of primary electron–ion pairs formed. However, the fluctuations on this number are not well described by Poisson statistics. The fact that the total energy used to create electron–ion pairs must equal the energy of the gamma reduces the fluctuations. The energy resolution of X-rays of 5.89 keV in argon is about 11% FWHM.

For neutron detection, either $^{10}BF_3$ or ^{3}He gas can be used. The incoming neutron reacts with the boron or helium isotope by a nuclear reaction to form the secondary reaction products. In case of ^{10}B a ^{7}Li and an α and in case of ^{3}He a ^{3}H and an α are produced and are moving in perpendicular direction from the reaction point through the gas. Thereby they lose their kinetic energy by collisions with electrons of the gas atoms, which leads to a creation of electrons and ions. This ionization is then detected by the process described above. As the reaction products have rather large path lengths in the gas, it is likely that one of secondary particles hit the wall of the tube, before it releases all its energy. This is seen in the pulse height spectra by a step-like form of the distribution.

Proportional tubes can also be used as position sensitive detector. By using a resistive wire, the ratio of charges at both ends of the wire determines the position. In neutron scattering, stacks of such detectors are used to cover large areas. The position resolution along the wire direction is typically about 1% of the wire length. The perpendicular position resolution is determined by the diameter of the tube.

3.3 Multiwire Proportional Chamber

A method to improve the position resolution of proportional tubes is the use of Multiwire Proportional Chambers (MWPC), developed by G. Charpak. In the simplest case a MWPC consists of gas volume with parallel anode wires between two cathode layers.

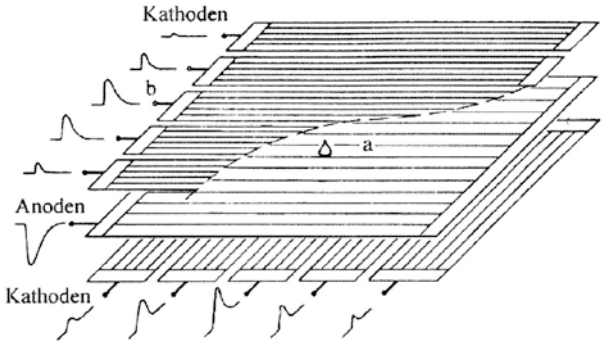

Fig. 6: Principle of the avalanche centre-of-gravity-method. The avalanches surrounding a wire induce a positive pulse on the cathode strips. The pulse height of the induced pulse is measured and the centre-of-gravity of the pulse height distribution is computed and gives the position of the avalanche.

With MWPCs a two dimensional position reconstruction is possible. The first coordinate is given by the position of the anode wire fired. The second coordinate is given either by cathode strips or by charge division of the anode wire. The position resolution is determined by the distance of the anode wires and the length of the ionization track. Typically, the position resolution is in the range of a few mm. The distance between the anode wires is determined by the Coulomb repulsion of the wires and is typically ~ 2mm. The local rate capability is about 10-20 kHz.

For X-ray detection the MWPC is filled with high-Z noble gases (e.g. Argon or Xenon) together with a quenching gas. For slow neutron detection ^{3}He is used together with CF_4 or Propane to reduce the track length. There, a high pressure is needed to achieve a sufficient detection efficiency which unfortunately also implies thick entrance windows. A spatial resolution of 0.4 mm has been achieved by a 8 bar ^{3}He and 6 bar propane gas mixture.

4 Semiconductor Detectors

A semiconductor detector, as its name implies, is a device that uses a semiconductor to detect particle radiation. Usually, doped silicon or germanium is used for semiconductor detectors, but today there are also other materials available, e.g. CdTe or CdZnTe, which can easily be used at room temperature.

In particle physics they are heavily used for detection of traversing charged particles. While semiconductor detectors play a minor role for neutron detection, they are very important for energy resolving X-ray detection.

4.1 General Operation Principle

The general operating principle of semiconductor detectors is based on the creation of electron-hole pairs by ionizing radiation, which are then collected by an electric field. Such an electric field is formed within the semiconductor detector by the method of a pn-junction with reverse bias voltage.

With the formation of a pn-junction a special zone is created at the interface between the two materials. The difference in the concentration of electrons and holes between the two materials leads to an initial diffusion of holes towards the n-region and a similar diffusion of electrons towards the p-region. As a consequence, the diffusing electrons fill up holes in the p-region while the diffusing holes capture electrons on the n-side. As the n and p regions were initially neutral, this recombination of electrons and holes causes a charge up on either side of the junction. This creates an electric field across the junction which counteracts and finally stops the diffusion process. A region of immobile space charge is then left, which is called the depletion zone. It has the special property that there are no mobile charge carriers. Any electron or hole created in this zone by ionizing radiation will be swept out by the electric field. As the average energy required to create an electron-hole pair is some 10 times smaller than in gaseous detectors, the amount of ionization produced for a given energy is an order of one magnitude larger, resulting in an increased energy resolution. Furthermore, the higher density also results in a higher stopping power.

4.2 Silicon p-i-n Detectors

Fig. 7 shows the basic configuration used for operating a junction diode as a radiation detector. Semiconductors cannot be contacted by directly depositing a metal on the semiconductor material, because such contacts usually result in the creation of a rectifying junction with a depletion zone extending into the semiconductor. In order to avoid this formation, heavily doped layers of n^+ and p^+ material are used between the semiconductor and the metal leads. Because of the high dopant concentrations, the depletion depth is then essentially zero, which forms the ohmic contact.

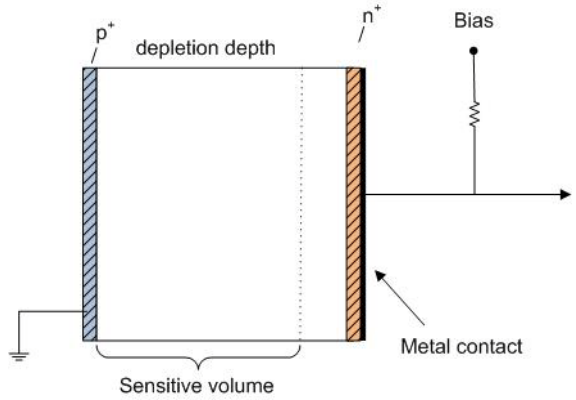

Fig. 7: The semiconductor detector is based on the diode with reverse bias voltage.

Simple silicon junction detectors have relatively small depletion depths, which are typically between 60 um and a few millimetres. They are particulary suitable for alpha and beta particles, but are relatively insensitive for X-rays because of the low absorption cross section. In order to obtain thicknesses larger than a few millimeters very high resitivities are required, which can only be obtained with intrinsic materials or eventually compensated semiconductor. This is achieved by the lithium drifting process for forming compensated material. Junctions formed with compensated materials are known as p-i-n junctions and posses properties different from regular pn-junctions. In particular, there is no space charge in the compensated zone, which implies an almost constant electric field.

Silicon p-i-n semiconductor detectors have large depletion depths of 10 mm and more. As the detection efficiency is a function of the thickness of the depletion layer, they can serve as efficient detectors for X-ray with a fairly good energy resolution. For example, for 5.9 keV X-rays from ^{55}Fe an energy resolution of 150 eV is routinely obtained with an detection efficiency of almost 100%. For higher energies above approximately 60 keV, photons interact almost entirely through Compton scattering. At these X-rays often fail to deposit all its energy in the silicon p-i-n detectors. Above 100 – 150 keV the detectors are seldom used for spectrometry.

4.3 Avalanche Diodes

With normal semiconductor detectors the objective is to collect all charge carriers that are created by the incident radiation. By raising the reverse bias voltage, a sufficiently high electric field is achieved, which enable the migrating electrons to create secondary ionization and finally an charge avalanche. The gain of such avalanche photodiodes is strongly dependant on the applied voltage and temperature. At stable operation conditions, gains of up to several hundred in the total collected charge are possible before breakdown.

The advantage of avalanche photodiodes exhibits if the photoelectric effect is used to convert light or soft X-rays to electricity. The charge multiplication permits use of avalanche photodiodes with sufficient signal-to-noise ratio, even for the detection of very low energy radiation. Thus they have found widespread application in the detection of low energy X-rays.

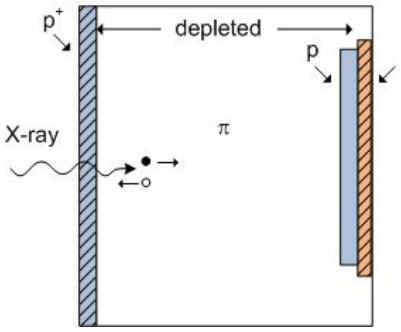

Fig. 8: Sketch of the avalanche photodiode operation principle. The incident radiation interacts in the π-region that constitutes most of the diode thickness. The electric field at the pn+ region is very high, so that charge multiplication occurs.

Silicon photomultipliers (SiPM) are silicon single photon sensitive devices built from an avalanche photodiode array on common Si substrate. The idea behind this device is the

detection of single photon events in sequentially connected Si APDs. The dimension of each single APD can vary from 20 to 100 micrometres, and their density can be up to 1000 per square millimeter. Every APD in SiPM operates in Geiger-mode and is coupled with the others by a polysilicon quenching resistor. Although the device works in digital/switching mode, the SiPM is an analog device because all the microcells are read in parallel making it possible to generate signals within a dynamic range from a single photon to 1000 photons for just a single square millimeter area device.

5 Scintillation detectors

Scintillation detectors make use of the fact that certain materials, when struck by nuclear radiation, emit a small flash of light, i.e. a scintillation. When coupled to a light detection device, e.g. a photomultiplier, these scintillations can be converted into electrical pulses which can be analysed and counted electronically to give information concerning the incident radiation.

5.1 Scintillation material

A scintillator can be described as a material that converts the energy of an incident particle or energetic photon into a number of photons of much lower energy in the visible or near visible range. There are both inorganic and organic materials showing this property, but the mechanism on which the scintillation is based is different for both types. While the emission of scintillation light in inorganic scintillators is based on the properties of the crystal lattice, in organic scintillators it is based on the molecular properties of the organic matter. Here, only inorganic scintillators are described, because this type is much higher importance for X-ray and slow neutron detection.

Inorganic scintillators are grown in a crystalline form and are doped with an activator material. Fig. 9 shows the electronic band structure of inorganic scintillators with its valence, exciton and conduction band. One criterium for the selection of the activator material is that its energy levels are located between the valence and exciton band.

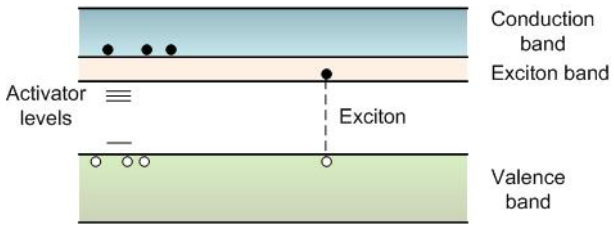

Fig. 9: Electronic band structure of inorganic scintillators. Besides the formation of free electrons and holes, loosely coupled electron-hole pairs known as excitons are formed. Excitons can migrate through the crystal and be captured by impurity centres.

When particle radiation enters the crystal, two principal processes can occur. It can ionize the crystal by an exciting an electron from valence band to the conduction band, creating a free electron and a free hole. Or it can create an exciton by exciting an electron to a band located just below the conduction band (exciton band). In this state the electron and hole remain bound together as a pair. However, the pair can move freely through the crystal. If the crystal now contains impurity atoms, electronic levels in the forbidden energy gap can be locally

created. A migrating free hole or a hole from an exciton pair which encounters an impurity centre, can ionize the impurity atom. If now a subsequent electron arrives, it can fall into the opening left by the hole and make a transition from an excited state to the ground state, emitting radiation if such a de-excitation mode is allowed. If the transition is radiationless the impurity centre becomes a trap and the energy is lost to other processes. Sometimes, the excited state is metastable, so the relaxation back out of the excited state is delayed (necessitating anywhere from a few microseconds to hours depending on the material): the process then corresponds to either one of two phenomena, depending on the type of transition and hence the wavelength of the emitted optical photon: delayed fluorescence or phosphorescence, also called after-glow.

Important properties of scintillators are the light yield, the emission wavelength and the decay time of the excitation. These properties largely depend on the activator material. The light yield is the amount of light delivered by the scintillator per incident particle energy. As the light is emitted by the activator atoms, the light yield is dependent on the concentration and the efficiency of the activator atoms in the crystal lattice. A high light yield is favourable, because it offers a better energy resolution. Also the emission wavelength and the decay time of the excitation are related to the activator atoms. The scintillation material should be transparent for the emitted light and the emission wavelength should be adapted to absorption characteristic of the light detection device. This is typically in the range of 400 nm, which corresponds to about 3 eV for the difference between ground and excited states of the activator. Finally, short decay times are favourable in order to achieve a high count rate capability of the scintillation detector.

Most commonly used activators for scintillators are Thallium, Europium or Cerium. There is a large variety of different scintillators available The most efficient converter of radiation energy to visible light is the thallium activated sodium iodide scintillator, NaI(Tl). It exhibits a light yield of about 40000 photons per MeV incident energy. Because of the relatively high atomic number of the iodine, it is well suited for gamma ray detection. However, the material is hygroscopic and must be encapsulated to protect it. The replacement of the sodium by caesium yields another very efficient scintillator, the CsI(Tl) scintillator. It is not hygroscopic and its stopping power for gammas is better than NaI(Tl). The light yield for a given gamma energy is 60000 photons per MeV and even higher as for NaI(Tl). But, the maximum of emission wavelength is around 540 nm, which is not well matched to the spectral sensitivity of photomultipliers. By usage of photomultipliers for light detection, the amount of light measured is only 60% of that for NaI(Tl). Standard scintillators for neutron detection are cerium activated glass scintillators, which contain a high amount of enriched lithium for the neutron capture. Such ^{6}Li-glass scintillators emit about 6600 photons per captured neutron with a peak wavelength of about 400 nm. It has a decay time of 75 ns, which allows for high count rates, and already 1 mm thickness is sufficient for an efficient slow neutron detection. Europium activated lithium iodide, LiI(Eu), is another important scintillator for slow neutron detection, which offers a higher light output than Li-glass. However, it is also highly hygroscopic and needs to be encapsulated. The brightest scintillator is silver activated zinc sulfide, ZnS(Ag). It is available in powder form, but it is not transparent. So, only thin layers of ZnS(Ag) scintillators can be applied. For slow neutron detection this material is mixed with enriched ^{6}LiF to form scintillators of thicknesses up to 450 µm.

5.2 Photomultiplier Tubes

A common method to detect light emitted by a scintillator is the use of photomultiplier tubes (photomultipliers or PMTs). Photomultipliers are vacuum tubes which are able to convert light into a measurable current and they are extremely sensitive in the ultraviolet, visible, and near-infrared ranges of the electromagnetic spectrum.

Fig. 10 shows a schematic diagram of a typical photomultiplier. A photomultiplier consists of a photosensitive cathode followed by an electron collection system, an electron multiplier section (dynodes) and finally an anode from which the final signal can be taken. The housing of a photomultiplier is an evacuated glass tube.

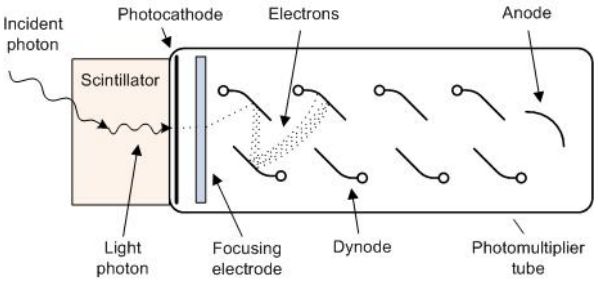

Fig. 10: Photomultiplier tube with head-on configuration.

During operation a high voltage is applied to the cathode, dynodes and anode such that a potential ladder is set up along the length of the cathode – dynode – anode structure. When an incident photon from a scintillator impinges upon the photocathode, an electron is emitted via the photoelectric effect. Because of the applied voltage, the electron is then directed and accelerated toward the first dynode, where upon striking, it transfers some of its energy to the electrons in the dynode. This causes secondary electrons to be emitted, which in turn, are accelerated towards the next dynode where more electrons are released and further accelerated. An electron cascade down the dynodes is thus created. At the anode, this cascade is collected to give a current which can be amplified and analyzed. If the cathode and dynode systems are assumed to be linear, the current at the output of the photomultiplier will be directly proportional to the number of incident photons. As the number of photons produced in the scintillator is proportional to the energy deposited, the output of the photomultiplier is also proportional to the energy that the particle radiation has left in the scintillator.

An important characteristic of photomultipliers is the quantum efficiency, which is the quotient of the number of photoelectrons released by the photocathode to the number of incident photons. This quantity is wavelength dependant and strongly related to the type of photocathode. Typically bialkali photocathodes are used which show a quantum efficiency of about 25% at a peak wavelength of 400 nm. The potentional between neighboring dynodes is adjusted by a voltage divider circuit and is in the range between 50-200 V. Photomultipliers are usually equipped with 10-16 dynodes. With a secondary emission factor of the dynodes of 3-4, this results in overall amplification of 10^5 - 10^9.

Photomultipliers are rugged light detection devices with a high amplification. Nevertheless photomultipliers are also influenced by environmental factors. The most critical factor are external magnetic fields. It is obvious, that already small magnetic fields are sufficient to

deviate the electron cascade from its optimum trajectory and thereby affect the operation characteristic. For small magnetic fields a shielding with a mu-metal screen around the photomultiplier may help, but at higher magnetic fields, other light detection devices, e.g. avalanche photodiodes, must be used.

5.3 Anger Camera Scintillation Detectors

The Anger camera principle is a simple well proven method to build cost efficient large area, position sensitive scintillation detectors. With this method, the light emitted by an impinging particle in the scintillator, is spread via a light disperser over several photomultiplier tubes. By analyzing the signals of the photomultiplier tubes, the event can be computed (e.g. by centre-of-gravity calculation). Thus, with a small number of photomultiplier tubes, a spatial resolution may be achieved, which is much smaller than the tube dimensions.

Anger camera detectors have been built for X-ray and neutron detectors. A construction for slow neutron detection is shown in Fig. 11, which utilizes a thin ^{6}Li-glass scintillator for neutron capture. In practice, there is a small air-gap between the scintillator and the light disperser. Thus, by total reflection in the scintillator, the light spread is limited to a cone that strikes the photomultiplier array. This is mainly to facilitate the reconstruction method. For Anger camera detectors, the thickness of the light disperser has to be adapted to the diameter of the photomultipliers.

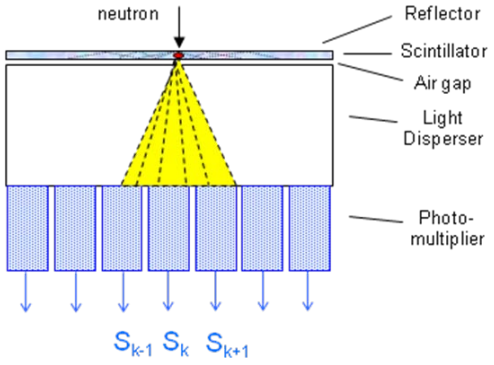

Fig. 11: Sketch of the Anger camera principle. Light produced by the neutron capture in the scintillator is spread over an array of photomultipliers. By analysing the pulse heights of the photomultiplier, the position of the neutron capture can be computed.

6 Integrating Detectors

As the name indicates, integrating detectors are not readout on a event basis, but rather accumulate information about radiation interactions over a longer period of time. The simplest case of such detectors is the photographic film used for the detection of X-rays in medical imaging. An advantage of integrating detectors is usually the high position resolution, but due to the missing event information interfering effects cannot be removed.

6.1 Image Plates

Image Plates are integrating position sensitive detectors that are based on photostimulable phosphors. By exposure of such materials with ionizing radiation, the excited electrons in the

phosphor material remain trapped in colour centres of the crystal lattice until stimulated by the second illumination.

The commonly used material is BaFBr:Eu^{2+}, in which the ionizing radiation partly ionizes Eu^{2+} ions to Eu^{3+}. The lose electron enters the valence band of the crystal and becomes trapped in the ion empty lattice of the crystal. By illumination with visible light (e.g. He-Ne-laser) the trapped electrons are lifted to the valence band and are catched by Eu3+ ions. Thereby characteristic Eu2+ luminescense light is emitted, which can be detected by photomultipliers. The intensity is proportional to the radiation deposited. After readout of the image plate the whole information is erased by intense white light. Then it can be used for new images.

Image plates can directly be used for X-ray detection. In case of neutrons the material is made sensitive by mixing it with Gd_2O_3-powder. Neutrons are then absorbed by ^{155}Gd or ^{157}Gd and registered by the subsequent emission of conversion electrons, Auger electrons and X-rays. The detection efficiency for thermal neutrons is small (~23%) and because of the high-Z materials it is gamma sensitive.

6.2 Charge Coupled Device (CCD)

A charge-coupled device (CCD) is a silicon device with a two dimensional array of tiny potential minima, each covering an area of a few microns. When struck by radiation, electrons are released which are then trapped in these minima. This charge information is then readout by successively shifting the charge from one minimum to the next until it reaches the output electronics. CCD's are mainly used for light imaging purposes and are extremely sensitive, low noise devices. It can be used as a large X-ray detector in combination with a phosphor screen and a fiber optic taper as shown in Fig. 12.

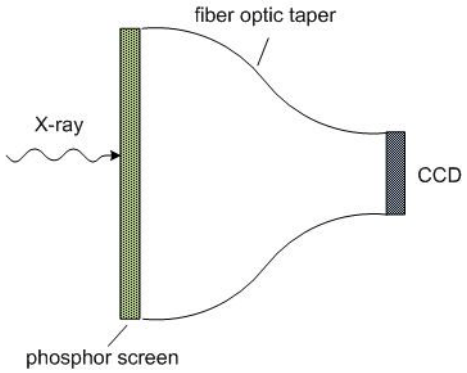

Fig. 12: Building blocks of a X-ray CCD detector: X-rays are first converted by the phosphor screen. The fiber optic taper focus the image on the CCD, where the photons are detected.

As phosphor screen most commonly $Gd_2O_2S(Tb)$ is used, which emits mainly green light. This material is available as powder which is bound with a binder material onto an X-ray transparent window (aluminized Mylar). The fiber optic taper is to focus the output image of the phosphor screen onto the CCD chip. It usually consists of many glass fiber light guides, which are melted and stretched to create a typical demagnification. Depending on this demagnification, there is a large attenuation of the number of photons by the fiber optic taper. Typically, only about 20% of the emitted photons are finally detected by the CCD.

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