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Novel detection technologies for nuclear security

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Radiological and Nuclear Threats to Critical Infrastructure:

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Abstract

Radiation detectors are used in nuclear security to detect nuclear and other radioactive materials outside of regulatory control. In nuclear security, the operational environment and detector technologies are constantly evolving. This document provides an overview of recent developments in radiation detection technologies that are likely to have an impact on nuclear security in the near future. The four main topics covered are: detectors for gamma-ray spectrometry, neutron detectors, data acquisition and source localisation.

This document will be published together with another report that concentrates on the impact of novel detection technologies from an operational point of view. The focus of this document is on technical aspects of the technologies.

Acronyms and abbreviations

$CeBr_3$	An alternative to LaBr, not exhibiting the internal radiation of La
CLYC	Cs_2LiYC_6:Ce: crystal belonging to the elpasolite scintillator family
CLLB	$Cs_2LiLaBr_6$(Ce): scintillator material sensitive to gamma and neutron radiation
CLLBC	$Cs_2LiLa(Br6)_{90\ \%}(Cl6)_{10\ \%}$: elpasolite crystal with excellent neutron and gamma radiation response
DSP	Digital signal processor: microprocessor optimised for digital signal processing
eV	Electron volt: unit of energy. Gamma-ray and neutron energies are typically expressed in kilo-electron volts (keV) or mega-electron volts (MeV)
FPGA	Field-programmable gate arrays
FWHM	Full width at half maximum: measure of detector energy resolution
HPD	Hybrid photodetector: photosensor
HPGe	High-purity germanium detector
$LaBr_3$:Ce	A transparent scintillator material that offers the best energy resolution obtained so far.
MAPMT	Multianode photomultiplier tube: photosensor
PMT	Photomultiplier tube: photosensor
PSD	Pulse-shape discrimination
PSPMT	Position-sensitive photomultiplier tube: photosensor
PVT	Polyvinyl toluene: plastic scintillator material
RN	Radiological and Nuclear
SDD	Silicon drift detector: photosensor
SiPM	Silicon photomultiplier: photosensor
ZnS	Zinc sulphide: inorganic scintillator material

1. Introduction

Radiation detection and identification equipment is used by front-line officers, or installed at checkpoints, such as at road and rail border crossings, airports, seaports and at nuclear facilities. Recently, more and more mobile or transportable equipment is being used, e.g. to secure mass events, or for quick deployment in case of emergency.

This document aims to present an overview of novel detection technologies that are likely to have an impact on nuclear security and emergency preparedness in the near future. The detection technologies covered are capable of recording gamma rays from 50 keV to 10 MeV (3-10 MeV refer to neutron-induced photons) or neutrons from 0.024 eV (thermal) to 20 MeV. Rather than discussing the different technologies in detail, this report focuses on the pros and cons of the technologies from the point of view of nuclear security.

1.1. Detector standards

When novel technologies are used as an alternative to established technologies, they should first be checked against existing standards, specifying performance requirements and test methods. However, when the novel technology has a considerable impact on the performance of instruments, or enables new features, the existing standards may not be fully applicable. New, or improved, standards may be required.

An example of a new technology that required revision of standards was the use of scintillator material for neutron detection. Unlike ^{3}He proportional counters traditionally used for neutron detection, these enhanced scintillators rely on discriminating the shape of the pulse between a photon and neutron. False detection of neutrons or photons is not uncommon when the pulse-shape discrimination algorithm is not correctly set. Radiation detection equipment is categorised into nine different types, each supported by IEC and ANSI standards, as follows.

Instrument category	*IEC standard*	*ANSI standard*
radiation portal monitors	IEC 62244	ANSI N42.35
spectroscopy-based radiation portal monitors	IEC 62484	ANSI N42.38
alarming personal radiation devices	IEC 62401	ANSI N42.32
spectroscopy-based alarming personal radiation detectors	IEC 62618	ANSI N42.48
handheld instruments for the detection and identification of radionuclides	IEC 62327	ANSI N42.34
highly sensitive handheld instruments for photon detection	IEC 62533	ANSI N42.33
highly sensitive handheld instruments for neutron detection	IEC 62534	none
backpack-type radiation detector	IEC 62694	ANSI N42.53
vehicle-mounted mobile systems	IEC 63121	ANSI N42.43

It is important to note that these standards do not only specify radiological requirements and test methods; they also place strict requirements on environmental, mechanical, electrical and magnetic conditions, such as ambient temperature, temperature shock, relative humidity, low/high temperature start-up, IP (degree of protection) classification, drop and vibration testing, microphonic/impact, mechanical shock, electrostatic

discharge, radio frequency immunity, radiated emissions, magnetic fields, and voltage and frequency fluctuations. These non-radiological requirements specified in IEC 62706 are easily overlooked when developing novel technologies. Again, standards are an important information source to consider during research and development activities.

In addition to the standards specifying performance criteria, there are two relevant data format standards:

- IEC 62755/ANSI N42.42: Radiation protection instrumentation: Data format for radiation instruments used in the detection of illicit trafficking of radioactive materials. The XML data format is supported by many instruments on the market.
- IEC 63047: Nuclear instrumentation: Data format for list-mode digital data acquisition, used in radiation detection and measurement. This new standard is used to present raw data from detectors and has a particular added value when time-correlated data needs to be analysed.

The data format standards are relevant when novel technologies are integrated into a larger system, or when data from different systems has to be processed in a uniform way, e.g. for expert support.

2. Detectors for gamma-ray spectrometry

In this chapter, we will discuss the novel materials and sensors that are becoming commercially available and their possible use in radiation detection systems. However, we will begin with some common spectrometry system definitions.

A scintillation radiation detector consists of a scintillator material and a photo sensor. The impacting radiation interacts in the scintillator material producing optical photons. These optical photons are converted into an electric pulse in the light sensor. Nowadays, there are many kinds of scintillator materials and also many types of light sensors that can be combined in order to build a detector.

In the case of gamma detection, the scintillating material is usually a crystal, where the deposited energy is converted to light of a specific wavelength and where the intensity of this light is proportional to the deposited energy. Further, the crystal has to be transparent to its own light emission. The crystal surface is coated with a reflective material so that the light produced is directed to one end of the crystal.

The energy deposited in the material can be determined by coupling a light sensor to the crystal surface. The sensor converts the light intensity to an electric charge that is amplified and transformed into a current pulse.

Further, it should be mentioned and will be discussed that semiconductors can also be used both as detection material and sensors.

Most equipment of interest for radiation spectroscopy operates in pulse mode; the instrumentation is thus designed to record each individual quantum of radiation that interacts in the detector material. In most common applications, the time integral of each burst of current, the total charge deposited or the intensity of the light produced is recorded, since the energy deposited in the detector should be directly related to those parameters in order to build a useful detector.

We will first define some performance parameters, such as efficiency, energy resolution and peak-to-background, as these are common to all radiation detectors and determine the specific use of the equipment.

2.1. Key parameters

Efficiency

Efficiency is the share of gamma rays emitted by the source that are counted by the detector. However, the absorption of gamma rays (and neutrons) by the material is a statistical process, where the gamma rays have to undergo specific reactions and can travel long distances, or even partly escape the detector.

Decay time

Further, the decay time of the light pulse being emitted determines how fast the crystal recovers and thus the dose rate it can handle before saturation. For example, LaBr has a decay time of 16 ns, while for a CsI(Tl), it is 1000 ns. LaBr can thus be used to detect much higher intensities and maintains good resolution compared to a CsI(Tl).

Internal radioactivity

Some materials, e.g. lanthanum (as in LaBr) exhibit internal radiation, usually of very low activity, which may mask the signal of interest and reduce the sensitivity if the detector. In nuclear security applications the internal contamination can also be an advantage, since it can be used for energy calibration of the detector.

Hygroscopicity

Most of the scintillator materials are hygroscopic, i.e. they absorb water and therefore need to be encapsulated to avoid rapid deterioration. In most scenarios, this is not a major drawback as the detector has to be protected in any case, especially as the connection to the sensor is a weak spot. Energy resolution

In most applications of radiation detectors, the objective is to determine the isotopes contained within the source, and thus the energy distribution of the incident radiation has to be determined. The energy resolution is usually defined as the 'Full Width at Half Maximum (FWHM)' of each peak in the obtained spectrum. The FWHM indicates the resolving power of the detector, i.e. how close two peaks can be in energy and still be separately determined. For scintillator detectors, the value of FWHM is given in per cent of the incident energy, (*E*), (see Figure 1). Depending upon the material, the resolution ranges from 2 %-10 %. To resolve the two peaks of ^{60}Co (1173, 1332 KeV) and to resolve these from natural background from ^{40}K (1473 KeV) one need a resolution of <10 %. Further, as mentioned above, a linear response to energy is important and this comes with better resolution. However, the more performant crystals can only be obtained in a relatively small size; as the price of the crystal is directly coupled to the performance and size, one has to choose the crystal that best fits the task.

For scintillators, the energy resolution is mainly determined by the light yield, which is roughly the total number of photons produced (per energy unit) by a particle completely absorbed by the material. The scintillator material emits light of a specific wavelength, while the light sensor that is coupled to the sensor has to be well-adapted to the specific wavelength. This process is not perfect and adds to the final efficiency of the detector.

Peak-to-Compton or peak-to-background

The absorption spectrum of gamma radiation of interest for RN detection (i.e. gamma rays of <5 MeV) has two main features: the full energy peak and the Compton distribution. If the gamma ray is fully absorbed by exciting electrons within the crystal, full energy peak will occur. However, if the gamma ray undergoes inelastic scattering on an electron, it loses energy, giving rise to a continuous (background) distribution towards lower energies that might cover other peaks at lower energies. Some Compton gammas may also arrive from outside the detector following scattering in surrounding material and can thus hamper the directional detection. In RN scenarios, the Compton edge can be used to determine possible shielding of the actual source.

Usability parameters

When choosing a scintillator material, one has to take into account certain parameters in relation to the usability of the final detector. The final efficiency of a detector depends upon its physical size. However, certain materials cannot be made big and a drone cannot carry a very heavy detector, etc. The pros and cons will be discussed in more detail for each case:

- cost;
- maximum active volume;
- temperature stability;
- robustness (fragile);
- hygroscopic;
- ageing;
- difference between actual and theoretical performance;
- maturity (commercial availability, technology readiness level).

2.2. Scintillator materials

Both **organic** and **inorganic** materials are used for scintillation detectors. **Inorganic crystals** form a class of scintillating materials with much higher densities (typically 4-8 g/cm^3) than **organic plastic scintillators** (1 g/cm^3).

Due to their high density and high effective atomic number, inorganic scintillators can be used in applications where a high stopping power, or a high conversion efficiency for electrons or photons is required. Many of these crystals also have a very high output of light and can therefore provide excellent energy resolution down to very low energies (few hundred keV).

Some crystals are intrinsic scintillators in which the luminescence is produced by a part of the crystal lattice itself. However, other crystals require the addition of a few per cent of dopant, which is responsible for

producing the scintillation light — typically fluorescent ions, such as thallium (Tl) or cerium (Ce). The scintillation mechanism is the same in both cases. The dopant is indicated within brackets, e.g. the $LaBr_3(Ce)$ is a lanthanum-bromide crystal doped with cerium.

Inorganic scintillators are more expensive, due to the production procedure, but they have the advantages of high light yield and high density, leading to good energy resolution. Their disadvantages are their complicated crystal growth and that they often exhibit large temperature dependence.

Organic scintillators are relatively cheaper, and have the advantage of being very fast, easily-shaped and have lower temperature dependence. Their disadvantages are lower light yield, less energy resolution and that they are more easily radiation-damaged.

The ideal scintillator should provide not only a high light yield but also a high effective atomic number for good stopping power, a short decay time constant for fast response, and a good level of linear response for good energy resolution. In addition, chemical and mechanical robustness are needed to allow the scintillator detector to be used in many different applications and environments. Figure 1 displays a schematic ordering of the existing materials as a function of the expected energy resolution that can be obtained with their use.

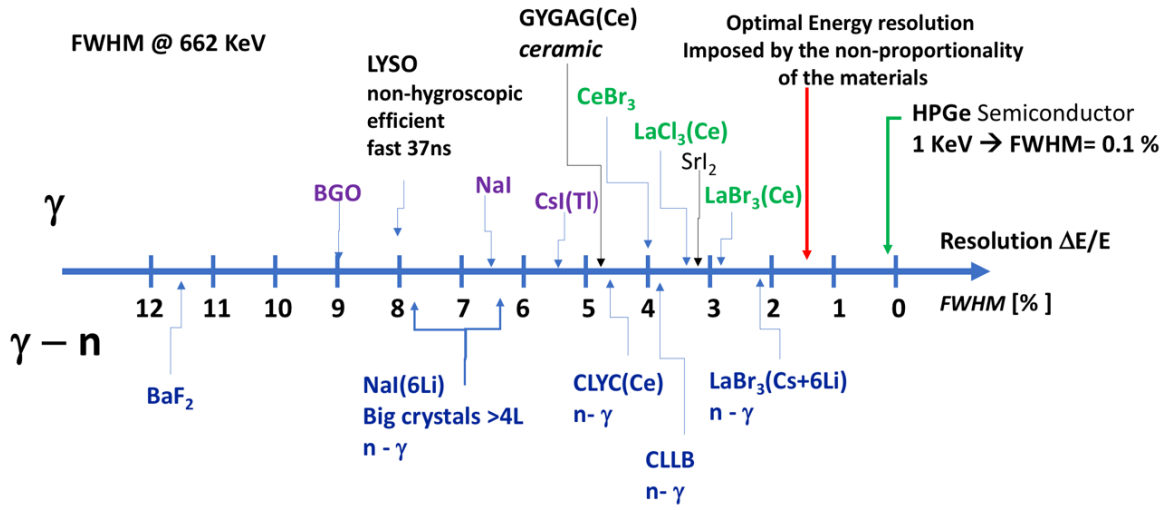

Figure 1. *Existing high-resolution scintillator materials ordered according to the energy resolution that can be obtained: FWHM of E/E in % at 662 KeV.*

The performances of new scintillator materials, and their possible use as detectors, are not well known and thus require specific characterisation. The results of such studies are of particular interest not only to researchers, but especially to the producers of these materials, in order to be able to make and sell detectors that can be commonly used in applications and not only for use by specialists of the field. Ensuring the availability of different materials and, especially, the availability of crystals in sizes that are useful for building detectors remains an ongoing and relatively slow process.

Alkali-halide scintillators

BGO, NaI(Tl) and CsI(Tl) have been routinely used for decades, due to their high light output and stable and reproducible production method. However, modern applications in high energy physics, nuclear medicine, geophysics and, today, homeland security, place more stringent requirements on the energy resolution and efficiency of relatively small detectors that can be easily carried around by a human or a robot.

The materials that have traditionally been used are listed below, together with some of their characteristics:

- NaI ⇒ acceptable energy resolution, non-linearity in energy, bad time resolution;

- BaF_2 ⇒ bad energy resolution, excellent time resolution;
- BGO ⇒ bad energy resolution, bad time resolution, excellent efficiency;
- CsI ⇒ inexpensive, relative good energy resolution, rugged, still a good alternative.

However, we would also like to identify a number of new, promising scintillator materials that recently have become available.

Cerium-doped chloride, bromide and iodide compounds

$LaBr_3(Ce)$ (average emission wavelength 380 nm) has become the new standard, exhibiting very good energy resolution in the order of 2.5-3 % at 662 keV and a very fast decay time of 18 ns. Co-doping the $LaBr_3(Ce)$ with any of Li+, Na+, Mg2+, Ca2+, Sr2+, and Ba2+ can tailor the response for different applications. The $LaBr_3(Ce+Sr)$ has improved resolution (2.2 %) and improved linearity with energy and will, in near future, replace the standard $LaBr_3(Ce)$ (Alekhin et al., 2013).

$LaCl_3(Ce)$ (average emission wavelength 350 nm) has slightly worse energy resolution (4 %) than $LaBr_3(Ce)$, but) but is otherwise more or less equivalent. Due to the difference in decay time, $LaCl_3(Ce)$ and $LaBr_3(Ce)$ can be used together in phoswich configurations.

$SrI_2(Eu)$ (average emission wavelength 480 nm) has very good energy resolution (3 %), and contains no internal radioactivity, but is characterised by a slow signal and self-absorption. On the one hand, the long decay time constant of $SrI_2(Eu)$ could be a critical aspect in case of high-rate experiments; on the other hand, it makes this material a good candidate for use as a second-stage crystal in a phoswich telescope.

$CeBr_3$ (average emission wavelength 370 nm) is characterised by an energy resolution that is a little worse than that of $LaBr_3(Ce)$, but with the convenient advantage of having no internal radioactivity. This could be a good detector for low background experiments and for medical applications, such as positron emission tomography, in which a large number of detectors, providing good timing resolution, are involved. As $CeBr_3$ is not doped, even very large volume crystals are not found to suffer from inhomogeneity.

GYGAG(Ce) (average emission wavelength 540 nm) is a transparent ceramic oxide and is therefore not affected by crystal growth problems. It is neither hygroscopic, nor does it contain internal radioactivity. GYGAG(Ce) seems to be an excellent detector providing high efficiency and a good energy resolution of 5 % at 662 keV. Furthermore, ceramic detectors offer the attractive possibility of being produced in any shape or dimension, and of being more stable to mechanical shock and degrading less in humid conditions than halide single crystals. However, GYGAG(Ce) ceramics are not yet commercially available.

YAP, $YAlO_3(Ce)$: Yttrium orthoaluminate has short decay time (25-30 ns), it can stand high count rate and has light yield 40 % of NaI., YAP is mainly used for X-ray imaging and positron emission tomography. To date, only relatively small sizes of crystals have been obtained.

LYSO and LSO (average emission wavelength 420 nm) is cerium-doped lutetium-based scintillation crystal. Compared to NaI(Tl), it has a high density (7.1 v 3.67 g/cm3), a very fast decay time (45 v. 250 ns), a comparable light yield (27600 v 38000 photons/MeV) and is non-hygroscopic. The output is well matched to the sensitivity curve of SiPMs. They are, however, problematic due to high internal radiation.

Plastic scintillators

Organic plastic scintillators are mainly used for gamma-ray detection in applications where high detection efficiency is needed for an affordable price. For example, the majority of radiation portal monitors for vehicles are based on large PVT scintillator panels. The main disadvantage of plastic scintillators is their poor isotope identification capability because the recorded spectrum does not contain full energy peaks. In addition, the scintillation light yield of PVT drops over time.

Two alternative methods for isotope identification with plastic scintillators have been developed. Rather than high-precision spectroscopy, the main motivation for these studies has been to enable the discrimination of naturally occurring radioactive materials from man-made sources. One approach is to use spectrum analysis methods that utilise the energy deposited in the detector by Compton-scattered gamma rays. In the simplest form, this can be done by comparing the count rates within different energy windows

(Ely et al., 2006). More advanced deconvolution methods utilise the whole energy spectrum, with a large number of channels. Another approach is to load the plastic scintillator with heavy elements, such as bismuth, which gives rise to full energy photopeak (Rupert et al., 2012). One downside of this approach is that the loading typically also reduces the light yield and transparency of the scintillator.

2.3. Semiconductors

CdZnTe

CdZnTe is a room-temperature semiconductor detector with a theoretical maximum energy resolution of approximately 0.5 % (FWHM) at 662 keV. However, the practical resolution of the CdZnTe detectors is significantly limited by charge carrier trapping.

The charge-collection efficiency in CdZnTe is strongly dependent on the gamma-ray interaction location. Therefore, the charge from different gamma-ray interactions that happen in random locations inside the detector volume is collected with different efficiencies, which leads to peak broadening in the recorded energy spectrum.

In order to compensate for the charge-trapping effects, different approaches are used. In unipolar readouts, the signal is based solely on electrons and not on holes. Due to the much higher mobility of electrons compared to holes, the trapping is less pronounced for electrons. A unipolar readout is typically achieved by shaping the electric field within the detector so that it is otherwise fairly constant but rises rapidly close to the cathode.

In order also to compensate for electron trapping, depth-sensing methods can be applied. For this purpose, the ratio of the anode (electron) signal and the cathode (hole) signal is measured. The ratio of the two signals is proportional to the interaction depth, which, in turn, is used to apply correction parameters to compensate for electron trapping.

The best energy resolution is achieved by combining depth sensing with a 2-D position-sensitive readout. This method enables the gamma-ray interaction point to be reconstructed in 3-D, which is used further in order to correct location-specific electron trapping caused by material non-uniformities. With this technique, an energy resolution of 1 % FWHM at 662 keV can be achieved. This approach is mainly used in CdZnTe Compton cameras, where 3-D reconstruction is required for imaging, in any case.

2.4. Bolometers

Bolometers (or cryogenic microcalorimeters, as they are also called) can be used for X-ray and low-energy gamma-ray spectrometry. They provide energy resolution that is an order of magnitude better than what can be achieved with the best HPGe semiconductor detectors. For example, at 100 keV, energy resolution better than 150 eV has been measured (Ali et al., 2008).

Bolometers consist of a gamma-ray absorber and a highly sensitive semiconductor thermometer that operates close to its transition temperature from superconducting to normal state. In this temperature range, tiny changes in temperature have a large impact on resistivity, which enables the temperature rise caused by the absorbed gamma ray photon to be determined with extremely high precision.

Due to low efficiency, low maximum count rate and the complexity of cooling to superconducting temperatures, this technology is currently mainly only feasible for laboratory measurements.

3. Neutron detectors

A typical neutron detector consists of three components, as follows.

- **Converter**: converts the neutrons into charged particles or gamma rays. As neutral particles, neutrons do not ionise directly.
- **Sensitive volume**: converts the charged particles or gamma rays produced in the converter into electric signal or light. If light is produced, it must be further converted into an electric signal with a photosensor.
- **DAQ electronics**: record the electrical signal produced.

The detector may also have additional components to improve detection efficiency.

- **Moderator**: used to slow down the neutrons to the energy range at which the detector is most sensitive.
- **Reflector**: reflects neutrons that would otherwise pass by or through into the converted material.
- **Shield**: can reduce detection sensitivity in certain directions (collimation), or prevent gamma rays from entering the detector.

Single detector components can also have multiple functionalities. For example, the same material can act as a moderator, converter, and sensitive volume.

3.1. Key parameters

Neutron-detection efficiency

The conversion efficiency of neutron detectors depends on the cross-section and quantity of the neutron-sensitive material. The cross-section, and therefore also the detection efficiency, depends strongly on the neutron energy. The quantity of the neutron-sensitive material is often limited by the maximum size at which the signal produced by the neutron can be efficiently recorded. The geometry of the detector unit also has a significant impact on efficiency: for example, detection efficiency can be maximised by using layers that reflect thermal neutrons through the neutron-sensitive area multiple times.

Gamma insensitivity

In nuclear security, neutron sources are considered a greater threat than gamma-ray sources. Therefore, even a high dose of gamma rays should not cause a neutron alarm. To prevent the use of gamma-ray sources to mask the illegal transportation of neutron sources, the presence of gamma rays should not reduce the neutron detection efficiency of the detector. Some neutron detector types are inherently insensitive to gamma rays, whereas other detectors use pulse-shape analysis for neutron-gamma discrimination (see Section 4.3).

Sensitivity to fast neutrons

Typical energies of fission neutrons and neutrons produced by other neutron sources are in mega-electron volts (MeV). Therefore, to achieve the maximum sensitivity for unmoderated neutron sources, the detectors should be sensitive not only to thermal but also to fast neutrons. Although certain detector types are inherently sensitive to fast neutrons (see Section 3.3), the most common approach is to include moderator materials that reduce the speed of fast neutrons, thereby turning them into thermal neutrons. A detector capable of distinguishing between thermal and fast neutrons, and possibly providing even more detailed information on the energy spectrum, can be used to identify the source type and existence of possible shielding.

Usability parameters

In addition to the performance related parameters, there are also several practical factors that limit the use of certain neutron detector types, as below.

- **Toxicity**: detector materials may be toxic, which both complicates the manufacturing process and causes a potential hazard if the detector case is damaged.
- **Flammability**: detector materials may be flammable, which limits the use of the detector especially in nuclear installations.
- **High pressure**: gaseous detector materials are sometimes compressed in high pressure containers and are therefore restricted from being transported in airplanes.
- **Size**: certain detector types only work efficiently in large systems, such as radiation portal monitors. In the case of other detector types, it is only feasible for them to be manufactured in small sizes.
- **Cost**: if the production of the neutron-sensitive material requires isotope enrichment or artificial production of the isotope, the material costs can be significant.
- **Material availability**: The production of some neutron-absorber materials does not meet the demand. Materials may also be subject to export and transit control.

3.2. Thermal neutron detection

Neutron detectors used for nuclear security applications are typically based on thermal neutron absorption for two reasons. First, the thermal neutron absorption cross section of certain materials is very large, enabling excellent detection efficiency even with relatively small amounts of converter material. Second, neutron absorption in specific converter materials releases significant amounts of energy (Q value ~ MeV). Therefore, the absorption signal is relatively easy to detect.

3.2.1. Converter materials

Properties of typical converter materials used for thermal neutron detection are listed in Table 1.

Material	*Cross section*	*Signature*	*Natural isotope abundance*
^{3}He	5 300 b	^{1}H (0.57 MeV), ^{3}H (0.19 MeV)	0 %
^{6}Li	940 b	^{4}He (2.1 MeV), ^{3}H (2.7 MeV)	7.5 %
^{10}B	3 800 b	^{4}He (1.5 MeV), ^{7}Li (0.84 MeV)	20 %
^{113}Cd	20 000 b	γ cascade (up to 9 MeV)	12 %
^{156}Gd	61 000 b	γ cascade (up to 8 MeV)	15 %
^{157}Gd	260 000 b	γ cascade (up to 8 MeV)	16 %

Table 1. *Converter materials often used for thermal neutron detection. Signature refers to the disintegration products upon which the recorded signal is typically based.*

^{3}He

In the past, ^{3}He has been the most popular converter material for neutron detectors. Unfortunately, the production of this artificial isotope does not meet the current demand. The shortage of ^{3}He has been the main driving force for the development of alternative neutron detection solutions for nuclear security applications.

^{6}Li

Neutron absorption in ^{6}Li produces two heavy charged particles that share almost 5 MeV of energy. Due to the moderate cross section and low natural abundance of the isotope, natural lithium is seldom adequate for neutron detectors. Instead, ^{6}Li concentration needs to be increased by enrichment (typically 95 atom %). The limited number of lithium enrichment facilities and large amounts of toxic mercury needed for the enrichment process have raised concerns on the availability and price of enriched ^{6}Li in the future.

^{4}He and ^{3}H produced in the absorption process can only penetrate some micrometres of solid material. Therefore, ^{6}Li converter is only efficient as a thin layer, or as small particles very close to the sensitive volume. ^{6}Li can also be one of the components of the sensitive volume.

^{10}B

Similar to ^{6}Li, ^{10}B also disintegrates into two heavy charged particles in neutron absorption. The advantage of ^{10}B over ^{6}Li is the significantly higher cross section and natural abundance. Therefore, boron can often be used in natural form. The main disadvantage compared to ^{6}Li is the lower Q value of the reaction (2.3 MeV) and higher mass of the disintegration products. This generally results in a weaker signal and, if a separate converter layer is used, it must be even thinner than the ^{6}Li converters.

^{113}Cd

Unlike neutron absorption in ^{3}He, ^{6}Li or ^{10}B, absorption in ^{113}Cd does not cause disintegration. Instead, a cascade of gamma rays with a total energy of 9 MeV is produced. Some of these gamma rays have distinct energies, but most of them form a continuum due to the high density of states at high excitation energies. To distinguish the neutron absorption signal from artificial and natural gamma background, a large enough fraction of absorption gamma rays must be recorded. This limits the minimum size of the detector systems.

Because the neutron absorption cross section of ^{113}Cd is very high and the penetrating gamma rays enable the use of thick converters, isotope enrichment is not required. Cd is sometimes avoided in detectors due to its toxicity.

^{156}Gd and ^{157}Gd

Natural gadolinium is used in neutron detectors in the same way as cadmium. The advantages of Gd over Cd are a higher neutron capture cross section and lower toxicity. Therefore, gadolinium is often favoured over cadmium.

3.2.2. Detector types

3.2.2.1. Proportional counters

In the past, the vast majority of neutron detectors used for nuclear security have been either ^{3}He- or BF_3 (enriched ^{10}B)-filled gas proportional counters. The advantages of the design are its simplicity, efficiency and insensitivity to gamma rays. Sensitivity to fast neutrons is achieved by adding moderating material such as polyethylene around the gas filled detector tubes.

Neither ^{3}He nor BF_3 are favoured in modern neutron detector design. Due to the global shortage of ^{3}He, detectors that rely upon the availability of this isotope are not sustainable. The use of BF_3 is avoided due to its toxicity.

^{10}B lining

An alternative approach to the use of proportional counters for neutron detection is to line the inner surface of the counter tube with ^{10}B. The counter tube is filled with non-toxic gas, such as a mixture of Ar and CO_2,

which will not react with thermal neutrons. The B-10 lining must be very thin to allow the decay products to reach and ionise the gas. The low total amount of ^{10}B is the greatest challenge for detector efficiency. The problem can be somewhat overcome by maximising the surface area of the boron lining by using a baffle structure inside the tube. In addition, since only one of the two particles produced in the neutron absorption is emitted towards the gas volume, the ionisation signal can be relatively small. Thus, the gamma-ray rejection may be inadequate in strong gamma background. Boron-lined proportional counters are manufactured, for example, by Centronic (www.centronic.co.uk), Photonis (www.photonis.com) and GE Measurement & Control (www.gemeasurement.com).

B-10 nanoparticle aerosol

A proportional counter based on B-10 nanoparticle aerosol is a very novel approach for neutron detection (Amaro et al., 2017). In this detector design, B_4C spheres with a diameter smaller than the ranges of the disintegration products (^4He and ^6Li) in B_4C are mixed with the gas inside the proportional counter. Since the converter material is present as an aerosol inside the gas and not on the surface, both the ^4He and ^6Li can contribute to the ionisation. In addition, the amount of ^{10}B is not limited by the inside surface area of the counter tube. The method is still under development and the neutron detection efficiency does not yet match other commercial solutions. The greatest challenge of this technology is preventing the attachment of particles to the chamber walls.

3.2.2.2. Scintillators

^6Li/ZnS

^6Li/ZnS scintillator neutron detector consists of a mixture of LiF neutron converter and ZnS scintillator. Typically, the Li used in LiF is enriched to 95 % in ^6Li. ^4He and ^3H produced in the neutron absorption in ^6Li deposit their energy into ZnS. ZnS is a bright inorganic scintillator with negligible quenching. Therefore, the number of photons produced per neutron absorption can be very large — up to 160 000 (van Eijk,2004). The limiting factor of the detector design is that the ZnS mixture is not especially translucent to its own luminescence. Thus, to enable the scintillator light to be collected on a photosensor, ^6Li/ZnS is used in the form of screens with a maximum thickness of less than one millimetre. This limits the maximum amount of ^6Li and the neutron absorption efficiency of the screens. Due to the high price of enriched ^6Li, ^6Li/ZnS screens are also fairly expensive. ^6Li-ZnS screens are manufactured by Scintacor (www.scintacor.com), Eljen (http://eljentechnology.com, EJ-420) and Saint-Gobain (www.crystals.saint-gobain.com, BC-704).

^{10}B/ZnS

The basic principle of ^{10}B/ZnS neutron detector is very similar to ^6Li/ZnS, but instead of ^6Li, the scintillator detector uses ^{10}B as a converter material. ^{10}B has a significantly higher neutron capture cross section than ^6Li. Therefore, a screen with the same thickness can theoretically provide much higher neutron efficiency. In addition, unenriched natural boron can also be potentially used, which would drastically cut the cost of the raw materials. The main disadvantage of ^{10}B compared to ^6Li is the significantly lower Q value and higher mass of particles produced in the neutron capture reaction. Thus, the amount of light per neutron absorption is also smaller, which complicates the collection and detection of the optical signal. Different approaches for manufacturing of ^{10}B/ZnS scintillators are under investigation (Guzmán-García et al., 2016) (Nakamura et al., 2014). Ready-made neutron detector units based on ^{10}B/ZnS are manufactured by Bridgeport Instruments (www.bridgeportinstruments.com).

^6Li and loaded liquid scintillator

Organic liquid scintillator detectors can be made sensitive to thermal neutrons by loading the scintillator liquid with a suitable neutron absorber. Thus, the same liquid volume has three functionalities: neutron moderation, conversion and scintillation. Liquid scintillators are also suitable for the detection of fast neutrons via scattering reaction (see Section 3.3).

Liquid scintillator loaded with ^6Li can achieve almost 100 % efficiency for thermal neutrons (Bass et al., 2013). This is possible since the total amount of Li-6 in the detector can be high and both the ^4He and ^3H produced in the neutron absorption are practically fully contained within the scintillator volume. Unfortunately, the gamma discrimination capability is often inadequate for nuclear security applications.

Due to the strong quenching of the light yield for densely ionising particles, the number of photons produced in neutron absorption is equivalent to the number of photons produced by a 400 keV electron. Thus, the gamma discrimination cannot be based on the amplitude of the signal, but requires the use of pulse-shape discrimination methods (see Section 4.3). This can only be achieved with DAQ electronics with high sampling rate. Li-6 loaded liquid scintillators are not commercially available.

^{10}B-loaded liquid scintillator

Liquid scintillator detectors loaded with ^{10}B operate in the very same way as liquid scintillators loaded with ^{6}Li. Due to the high neutron capture cross-section of ^{10}B, good neutron capture efficiency can be achieved with relatively small boron concentration. Thus, the optical properties of the scintillator are not significantly sacrificed by the loading. The loading can be made either by using natural boron, or boron enriched in ^{10}B. The main disadvantage of the ^{10}B-loaded liquid scintillators is the relatively poor gamma-ray discrimination capability. Because of the lower Q value of the ^{10}B absorption reaction compared to ^{6}Li and even stronger quenching, the number of photons produced in neutron absorption corresponds to a 50-100 keV electron (Pino et al., 2014b). Therefore, the identification of thermal neutrons requires pulse-shape analysis. Even with fast DAQ electronics and advanced pulse-shape analysis algorithms, false neutron signals are expected in intense gamma field. Loaded scintillator liquids are manufactured, for example, by Eljen (www.eljentechnology.com) and Saint-Gobain Crystals (www.crystals.saint-gobain.com/).

Gadolinium-loaded liquid scintillator

Gadolinium-loaded organic liquid scintillators consist of a mixture of scintillator liquid and natural gadolinium. Like in ^{6}Li- and ^{10}B-loaded liquid scintillators, this mixture acts as a neutron moderator, converter and active volume. Neutron absorption in ^{156}Gd or ^{157}Gd produces a cascade of gamma rays. The separation between neutron-induced signal and background gamma rays is based on the high total energy of the gamma cascade produced in neutron absorption. Therefore, to achieve good neutron-gamma discrimination, a large fraction of the capture gamma rays must be recorded with the scintillator, which limits the minimum size of the detector volume. It is worth noting that the discrimination cannot be improved with pulse-shape analysis, because the detection of neutrons is also based on gamma rays. Due to the very high neutron capture cross section, excellent neutron capture efficiency is typically achieved with natural gadolinium. Gadolinium-loaded liquid scintillators are common in neutron and neutrino research where large and affordable detectors are preferred. In these applications, the capability to identification fast neutrons based on pulse shape is often utilised. Gadolinium-loaded liquid scintillators are seldom used for nuclear security applications. Scintillator liquids loaded with natural gadolinium are manufactured, for example, by Eljen (www.eljentechnology.com) and Saint-Gobain Crystals (www.crystals.saint-gobain.com/).

Cadmium-loaded liquid scintillator

The properties of cadmium-loaded liquid scintillators are very similar to gadolinium-loaded scintillators. Gadolinium is typically favoured over cadmium as a loading material due to its higher neutron capture cross section and lower toxicity. Cadmium-loaded scintillators liquids are not commercially available.

^{6}Li-loaded plastic scintillators

^{6}Li can be used to load plastic scintillators to make them sensitive to thermal neutrons. The operating principle of the detector is very similar to that used in a ^{6}Li-loaded liquid scintillator, but instead of liquid, solid organic scintillator material is used. These two detector types have also the same main advantages and disadvantages. For example, identification of neutrons requires careful pulse-shape analysis (Pawełczak et al., 2014; Zaitseva et al., 2013). However, unlike some scintillator liquids, plastic scintillators are non-toxic and non-flammable. Lithium can either be part of the plastic bulk or incorporated into the plastic scintillator in nanoparticles (Breukers, Bartle and Edgar, 2013). ^{6}Li-loaded plastic scintillators are not commercially available.

^{10}B-loaded plastic scintillator

The properties of ^{10}B-loaded plastic scintillators are very similar to those found in ^{10}B-loaded liquid scintillator. The main challenge is the poor gamma rejection capability of the material. However, recent studies have shown that detectors with improved neutron-gamma discrimination can be produced

(Pawełczak et al., 2014). Due to the ease of loading and high neutron capture cross section, both enriched and natural boron can be used in the detector. Boron-loaded scintillator plastics are manufactured, for example, by Eljen (www.eljentechnology.com) and Saint-Gobain Crystals (www.crystals.saint-gobain.com/).

^{6}Li-lined gas scintillators

Thermal neutron detectors can also be built using a combination of solid converter material and gaseous scintillator. The technology is not widely used and it apparently suffers from the same limitation as the ^{10}B-lined proportional counters, namely that the converter lining must be very thin to allow the charger particle produced in neutron absorption to reach the scintillator gas, which limits the efficiency of the detector. ^{6}Li-lined ^{4}He scintillator detectors are manufactured by Arktis (www.arktis-detectors.com/) and they have also patented the technology (Gendotti and Chandrasekharan, 2016).

^{6}Li glass scintillators

^{6}Li-enriched, cerium-activated glass scintillators have been used for neutron detection for decades. The glass scintillators are very robust and can tolerate temperature variations and a wide variety of chemicals. Due to the good transparency, high neutron detection efficiency can be achieved with thick detectors. Unfortunately, lithium glass scintillators have poor gamma-ray discrimination capability for two reasons:

1. neutron and gamma pulse shapes are almost identical, making them difficult to distinguish using PSD techniques;
2. discrimination based on pulse height is inefficient, because of strong quenching that reduces the height of neutron absorption signal to the same level as 1.5 MeV gamma rays (van Eijk, 2004).

^{6}Li glass scintillators are manufactured, for example, by Scintacor (www.scintacor.com) and Saint-Gobain Crystals (www.crystals.saint-gobain.com).

3.2.2.3. Semiconductors

Compared to scintillators or proportional counters, using semiconductor neutron detectors to manufacture highly efficient devices is relatively expensive due to the required large volume of neutron-sensitive material. Therefore, semiconductor detectors are typically only used for special applications, such as neutron imaging or neutron spectrometry (Hoshor et al., 2015). Semiconductor neutron detectors can provide excellent spatial resolution down to micron level, which is very difficult to achieve with other approaches.

Semiconductor neutron detector can be split into two main categories based on the conversion mechanism. In direct conversion, the material sensitive to neutrons is part of the p-n junction. Thus, the neutron-induced charged particles can be directly detected. In indirect conversion, the p-n junction is coated with a thin film of converter material. For indirect conversion, the converter material must be very thin to enable the charged particles produced in the converter to reach the p-n junction and produce a detectable signal. Thus, direct conversion typically enables higher total efficiency. Unfortunately, the process of using neutron converter materials in manufacturing of semiconductors is poorly understood. In indirect conversion, mature semiconductor processing technologies can be used instead.

Typical converter materials used in semiconductor detectors to detect thermal neutrons are Li-6, B-10 and Gd-157. Unlike in scintillator detectors, where the signal from gadolinium is based on the emitted gamma rays, in semiconductor detectors the signal is based on conversion electrons at energies or 79 and 182 keV.

An extensive review on semiconductor neutron detectors is found in the References section (Caruso, 2010).

3.3. Fast neutron detection

A vast majority of neutron detectors used for nuclear security are inherently only sensitive to thermal neutrons. Instead of recording fast neutrons directly, moderators are used to slow down the fast neutrons to thermal energies. This section concentrates on the detector types that are directly sensitive to fast neutrons. The main advantages of direct detection of fast neutrons are as listed below.

- Since it is unlikely that fast neutrons have scattered, they retain directional history, which can be used for source localisation and neutron imaging.

- Direction information also helps to improve sensitivity by reducing the background as it only accepts neutrons from certain angles. Since the energy spectrum of fission neutrons is quite similar to the energy spectrum on cosmic neutrons, the energy information alone cannot be used to reduce background efficiently.
- Through the use of neutron energy information, the type of the source (AmBe, fission, shielded) can be determined.
- When a separate moderator is not required, the detector can very compact

The main challenges in fast neutron detection are poor neutron-gamma separation and low efficiency.

3.3.1. Detection methods

The most common approach for the detection of fast neutrons is to record recoil particles resulting from the elastic scattering of fast neutrons. Hydrogen is often favoured as a scatter medium, as, unlike in scatter from heavier elements, the total kinetic energy of the neutron can be transferred in a single scatter. Given that the transferred energy depends on the scatter angle, calculation of the original energy of a single neutron requires that both the recoil energy and angle are recorded. However, the energy distribution of scatter events can provide a statistic estimate of the energy distribution of the neutron flux. Heavier target nuclides, such as deuterium are sometimes favoured, since they result in a narrower energy distribution than ^{1}H target (Lawrence et al., 2013).

Detection of fast neutrons can also be based on nuclear reactions induced by fast neutrons. Some of these reactions require that the neutron energy exceed a certain threshold. Alternatively, the neutron energy can be determined based on the kinetic energy of the reaction products. Unfortunately, due to the relatively low reaction cross sections, the neutron detection efficiencies achieved with these methods are typically too low to be used for nuclear security applications.

3.3.2. Detector types

Stilbene

Stilbene is an organic solid scintillator material used for fast neutron detection. The detection is based on the elastic scatter of neutrons from the hydrogen atoms in stilbene. The most outstanding feature of stilbene is its good pulse-shape discrimination between neutron and gamma-ray events (Kim, Cho and Kim, 2013). The use of stilbene has been limited as a result of the price and availability of material. However, the recent development in manufacturing processes has both increased the maximum size of the scintillator crystals and reduced the price (Zaitseva et al., 2015). Stilbene crystals are manufactured, for example, by Inrad Optics (http://inradoptics.com).

PSD plastic scintillator

Standard plastic scintillators commonly used for gamma-ray detection are not suitable for fast neutron detection in nuclear security applications. The pulse shapes of gamma-ray interaction and recoil protons from scatter of fast neutrons are practically identical. Thus, the gamma and neutron signals cannot be distinguished from each other.

However, plastic scintillators especially designed for fast neutron detection are also available. The pulse-shape discrimination between neutron and gamma-ray events in these scintillators is worse than in stilbene, but still adequate for many applications. These PSD plastic scintillators are available in many sizes. The material is typically about 10 times more expensive than standard PVT, but still significantly cheaper than Stilbene. PSD plastic scintillators are manufactured for example by Eljen (www.eljentechnology.com) and Saint-Gobain Crystals (www.crystals.saint-gobain.com/).

PSD liquid scintillator

PSD liquid scintillators are a common choice for the detection of fast neutrons. As with stilbene and PSD plastic scintillators, the detection of fast neutrons is based on the elastic scatter from hydrogen, which is separated from gamma-ray events with pulse shape discrimination. The pulse shape discrimination capability between neutron and gamma-ray events is comparable to stilbene (Kim, Cho and Kim, 2013). PSD scintillator liquids are relatively inexpensive. In applications where enhanced spectroscopic capability is

required, deuterated liquid scintillators may be favoured (Lawrence et al., 2016). Some of the scintillator materials are also available with neutron absorber loading, which enables a combined detection of fast and thermal neutrons (see Section 3.2.2). PSD scintillator liquids are manufactured, for example, by Eljen (www.eljentechnology.com) and Saint-Gobain Crystals (www.crystals.saint-gobain.com/).

Gas scintillators

Due to strong quenching, unambiguous separation of neutron recoil and gamma-ray interaction events in solid and liquid scintillator materials is difficult for neutrons with less than 2 MeV of kinetic energy (Tomanin et al., 2014; Pino et al,. 2014a; Enqvist et al., 2013). Instead, gas-filled scintillators offer better neutron-gamma discrimination, especially for slower neutrons, for two reasons: first, due to the significantly lower electron stopping power of the gas, the maximum scintillation light yield produced by gamma rays is limited regardless of the gamma ray energy; second, because of inefficient recombination of electron-ion pares, scintillation-light yield for gamma-rays and neutrons is similar. Fast neutron detectors based on pressurised ^{4}He are manufactured by Arktis (https://www.arktis-detectors.com). A further advantage of ^{4}He is its excellent pulse-shape discrimination of neutrons and gamma rays (Jebali et al., 2015).

4. Combined gamma and neutron detection

Many detector types that are sensitive to neutrons are also sensitive to gamma rays. This opens up the possibility of using a single detector to detect both radiation types. The main challenge with this approach is to prevent gamma ray signals being misinterpreted as neutrons.

The neutron-sensitive plastic and liquid scintillators listed in Section 3.2.2.2 in particular, have a relatively high intrinsic efficiency for gamma rays. These detectors can also be used in the manufacture of highly sensitive systems requiring a large volume of material sensitive to neutrons and gamma rays. The feasibility of combined neutron gamma detection with boron-loaded liquid scintillator has also been demonstrated in practice (Paff et al., 2015).

Rather than listing all of the detector types that are sensitive to both types of radiation, this section concentrates on the detectors that have been specially optimised for combined neutron and gamma detection.

4.1. Detector types

4.1.1. Materials sensitive to both neutrons and gamma rays

Elpasolite scintillators: CLYC, CLLC, CLLB

Elpasolite scintillators are inherently sensitive to both to gamma and neutron radiation due to their lithium content. Increased efficiency of thermal neutrons is achieved by using lithium enriched in ^{6}Li. The amount of light produced in neutron capture in ^{6}Li corresponds to the photo absorption of a 3.0-3.5 MeV gamma ray. Thus, decent gamma-neutron discrimination is achieved by simply setting an energy threshold at 3 MeV (Glodo et al., 2011). The purity of the neutron signal can be further improved with pulse-shape discrimination (Glodo et al., 2012). Details on original research into the production of these crystals can be found in the References section (Doty et al., 2012).

CLYC, $Cs_2LiYCl_6(Ce)$ has an average emission wavelength of 390 nm. The internal radiation is practically absent in CLYC(Ce). The energy resolution for 662 keV gamma is in the order of 4.5-5 %. Intrinsic neutron capture efficiency of about 10 % with a peak resolution in the order of 3.5 % has been measured (Bourne et al., 2014). CLYC can be either ^{6}Li- or ^{7}Li- enriched. On the one hand the ^{6}Li-enriched CLYC (CLYC-6) has very high efficiency for thermal neutrons, which completely dominate the spectrum; on the other hand, the ^{7}Li-enriched CLYC (CLYC-7) can be used for neutron spectrometry (Giaz et al., 2016).

CLLC, $Cs_2LiLaCl_6(Ce)$ is a brighter scintillator than CLYC, enabling FWHM energy resolution as good as 3.4 % at 662 keV [10]. As a down side, the materials exhibit the same internal radiation as $LaBr_3(Ce)$ due to the presence of La.

CLLB, $Cs_2LiLaBr_6(Ce)$ has an even higher light yield than CLLC, which leads to an energy resolution of 2.9 % at 662 keV (Shirwadkar et al., 2011). The average emission wavelength is at 410 nm. As a down side, the pulse-shape discrimination capability is worse than in CLYC or CLLC. The materials also exhibit the same internal radiation as $LaBr_3(Ce)$ due to the presence of La. Big volume detectors 2"x2" are commercially available.

NaI(Tl) with Li

NaI(Tl) scintillators also sensitive to thermal neutrons can be produced by co-doping the scintillator with lithium enriched with ^{6}Li. Since the lithium concentration within the crystal can reach up to 8 %, very good detection efficiency for thermal neutrons is achieved (Yang, Menge and Ouspenski, 2017). The emission spectrum of lithium-doped NaI(Tl) is very similar to NaI(Tl) without lithium, but the resolution is slightly worse and emission decay time constant significantly longer. Neutron absorption in this material produces a signal with a significantly shorter decay time constant than the signal from gamma rays. In addition, the number of photons produced in neutron absorption corresponds to gamma rays with several MeV of energy. Therefore, very good gamma-neutron separation is achieved with a combination or energy and pulse-shape discrimination. NaI(Tl) scintillators co-doped with lithium are manufactured by Saint-Gobain Crystals (www.crystals.saint-gobain.com/).

4.1.2. Composite scintillators

A composite scintillator is made by optically coupling two scintillator materials together. One scintillator material is selected to be sensitive for neutrons and the other for gamma rays. The main advantage of this approach is that both scintillators can be instrumented with the same photo sensors and electronics. As a disadvantage, the pulse shapes or amplitudes of the two scintillators must differ enough to be distinguished from each other.

As an example, a composite scintillator that is sensitive to both gamma rays and neutrons can be built by adding a ^{6}Li/ZnS coating or film on top of a plastic scintillator (Wilhelm, Nattress and Jovanovic, 2017). The gamma-ray interactions in the plastic produce a very fast pulse, whereas the signal generated in thermal neutron absorption in ^{6}Li/ZnS is much slower. Thus, excellent pulse-shape discrimination can be achieved. It should be noted that the ^{6}Li/ZnS coating impairs the light collection from the gamma scintillator. Thus, the method is not well-suited for applications where the energy resolution for the gamma-ray detector is critical.

4.2. Neutron detection based on neutron-induced gamma rays

Neutron detection capability can basically be added to any gamma-ray detector by adding a material that converts neutrons into gamma rays in the vicinity of the detector. Since the gamma rays produced in neutron absorption typically penetrate the converter material very well, the converter layer can be thick enough to enable almost 100 % conversion efficiency for thermal neutrons reaching the converter. It is worth noting that recoding the gamma rays produced in the converter with good efficiency requires a large detector. Therefore, this method is best suited for radiation portal monitors.

Gd- and Cd-lined scintillators

Gadolinium and cadmium are excellent converter materials due to the high total energy of the gamma cascade produced in the neutron absorption. Good discrimination capability for background gamma rays is achieved by requiring that multiple gamma rays from the cascade are detected in coincidence. This technique has been used to add neutron sensitivity to gamma-radiation portal monitors with plastic scintillator detectors (Fanchini, 2016). The plastic scintillators also act as a neutron moderator and reflector, further improving the detection efficiency. Gd is typically preferred over Cd due to its lower toxicity.

Neutron identification based on high-energy gamma rays

In its simplest form, separate converter material is not even needed, but neutron detection can be based on neutron-induced gamma rays produced either in the source shield, environment, or in the detector itself. The main challenge of this technique is to distinguish between neutron-induced gamma rays and gamma rays from natural background or gamma-ray sources.

Neutron identification is based solely on the energy of the gamma rays. Typically gamma-ray energies above 3.3 MeV are used to identify neutrons, since this energy range is almost free from natural gamma-ray background (Holm et al., 2013). High-energy gamma rays can be recorded with a large NaI crystal that offers a good compromise between efficiency, resolution and price. Detection efficiency can be improved by adding a layer of converter and moderator material around the detector.

4.3. Signal identification methods

Efficient signal identification methods are needed for detectors that are sensitive to more than one type of radiation. For the detectors discussed in this document, signals are classified into up to three categories: gamma rays, thermal neutrons and fast neutrons. The misidentification of gamma rays as neutrons is especially problematic in security applications, since sensitivity requirements for neutrons are very high and the neutron detection capability should not be hindered by gamma rays. False identification would open up the possibility of using gamma-ray sources to mask the presence of a neutron source.

Signal identification is commonly based on three features, i.e. energy, pulse shape and capture time.

Energy

In the simplest case, a signal can be unambiguously identified based purely on the recorded energy. This may be the case in neutron detectors where the magnitude of the signal caused by fast or thermal neutrons is much higher than the maximum signal caused by gamma rays. In this case, the identification is based on a simple energy threshold. Signals above the threshold are classified as neutrons and signals below as gamma rays.

Pulse shape

The unambiguous separation of neutrons and gamma rays is often not possible based on the energy alone, requiring also analysis of the shape of the pulse (waveform). On certain materials, the signal pulse shape depends on the ionisation density, and, thus, on the type of particle interacting in the detector. Generally, higher ionisation density leads to a slower signal. For example, the signal caused by the recoil of fast neutrons with hydrogen is typically slower than the signal caused by Compton electrons produced in gamma-ray interaction. Similarly, the signal from ^{4}He and ^{7}Li produced in thermal neutron absorption in ^{10}B is also slower than the signal caused by gamma rays.

Pulse-shape analysis can be based on various techniques. A classic discrimination method is based on the ratio of the integrated detector waveform before and after a set time boundary. Better performance is sometimes achieved with advanced analysis techniques, such as artificial neural networks or wavelet transform (Ronchi et al., 2009; Singh and Singh, 2015).

Depending on the method used, pulse-shape analysis can sometime be implemented on the field-programmable gate arrays (FPGA) of the data acquisition system. If the pulse-shape analysis is done on personal computer, the signal waveform must be recorded and transferred to the computer, which leads into increased dead time and reduced maximum count rate.

Capture time

In detectors sensitive to both fast and thermal neutrons, the identification of fast neutrons can be based on so-called 'capture gaiting'. This method requires that the same neutrons produce two signals in the detector, one of which is a fast recoil and the other a thermal absorption. When the mean time difference between these two signals is known, it can be used to select events that are most likely caused by fast neutrons. For improved performance, the technique is combined with energy or pulse-shape discrimination that first helps to identify the thermal neutron signal (Wilhelm, Nattress and Jovanovic, 2017; Holm et al., 2014).

5. Photosensors

PMTs are still the most common light sensor used with scintillator detectors. However, several alternative photosensing techniques are also available, which may replace PMTs in the future.

Silicon photomultipliers (SiPM)

SiPMs are good candidates for detector readouts due to their small size, high sensitivity to single photons, efficiency, insensitivity to magnetic fields, low bias voltage, fast timing and linear pulse height response. These properties also allow SiPMs to be used in gamma spectroscopy and in neutron detection with scintillator detectors. SiPM detectors are manufactured, for example, by SensL (www.sensl.com), Hamamatsu (www.hamamatsu.com) and KETEK (www.ketek.net).

Silicon drift detectors (SDD)

With respect to traditional PMTs, SDDs offer a higher quantum efficiency and a very compact form factor. SDDs also have very low noise, as their output capacitance is independent from the area of the photosensitive surface. As SDDs do not have electron multiplication, low-noise amplification is needed to read the small signal. SDDs have especially been developed for applications where the best possible energy resolution is needed (Fiorini et al., 2006). These sensors are not commercially available.

Multi anode PMTs (MAPMT)

MAPMTs behave in the same way as multiple PMT tubes assembled in a single package. This photosensor type is thus often favoured in applications where the location of the scintillation needs to be recorded. For example, a single MAPMT can be used to instrument a segmented scintillator crystal for gamma-ray imaging (Kurosawa et al., 2009). MAPMTs from 4 (2 x 3) to 256 (16 x 16) anodes are manufactured by Hamamatsu (www.hamamatsu.com).

Metal package PMTs

In metal package photomultiplier tubes, a metal package is used instead of a traditional glass envelope. When compared with traditional PMT's, the main advantages are their smaller size and reduced sensitivity to magnetic fields. Metal package PMTs are manufactured by Hamamatsu (www.hamamatsu.com).

Hybrid photodetectors (HPD)

HPDs consist of a photocathode, vacuum tube and an avalanche photodiode. Photoelectrons from the photocathode are accelerated in the vacuum tube by a voltage difference towards the avalanche diode. The multiplication of the photoelectrons in the avalanche diode takes place in two stages: electron-bombardment gain followed by avalanche gain. Due to the very high gain of the first stage, HPDs produce better pulse-height resolution than PMTs. The total gain of HPDs is lower than of PMTs and HPDs are only available in limited sizes. Hybrid photodetectors with a diameter of effective area up to 6 mm are manufactured by Hamamatsu (www.hamamatsu.com).

6 Data acquisition

The miniaturisation of digital electronics has led to the availability of high-performance digital data acquisition systems that sample the detector signal at a high rate. Figure 2 presents a typical digital data acquisition scheme used with modern radiation detectors. Programmable logic (firmware) is implemented in FPGAs or DSPs and allows the digital samples to be processed at a high rate. The embedded algorithms extract the pulse properties of interest: the precise time when the pulse was observed (timestamp), a value proportional to the energy of the radiation (pulse height or integral), or more advanced pulse properties, such as its shape, rise time or decay time. On systems with sufficient data throughput, all samples in the digital signal (the waveform) may be transferred to a more powerful computer system for detailed analysis using advanced algorithms, which are not yet realised in firmware. Pulse properties or digital signals may be stored for offline processing or may be combined in real time with data from other detectors.

The technique of recording data obtained from the pulses individually is called 'list-mode data acquisition'. While this technique has already been in use for a few decades, the true potential of list-mode data acquisition has been unleashed by recent digital electronics, especially in applications where time-correlated data from multiple detectors is analysed.

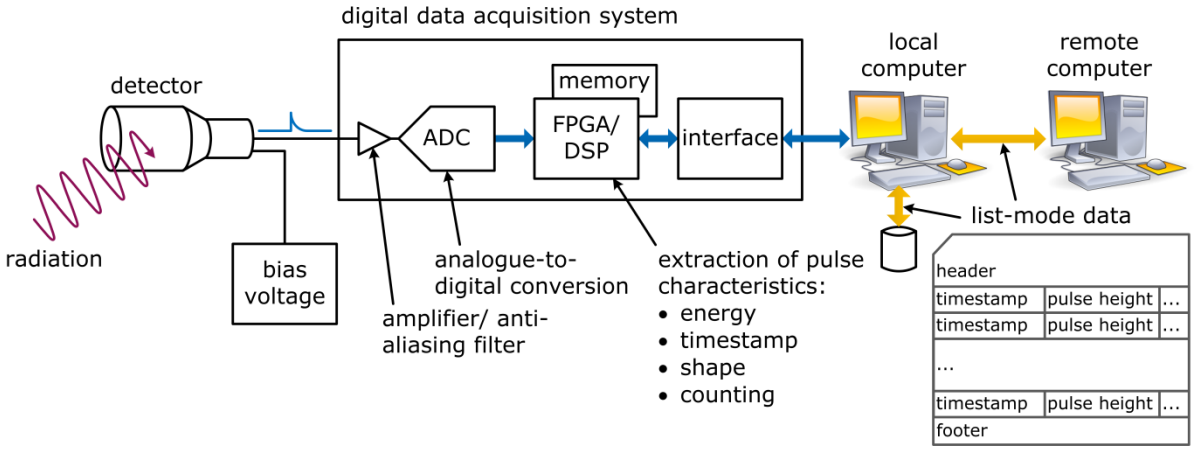

Figure 2. *Typical data acquisition scheme used with modern radiation detectors.*

6.1. Electronics

For decades, Moore's law predicted an exponential improvement in microprocessor performance. While the increase in performance of cutting-edge hardware, such as computer microprocessors would seem to have slowed in recent years, we continue to see rapid progress in other fields of electronics, and thus to different types of electronic devices. This extends to data acquisition systems, where it is now possible to digitise signals with higher resolution in time or amplitude at a lower cost and with lower power consumption than ever before. Similarly, the performance and power efficiency of both programmable logic and microcontrollers has improved rapidly, allowing ever more sophisticated real-time processing of the acquired data.

While specialised instruments, such as detectors for nuclear security applications rarely justify the level of specialisation and miniaturisation expected in, for example, mobile phones, we nevertheless benefit greatly from the advances of such electronics, as many of the circuits developed for such applications are often commercialised as general purpose devices. In particular, analogue to digital converters (ADCs) and digital logic are of great importance in DAQ systems.

For example, 14-bit ADCs used to digitise signals at tens of MHz of sampling rate, as used, for example, in a crystal scintillator-based gamma spectrometer or a Li6/ZnS-based neutron detector, are commercially available for less than EUR 10 per channel from several manufacturers (e.g. Analog Devices, Texas Instruments, Intersil and Microchip Technology). Following decades of development, these parts exhibit not only excellent performance, but also consume surprisingly little power (in the order of 50-100 mW/channel), and are physically quite small (14 mm/sq. mm or less). Thus, a multichannel DAQ system that may in the

past have required several bulky and expensive rack units, or the development of an application-specific integrated circuit, can today be built into a credit card-sized system for handheld devices using only off-the-shelf components.

Similarly, multi-GHz ADCs that were once astronomically expensive, and not always readily commercially available for integration into custom DAQ systems, are today available from several manufacturers at a relatively low cost. Examples potentially relevant to pulse-shape discrimination of pulses from fast scintillators include a EUR 130 2-channel 7-bit 1.5 Gsps device (ADC07D1520 by Texas Instruments), or a 2.5 Gsps 14-bit dual-channel device (ADC32RF82 by Texas Instruments): the latter, a specification that was beyond most people's wildest dreams a decade ago, is now available for a mere EUR 800.

While today's high-performance microprocessors produced for personal computers may not be the best match for the modest (by today's standards) digital signal processing needs of a handheld device, many of the same manufacturers are using only slightly less advanced semiconductor manufacturing processes to make a wide range of cheap and very power efficient microprocessors that will greatly outperform the workstation computers of past decades. Today, a EUR 5-10 device may suffice for implementing the signal processing required in a single channel system operating at tens of MHz, enabling, for example low-cost, battery-powered, handheld spectrometers.

Advances in semiconductor manufacturing also benefit FGPA devices, which are general purpose devices used for implementing the low-level digital circuits usually required when interfacing ADCs, and are also capable of implementing sophisticated digital signal processing. Such devices are often favoured when building data acquisition systems because they allow complex logic to be implemented without the expense or long development time of making application-specific integrated circuits. Like microprocessors, the performance, and thus price of such devices spans a wide range, so while the most powerful devices are both power-hungry and expensive, for most DAQ applications fairly simple FPGAs will suffice nowadays. A EUR 10-20 device may be enough for a system with a few ADCs operating at tens of MHz, whereas multi-GHz systems may require FPGAs in the hundreds of euros, especially if complex pulse-shape discrimination is to be performed in real time.

Finally, the expansion of the electronics industry is continuously making custom-designed electronics more affordable and easier to procure. Not only do today's computers enable advanced CAD systems to designing customized systems rapidly, but the non-recurring engineering costs — once a major investment when starting the production of a new device — has diminished. Similarly, where extensive interaction with manufacturers was once the norm, especially when outsourcing the assembly of circuits onto PCBs, the complete ordering procedure can nowadays often be completed online in a matter of hours.

6.2. List-mode data format

A major issue with digital data acquisition electronics is the lack of a standardised data format, which leads to a lack of interoperability between the hardware that acquires the data and the software that analyses the data. As a consequence, digital hardware cannot easily be interchanged with other models that offer new features of interest. Users and system integrators must therefore put time and effort into developing software to read the different proprietary formats.

Within the framework of European Commission Mandate M/487 to the European Standardisation Organisations, the JRC ERNCIP RN Thematic Group (RN TG) performed the pre-normative research necessary to propose the basic elements for a list-mode data standard, to the appropriate standardisation organisation. The work of the RN TG triggered the creation of a consortium of four EU Member State metrology laboratories (of which three are represented in the RN TG), which receives funding from the EU Horizon2020 research and innovation programme to contribute, along with the JRC, to the development of a new standard. In October 2015, on behalf of the EMPIR 14SIP07 'DigitalStandard' consortium, the JRC submitted a new work item proposal for a data format standard to the International Electrotechnical Commission (IEC), Technical Committee 45 'Nuclear instrumentation'. The JRC leads the development of the new Standard IEC 63047, together with the consortium partners and equipment manufacturers. The publication date of IEC 63047 'Nuclear Instrumentation — Data format for list-mode digital data acquisition used in radiation detection and measurement' is August 2018.

The IEC 63047 format is defined using ASN.1 (Abstract Syntax Notation One), which is a standardised syntax for specifying data formats (ISO/IEC 8824), complemented by a set of encoding rules that define the binary representation of data (ISO/IEC 8825). The ASN.1 specification of the list-mode data format IEC 63047 is human-readable and easy to understand. Software tools are available that create — from the ASN.1 list-mode specification — encoding and decoding routines in various programming languages for various computer platforms. The format is binary for performance reasons and independent of the platform or programming language. The standard enables collation of data from one or more detectors and one or more data acquisition devices. List-mode data packages may be stored in a file or may be streamed over a computer network. The data is canonically-encoded to allow authentication and encryption. The standard format is extensible: existing hard and software will continue to work when the standard is revised at a later stage. The IEC 63047 format is complementary to the IEC 62755 (ANSI N42.42) format. The format will allow the analysis and presentation of data combined from many sources, such as pulses, digital signals, logical values, position and orientation, measurements of any kind, and one and two-dimensional histograms. Features to allow precise timing and synchronisation are foreseen, as well as the representation of any kind of binary or text message.

To support the use of the standard, the JRC is preparing, in close collaboration with the ERNCIP RN TG, open source software for encoding and decoding binary IEC 63047 data, developing training material and a demonstration device built from off-the-shelf components.

7. Source localisation

Instruments for nuclear security are usually designed for the detection and identification of the radioactive source. However, a key piece of information required for field operations — where is the source? — is often missing. Today this is addressed in the Nuclear Security Detection Architecture (NDSA) by a Conops designed for choke point screening, i.e. measuring each person or item in an isolated environment. However, this is not possible in search operations where the measurement geometry is unknown. The frontline officers deserve better operational tools to support their core functionality.

The capability of an instrument to localise the source can be implemented in various ways. With detectors recording the direction of the incoming radiation, two detectors (or two measurements with the same detector) are typically required for localisation (see Figure 3) (Toivonen et al., 2017).

Figure 3. *Principle of source localisation with two direction-sensitive detectors.*

Collimated detectors

The most straightforward localisation method is to use a collimator that is rotated a full 360 degrees. This approach has two drawbacks: the system is heavy (10 kg, or more) and the localisation capability can only be implemented after an alarm signal has been received. However, an operational system (80 kg) has been built in the Russian Federation. In this implementation, a NaI detector is installed in a vehicle and a Pb collimator rotates continuously around the detector (Chuvaev, 2016).

Anti-collimated detectors

The overall idea of source localisation is based on a small shield around the detector that covers the detector's field of view, protecting it against the gamma rays arriving from a point source far away from the detector (>> 1m). Detection capability in search operations is not sacrificed while performing localisation. In fact, this approach is similar to traditional collimation, but without the drawbacks. The system is commercialised by Environics Ltd (RanidSOLO Spectrometric Radiation Source Locator for RanidPro200, 2017).

Gamma cameras

Gamma cameras can be built using three different principles: pin hole, coded aperture or Compton scattering. Such systems are now commercially available. They are well suited to non-dynamic situations with a large amount of radioactive material, but are not search devices that are suitable for the rapid detection of small signals. Portable CdZnTe-based gamma cameras are especially promising, as they can provide very good energy resolution without the need for cooling (iPIX — Ultra Portable Gamma-Ray Imaging System, 9/2015; Polaris-H Gamma Ray Imaging Spectrometer, 2017).

Segmented gamma detectors

A modern approach to solving the localisation problem is to use segmented detectors. The gamma rays may scatter inside the array (Compton scattering). If enough data is collected, the position of the source can be calculated. This can even be implemented in a small handheld device (IDEMIA, 2017).

Segmented neutron detectors

Neutron sources can also be localised with segmented detectors. By measuring the energy and locations of fast neutron scatter events with respect to the absorption location for multiple neutrons, the direction of the neutron source can be estimated statistically. Localisation can also utilise self-shielding, causing a difference in the number of scatter and absorption events on detector segments. The feasibility of this technique has been demonstrated with a relocatable radiation portal monitor prototype (www.nfacet.com).

Detector trace

Localisation can be based on the data processing of gathered spectra when the detector is in motion. GPS provides the position of the device. This data is enough to calculate the source position. The method works but requires further study in light of the uncertainties involved. A study was funded by MATINE in 2013 (Toivonen et al., 2013).

Network of detectors

Data from several instruments, located in different places, can be used to calculate the source position. The instruments must send their data to a central server (reachback centre), where the analysis is performed. This approach, based on simulated data, was shown to work well for a fixed array of detectors (Toivonen et al., 2011).

8. Discussion and conclusions

Novel detection technologies can impact nuclear security in two ways. First, some of the technologies can directly replace existing detection systems, providing gradual improvements to the detection capability. Second, other technologies require a rethinking of the nuclear security detection architecture as a whole. For example, detectors with automated source localisation capability can be installed in a flexible manner. Choke points may therefore not be needed for screening of cargo and people. With a higher level of automation, fewer human resources are required in the field. Combined with reliable data transfer, the final data analysis can be performed in a centralised expert support centre, optimally utilising data from multiple sensors.

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