1
Introduction

1.1
Exploring the Universe by Detecting Photons and Particles

Any of us, at least once in our live, while looking at the bright stars, during a clear night, has asked himself, what is the Universe? From what is all of it made and how did it all begin?

The human eye allows us to see objects emitting or reflecting light in the range of wavelengths from 380 to 760 nm, which is called the ''visible region of the spectrum.'' Therefore, our first experience in observing the Universe is in this visible region (see Figure 1.1).

The visible region is, however, a small part of the entire interval of electromagnetic radiations present in the Universe, ranging from the radiowaves to the gamma rays (Figure 1.2). Besides the electromagnetic radiation spectrum, various elementary particles with energies belonging to a wide range traverse the Earth's atmosphere and reach the ground level. The study of both radiations (electromagnetic radiation and particles) obviously provides much more information about the Universe and its properties than the simple observations made only in the visible region. The detection (and imaging) of this ''invisible'' messengers becomes possible only with the help of special devices, which have enabled scientists to achieve fundamental discoveries, for example, the existence of X-ray sources in the galaxy and γ-bursts. Radiation detectors are nowadays used in many laboratories for basic research and in various applied fields from medicine to industrial uses.

This book focuses on the so-called gas-filled detectors, which have several important advantages over other types, that is, the cost effectiveness of covering large detection areas, the insensitivity to magnetic fields and the capability to detect photons from visible light to X-rays, gamma radiation as well as charged particles.

According to their historical development, gaseous detectors can be schematically divided into two classes: ''first generation detectors,'' which feature a limited imaging capability (basically single-wire counters and parallel-plate spark and streamer chambers developed before 1968) and ''novel generation detectors'', which, developed after 1968, feature high position resolution, and the capability of performing an electronic image processing (multiwire proportional counters, drift

Imaging Gaseous Detectors and Their Applications, First Edition. Eugenio Nappi and Vladimir Peskov.

Figure 1.1 Sky view during a clear night. (For a color version of this figure, please see the Color Plates at the beginning of the book.)

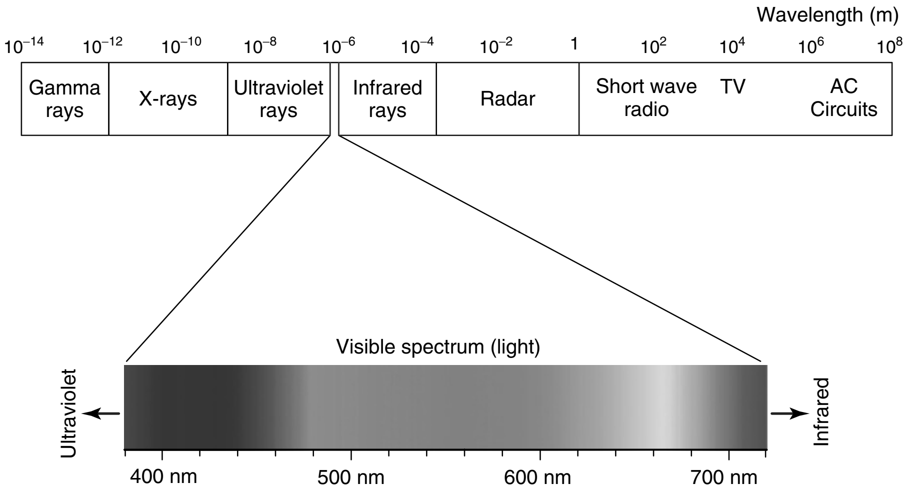


Figure 1.2 Schematic classification of the various intervals of the electromagnetic spectrum. (For a color version of this figure, please see the Color Plates at the beginning of the book.)

chambers, time-projection chambers, photosensitive detectors, and micropattern gaseous detectors).

"First generation" gaseous detectors are exhaustively described in numerous excellent books, see for example [1–5], therefore we will briefly review only the most significative examples of them in this book. Conversely, we will focus on developments and breakthroughs achieved after 1968.

1.2
Detectors of Photons and Charged Particles

Detectors can be classified into four main categories: vacuum, gaseous, liquid, and solid-state according to the medium in which the impinging radiation interacts.

In order to better describe the role of gas-filled detectors, hereinafter a short review of each category of existing position-sensitive detectors of photons and charged particles will be provided.

Most detectors work on the basis of the same operational principle and, as a consequence, they share a common design structure. They usually consist (with some rare exceptions) of the following four subsequent parts: (i) a transducer of the incident radiation into primary electrons, (ii) a primary electron multiplication structure, where the primary electrons create many secondary electrons, (iii) a transfer region, where secondary electrons are drifted by an electric field to the readout electrodes, and (iv) a collection-electrode structure.

The basic operational principle is as follows. The incident radiation creates primary electrons (in some cases electron–ion pairs) in the convertor. These electrons, under the influence of the applied (by the detector electrodes) electric field, drift to the electron multiplication structure, where each primary electron creates a certain number, A, of secondary electrons, often called the ‘‘multiplication factor.’’ Depending on the detector type, the multiplication factor ranges typically between 10^2 and 10^7. These secondary electrons are then collected on a system of electrodes where they produce fast electronic signals. The rise time of the electronic signal could be much less than microseconds. By measuring these signals (by front-end microelectronics equipped with compact charge-sensitive amplifiers or, in some cases, current amplifiers) one can electronically detect the radiation, obtain positional information about this radiation and, whenever necessary, visualize it (transfer it to a visible image), and measure its characteristics, for example, its energy.

The type of detector: ‘‘vacuum,’’ ‘‘gaseous,’’ and so on, indicates in what media the electron multiplication occurs. For example, in the case of a gaseous detector the multiplication occurs in gas media.

The majority of vacuum detectors are sensitive to visible light and to wavelength intervals close to the visible region: Ultraviolet (UV) and infrared. Some vacuum detectors, for example, Microchannel Plates (MCPs), can be sensitive to soft X-rays.

Modern gaseous imaging detectors can be sensitive to a wide range of wavelength intervals: from visible light to X-rays. They are also widely used for the detection of elementary charged particles.

Liquid detectors are usually used to detect strong fluxes of X-rays and high-energy particles. Finally, solid-state detectors, similar to gaseous detectors, are capable of detecting electromagnetic radiation from infrared to X-rays and are capable of detecting elementary particles. In some applications they are the main competitor of gaseous detectors.

Above, we discussed a very generalized detector structure, in fact some gaseous detectors do not contain the secondary electron-transfer region. Most of the conventional liquid detectors and some solid-state detectors do not have a multiplication structure but they only have the electron-transfer region; in this case only primary electrons are detected on the readout electrodes.

In practice, vacuum, gaseous, or solid-state detectors are very often combined with scintillators, or the so-called Cherenkov radiators (see Sections 6.4 and 9.1.1 for more details); this allows an extension of their sensitivity to photons and particles having very high energies.

In the following, each type of detector will be briefly discussed.

1.2.1 Vacuum Detectors

The combination of an electron accelerator and a vacuum imaging detector, known practically to everybody today, is the TV tube successfully used in some researches although, this device has a rather limited capability as a pure research tool. In many studies, scientists prefer to employ detectors having a much better sensitivity and timing characteristics and, most important, having a fast electronic readout allowing various bits of information online and offline to be stored and treated.

This is why most of vacuum detectors used in research today have a different concept from the TV set; they are usually based on vacuum detectors such as the MCPs and various position-sensitive vacuum photomultipliers which nowadays are widely used not only in laboratories, but also in space research and in various other applications (such as military or medical).

The most common vacuum detectors are the Photomultiplier Tubes (PMTs) [15].[1] Hereinafter, we describe another vacuum device, the Micro-Channel-Plate photomultuplier (MCP-PMT), which offers a high position resolution. A schematic design of the MCP-PMT is shown in Figure 1.3.

It consists of a ceramic envelope with a window transparent to the radiation to be detected (visible light, UV, or infrared radiation), housing an electron multiplication structure and a system of collection electrodes. The inner part of the window is usually coated with a thin layer of a photosensitive material called the photocathode, which converts the impinging light into primary electrons. In this design, capillary plates, called Micro-Channel-Plates (MCPs), are used as the multiplication structure. The MCP is a two-dimensional array of hollow lead-glass fibers fused together into a thin disk (see Figure 1.4).

The MCP features the following sizes: a diameter of 20 mm (some companies produce MCPs with an active area as large as $10 \times 10\ \text{cm}^2$), thickness up to 1–2 mm, hole diameter $\sim$10 μm. The open to total area ratio of the capillary plate is typically 50%. The flat surface of the capillary plates is metalized for allowing the

1) Vacuum photomultipliers have the same design and principle of operation as described in Section 1.2.1 for MaPMTs, however they are not position sensitive.

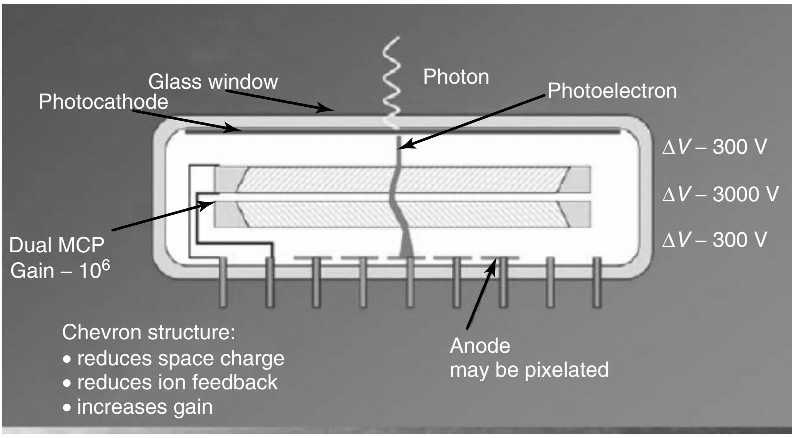
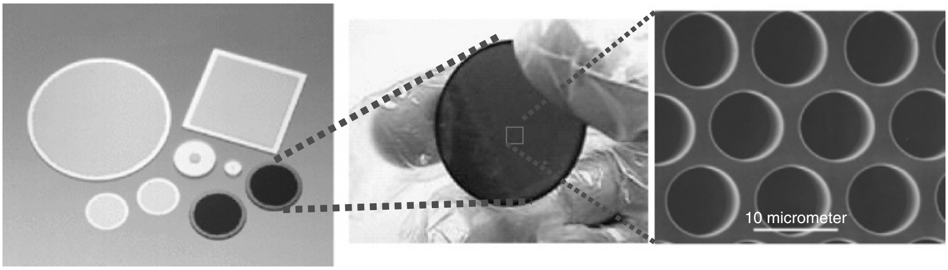


Figure 1.3 Schematic drawing of a MCP-PMT detector (from Ref. [6]).



Physical Parameters of MCP and CP

Material	Lead Glass
Outer Diameter (mm)	10–100
Package Density (cm^{-2})	–10^6
Thickness (mm)	0.2–2
Channel Diameter (μm)	5–200
Electrode Material	Inconel or Ni-Cr
Resistivity (Ω)	10^6–10^{10} : 10^{15}
Bias Angle (degree)	5–15 : 0

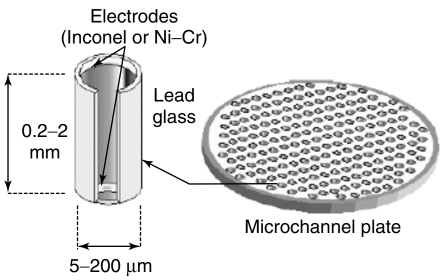


Figure 1.4 Capillary plates used in the MCP-PMTs (and in some other devices, for example, in gaseous detectors – see Sections 1.2.2 and 8.6.1.) (from Ref. [7]).

application of a voltage potential across the capillaries. The inner surface of each capillary is coated with a chemical compound featuring a high secondary electron emission factor.

The secondary-electron emission effect occurs whenever electrons with a high enough kinetic energies strike a surface inducing the emission of one or more additional electrons. The number of emitted secondary electrons depends not only on the energy of the primary electrons, but very strongly also on the surface material. Some materials, for example caesium antimony, feature an extremely high secondary-electron emission yield.

The principle of operation of a MCP-PMT is described hereinafter. The light hitting the photocathode creates, by photoelectric effect, photo-electrons which, under the influence of the electric field applied between the photocathode and the top surface of the capillary plate, accelerate and hit the inner surface of the holes in the capillary plate and create more secondary electrons. These electrons, in turn, because of the voltage potential applied between the capillary plate electrodes, accelerate and hit again the hole's wall and create more secondary electrons. By this effect, the multiplication process of the photo-electrons occurs. With a single capillary plate one can achieve a multiplication factor of about 10^3-10^4. In order to enhance the multiplication factors up to 10^6, usually two capillary plates operating in cascade mode are used. The created secondary electrons are subsequently collected by a system of discrete electrodes (strips or pads). The signals induced on these electrodes can be treated by several methods, depending on the particular application, an image of the radiation that hits the photocathode of the MCP-PMT is eventually obtained.

MCP-PMTs have an excellent position resolution (~10 μm) (see Figure 1.5), a very good time resolution (<100 ps) and a rather high efficiency for detecting photons.

Some MCP types are sensitive to X-rays and charged particles. Owing to all these unique properties, MCPs have a wide range of applications in laboratories and elsewhere.

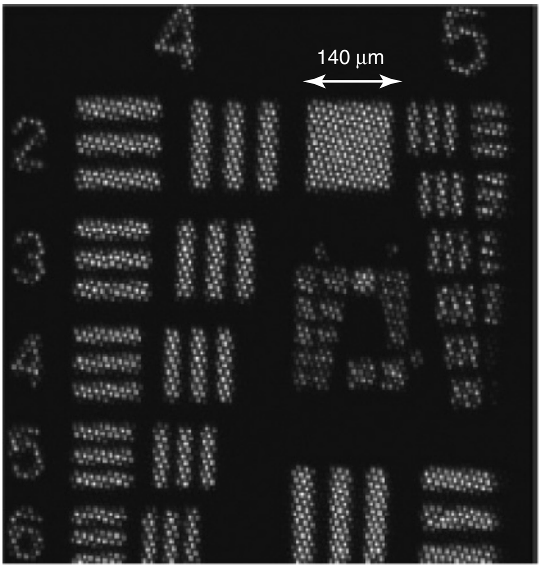


Figure 1.5 UV image of the US Air Force test pattern obtained with a MCP-PMT with hole diameters of 10 μm. The white spots correspond to the image of the holes, entailing that a position resolution of about 10 μm was achieved [8].

As any detector, MCP-PMTs also suffer of disadvantages. They have a relatively short ''lifetime'' (the time during which the device performance remains unchanged) along with low rate capability due to the high resistivity of the MCPs, and a limited radiation ageing (degradation of the MCP performance under the influence of a strong radiation flux).

Besides MCP-PMTs, another vacuum photon-imaging detector, widely used in basic research and applications, is the Multianode Photomultiplier (MaPMT) [9].

Actually, this device has a design very similar to the one shown in Figure 1.3 although, as multiplication structure, capillary plates are replaced by a system of subsequently located ''dynodes'' – a structure of secondary-electron emitters. The dynode geometry depends on the specific design. In fact some former MaPMTs prototypes were equipped with drilled plates, somehow similar to the capillary plates but made of different materials and having different size and dynode arrangement inside the MaPMT. At present, some commercial MaPMTs exploit fine-pitch meshes coated with a thin layer of a cesium-antimony secondary-electron emitter (see Figures 1.6 and 1.7).

The typical position resolution of a MaPMT is a fraction of millimeters. Despite the worse position resolution of the MaPMTs, compared to MCP-PMTs, other features, like the pulse height spectrum corresponding to single photons or the radiation hardness are superior.

Thus, despite the similar concept of these two imaging detectors they show different features because of some differences in their designs.

In the choice of which type of imaging detector one must use, many parameters should be evaluated: the lifetime, the level, the radiation hardness, the sensitivity to the magnetic fields, the time resolution, cost, and many others.

This is why in some applications MCPs are more suitable, whereas in others the MaPMTs are preferred.

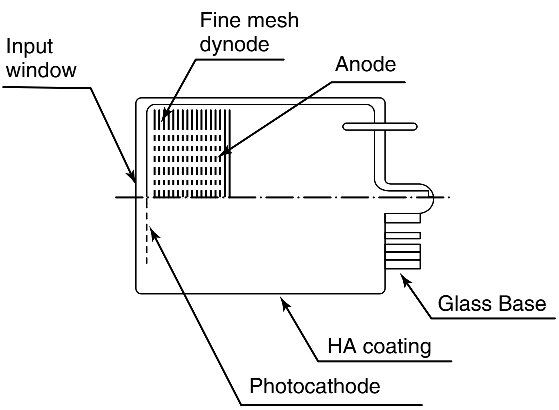


Figure 1.6 Schematic view of a commercially available MaPMT with fine mesh dynode structures [10].

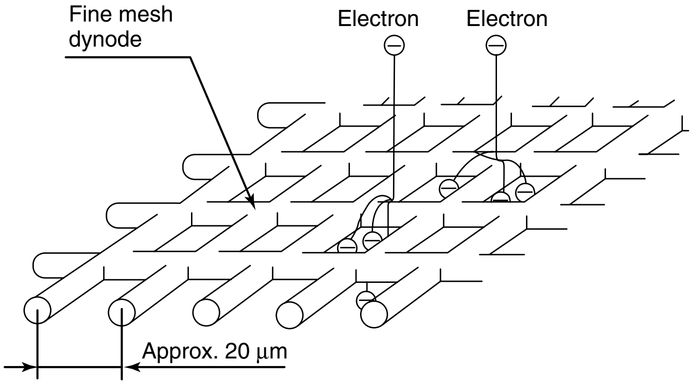


Figure 1.7 Schematic drawing showing the process of secondary-electron emission in the fine mesh electrode of a MaPMT [10].

1.2.2
Gaseous Detectors

Gaseous detectors are based on the process of electron multiplication in gases, which was discovered at the beginning of the last century by Townsend [11] and is now called the Townsend mechanism or Townsend avalanches process. In the remainder of this book, the principle of the gas avalanche-multiplication process will be discussed more times and a detailed description will be given. Through the development of the Townsend avalanches, a multiplication factor as high as 10^6-10^7 and a position resolution close to that obtainable with vacuum devices can be achieved (Figure 1.8).

Conversely to vacuum devices, gaseous detectors operating at a gas pressure of 1 atm do not suffer from any serious mechanical constraints, enabling the construction of cost effective very large sensitive area detectors (up to 10–100 m^2!)

1.2.3
Liquid Detectors

In these detectors, a liquid medium is used to convert the radiation (in the energy range from UV to X-rays and even to gamma rays) to primary electrons. Two main types of liquids are used: various hydrocarbons and liquified noble gases (Ar, Xe, etc.). In the first case, the detector operates at room temperature, whereas in the second case cryogenic temperatures are necessary. Most of the conventional liquid detectors (except some prototypes) do not have a multiplication structure. Therefore, they simply consist of an electron-conversion region and an electron-transfer region equipped with a system of readout electrodes (a dielectric plate covered with metallic strips or some, typically three, planes made of thin metallic wires). The radiation produces electron–ion pairs in the liquid medium that drift to the pickup electrodes and induce signals there. The image of the

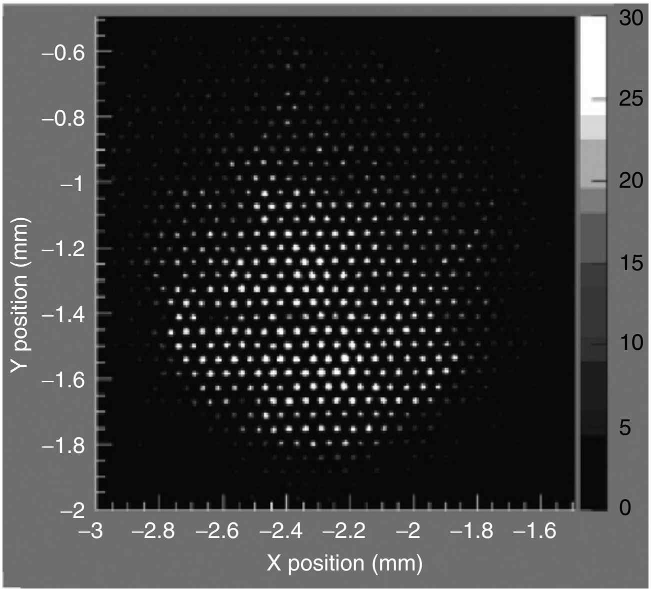


Figure 1.8 Image obtained by a gaseous detector (similar to that shown in Figure 1.4, but made of Kapton sheet) exploiting the electron multiplication process by Townsend avalanches occurring inside the holes. The hole pitch is 50 μm, meaning that a position resolution better than 50 μm was achieved [13]. (For a color version of this figure, please see the Color Plates at the beginning of the book.)

detected radiation can be reconstructed by a computer treatment of the acquired signals.

As an example, Figure 1.9 shows a gamma-ray image of the phantom of a human head (irradiated by a ^{60}Co beam) obtained using a warm liquid detector specifically designed for medical digital radiography applications [14].

Most noble-liquid detectors operate as ‘‘time-projection chambers’’ (see Sections 6.2 and 9.2.3 for more details). In these liquids, the absorbed radiation produces not only electron–ion pairs but also, simultaneously, a very short burst of scintillation light. This light is detected by a system of vacuum photomultipliers (PMTs). The PMT signals provide at what time the interaction of the radiation with the noble liquid occurred. The primary electrons, created by the radiation, drift toward the readout electrodes and induce signals there. By measuring simultaneously the arriving time of these electrons and their position on the readout plane, one can reconstruct the three-dimensional image of the interaction points of the various ionization tracks created in the liquid by the absorbed radiation. As an example, Figure 1.10 shows a 3D image of a muon track detected by the ICARUS (Imaging Cosmic And Rare Underground Signals) LAr detector [16].

Of course, such detectors without a multiplication structure have a limited sensitivity since only primary electrons are collected on the readout electrodes. For this reason, several groups have tried to exploit the avalanche multiplication

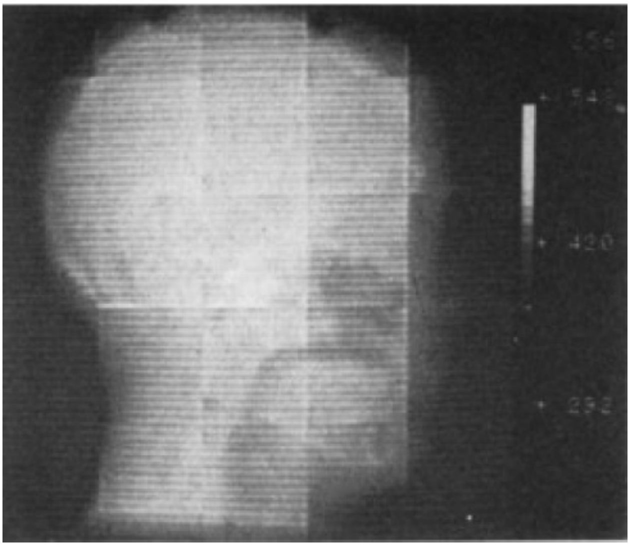


Figure 1.9 Liquid ionization detector imaging the head of an Alderson Rando phantom in a ^{60}Co beam.

process of primary electrons inside noble liquids. For example, in [17], the avalanche multiplication of primary electrons in a LXe detector has been achieved near very thin ($<10\,\mu m$) metallic strips manufactured on the surface of the readout glass plate. Note that a similar strip-based amplification structure was already used in the past to achieve avalanche multiplication in gases, and this detector type was called ''microstrip gas chamber'' (see Chapter 8). Another team [18] investigated the possibility of using a readout plate equipped with thin needles, which created avalanches near their sharp tips (a similar amplification structure was also used in gaseous detectors [19].)

However, today the most promising way to multiply primary electrons is by employing specially arranged electrode structure, which extracts primary electrons from the liquid phase to the gas phase (vapors above the liquid level). These electrons are subsequently multiplied by means of hole-type avalanche multipliers as those briefly described in Section 7.2.3. See Figure 1.11 and [20].

This method, owing to the high multiplication factor achieved, provides a so high sensitivity that researchers are even able to detect the few primary single photoelectrons created inside the noble liquids [21]. Probably, this technique will be used in various future noble-liquid detectors, especially for searching dark matter. Very likely, there will be the possibility to use the same method also in the case of some ''room-temperature'' liquids. Some preliminary experiments have already been performed in this direction (see for example [22] and references therein).

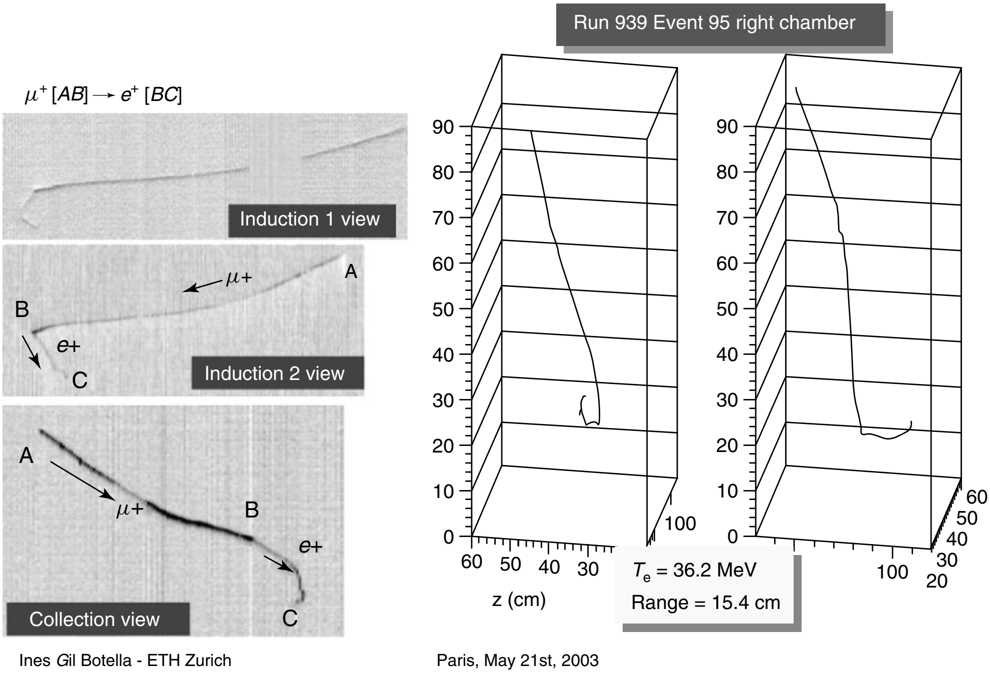


Figure 1.10 (right) 2D view of a stopping muon event. (left) The reconstructed (from timing measurement) 3D image, [16].

1.2.4 Solid-State Detectors

Solid-state imaging detectors are very popular nowadays and are used in many applications.

The most common solid-state detector is the so-called ''charge-coupled device'' or CCD,[2] widely used in modern photo- and video cameras. Beside this massive application, CCDs are often used in research as, for example, in astrophysics experiments as well as in commercial devices as those employed for medical imaging. However, CCD detectors have limited capacities when compared to other research tools since in many studies, scientists prefer to have detectors that operate much faster, have much higher sensitivity, and are capable of measuring the energy of the radiation.

There are various types and designs of solid-state detectors that satisfy the rapidly growing demands of researchers. The majority of the detectors used today, similarly to liquid detectors, do not have an amplification structure. Solid-state detectors have two main advantages over other detector types: (i) owing to their high density (almost 3 orders of magnitude higher than gases) the radiation-absorption region

2) For the invention of the CCD, W. Boyle and G. Smith were awarded the Nobel prize in Physics in 2009.

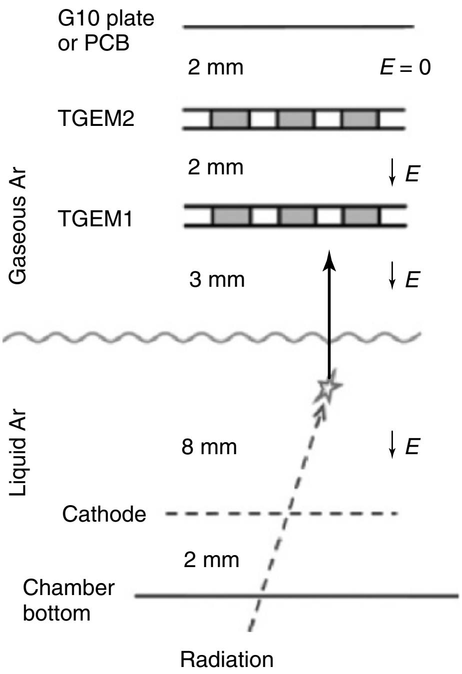


Figure 1.11 Schematic drawing of a noble-liquid detector in which primary electrons, created by the radiation inside the liquid volume, are extracted into the gas phase where they further experience an avalanche multiplication through a two hole-type structures called Thick GEM (TGEM) operating in cascade mode (from Ref. [20]).

and the amplification region (for the designs envisaging it) are very thin, which make the detector very compact in one dimension and (ii) the energy required to create an electron–ion pair in a solid-state detector is roughly 10 times smaller than that of the gaseous detectors, Therefore, the radiation creates ~10 times more primary electrons than in the case of gases. The latest feature allows, in some cases, detectable signals to be obtained even without the amplification structure. Moreover, this feature allows high energy resolutions (for more details about the definition of energy resolution see Section 3.1.2.1) to be achieved. Therefore, solid-state detectors are able to perform spectroscopic measurements: that is, a quite accurate measurement of its spectrum.

Among the various solid-state imaging detectors, the simplest design is the so-called CZT detector manufactured from a CdZnTe (CZT) semiconductor. This compound is based on CdTe in which a fraction of the Cd content is replaced with Zn. As a result, the excellent electron-transport properties of the initial material are preserved, but the high resistivity of the new material, allows a simple planar design to be used – see Figure 1.12. Such detectors operate similarly to liquid detectors without a multiplication structure: incident radiation creates primary electron–hole pairs (like the electron–ion pairs in liquids and gaseous detectors). Primary electrons drift to the anode electrode and induce signals there. By placing orthogonal strip electrodes on the two faces, or an array of pixelated electrodes on one face, a wafer can be segmented, thus enabling operation as a position-sensitive detector.

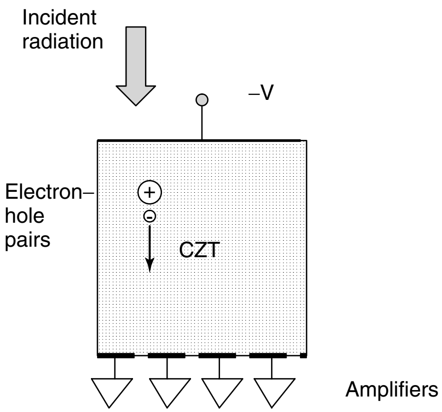


Figure 1.12 Schematic drawing of the CZT detector illustrating the principle of its operation.

The great advantage of the CZT (compared to some other semiconductor materials) is that it can satisfactory operate at room temperature. In some applications, the CZT detectors are cooled, allowing a further reduction of the leakage current and an improved signal-to-noise ratio.

One should notice that the CZT is a unique material. The first CZT detectors were developed in 1998 and they are now being used in more and more applications. Because of their high stopping power, CZT detectors are especially attractive for the detection of hard X-rays and gamma rays, making their applications to range from the medical and security fields to astrophysicals.

Most of the common semiconducting materials (for example, Si, GaAs, Ge) do not have highly enough resistivity and thus cannot be exploited in the simple arrangement shown in Figure 1.12: if one applies the voltage across the detector, a large leakage current occurs, which strongly enhances the noise level and imposes a major limit on the detector sensitivity. The leakage current is directly proportional (in a simplified model) to the concentration of the free charge carriers in the material. The standard way to reduce the leakage current is to create the so-called depletion zone and cool the detector. There exist two types of semiconductors: n-type, where the charge carriers are electrons, and p-type, in which the charge carriers are positively charged "holes." The p-n junction is the layer placed between the n- and p-type semiconductors – see Figure 1.13. If one applies a reversed electric field, a depletion zone with a reduced concentration of free carriers will be formed (like diodes with a reversed field). For simplicity, the picture presented here is very schematic. In reality, the regions close to the metallic contacts are very heavily doped and there are many other details to be considered. However, besides these details, the principles of operation and signal formation are the same as in the CZT detectors: radiation creates electron and ion holes in the depletion zone that then drift to the electrodes and induce signals there.

Solid-state detectors with microstrips or pad electrodes provide a very high position resolution (a few micrometers), fast response (up to a few nanoseconds), and excellent energy resolution. They are widely used in various fields (especially in

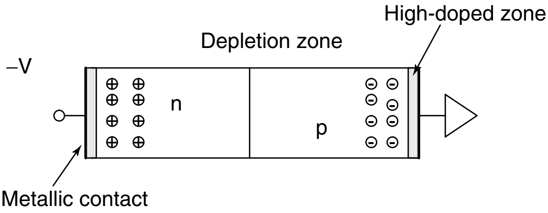


Figure 1.13 Schematic drawing of a solid-state detector with a depleted zone.

high-energy physics and astrophysics) as well as in many important applications, including medical ones.

Recently, the development of solid-state imaging detectors has gained a new momentum: new designs have appeared on the market that, similarly to gaseous detectors, are able to operate with avalanche multiplications (in this case, however, the avalanches occurs inside the solid material). Nowadays, the main interest of researchers is focused on the so-called "silicon photomultipliers" or SiPMs – a matrix of microdetectors (see Figure 1.14) each of them operating in avalanche mode. A series of several subsequent and rather sophisticated material treatments allows an extremely high electric field to be created in the p-n junction. One of them, for example, is the creation of a highly doped area around the junction. The principle of operation of this detector is very similar to that of the gaseous devices: primary electrons created by external radiation (for example, by visible light) inside the detector drift to the p-n junction where, in the region of very high electric field, they trigger the avalanches. Applying a reverse-bias voltage (typically 100–200 V), multiplication factors of about 100 can be achieved (see Figure 1.15).

When the applied bias voltage exceeds the limiting value $V > V_{BD}$, a continuous discharge develops in the detector volume. However, since each pixel is connected

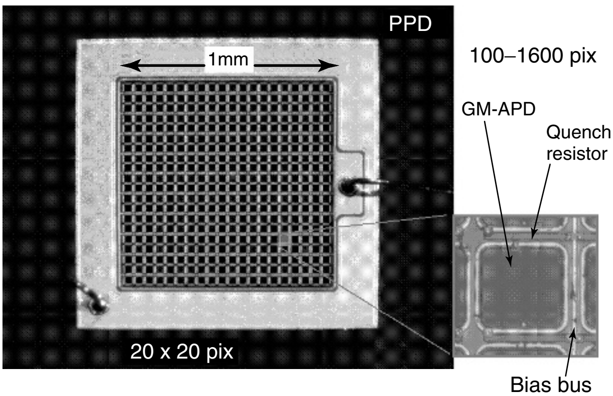


Figure 1.14 Photo of a SiPM matrix containing 20 × 20 pixels [23].

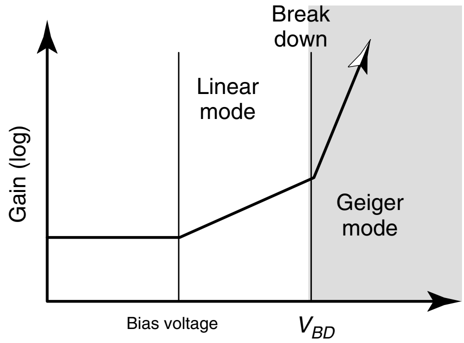


Figure 1.15 Typical dependence of the avalanche gain (multiplication factor) vs. the voltage applied to SiPMs [23].

to the common bias voltage through independent microresistors integrated within the sensor chip, the discharge is quenched because the effective bias voltage drops below V_{BD}. This mode of operation is named "Geiger mode" (GM). As will be shown in the next chapter, very similar effects occur in gas avalanche detectors called Geiger detectors. In Geiger mode, the multiplication factors achieved with SiPMs are sufficient to detect single photoelectrons (and thus single photons). In spite of a high rate of noise pulses (which can be strongly reduced by cooling) this detector can operate perfectly well at room temperature in the "coincidence mode" in which the readout electronics acquire the signals from the SiPM matrix within a short time interval defined by an external triggering device. An external trigger can be initiated, for example, by a charged particle traversing a system of detectors.

The photon detection efficiency of the SiPMs can be made even higher than that of vacuum photomultipliers, therefore SiPMs can compete with vacuum imaging devices in several applications.

Despite the great popularity of solid-state detectors, some of them suffer serious disadvantages, for example, high cost, the necessity for cooling and radiation damage induced by neutrons.

As will be shown later in this book, modern gaseous detectors, especially the micropattern one (see Chapter 8), are capable of competing with solid-state detectors in applications requiring a low cost or the coverage of large sensitive areas.

1.2.5
Combination of Imaging Detectors with Scintillators

In some studies and applications, imaging detectors are used in combination with scintillators. Scintillators are materials that emit a short burst (typically lasting less than 1 μs) of visible or UV light when a high-energy radiation (X-rays, gamma rays) is absorbed by them or when high-energy charged particles traverse them. In this way, the photodetectors that are originally sensitive only to UV or visible light

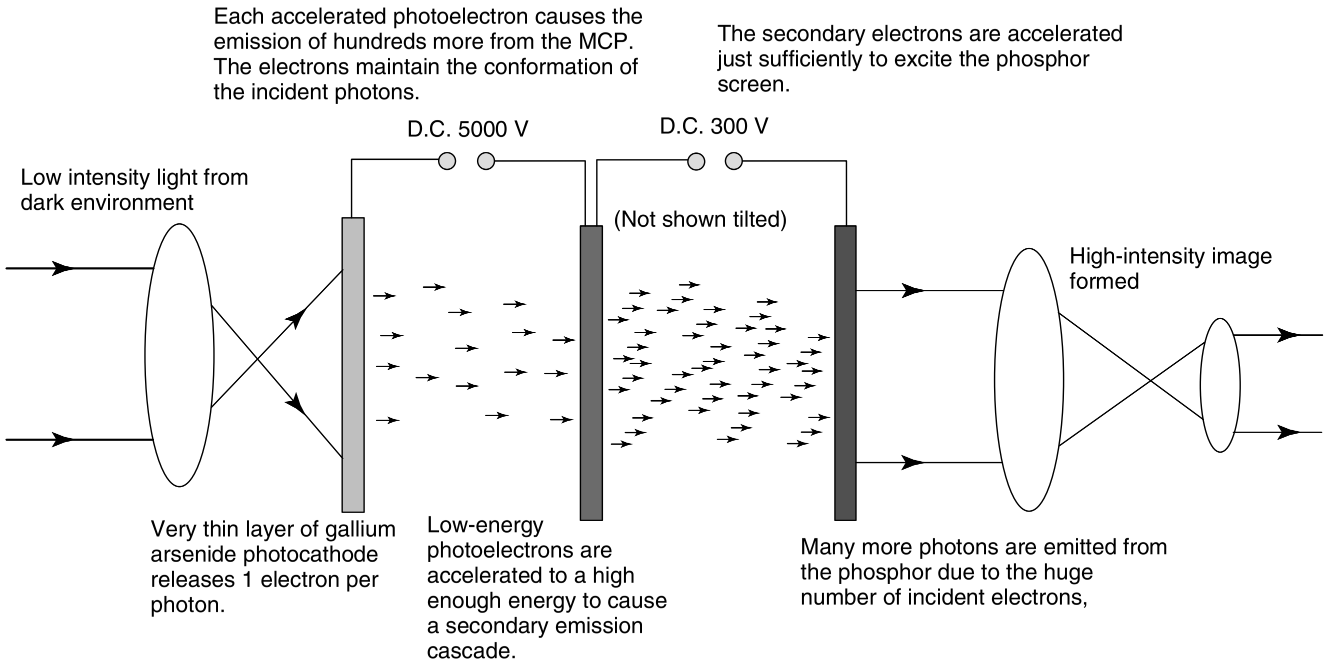


Figure 1.16 Schematic drawing illustrating the principle of operation of a night imaging device.

are able to detect high-energy radiations. In principle, scintillators can be gaseous, liquid, or solid. However, in practice, the most commonly used are solid scintillators, which are easy to handle and have sufficient stopping power for high-energy radiations. To better exploit the position sensitivity of the photodetectors, the coupled scintillators are usually segmented in small individual pieces. This approach, for example, is widely used in Positron Emission Tomography (PET).

1.2.6 Hybrid Imaging Detectors

Besides the four main types of imaging detectors, briefly described above (vacuum, gaseous, liquid, and solid), there exist also hybrid detectors, which combine two or more detector types into the same design.

Various vacuum, gaseous and liquid hybrid detectors designs have been developed.

1.2.6.1 Vacuum Hybrid Detectors

A typical example of a vacuum hybrid detector is the one employed in night imaging devices, which combine a standard image intensifier[3)] with a MCP and, in some cases, MCPs and CCDs. Figure 1.16 schematically shows such a design. This detector, depending on the photocathode material can be sensitive in the range from infrared to UV. The photons undergo a photoelectric effect, which create photoelectrons that are accelerated and hit the MCP where they produce secondary electrons. These electrons, extracted from the MCP, again accelerate, hit and excite a phosphor screen. The image obtained on the phosphor screen can then be read out by several methods: either simply using the human eye or, in more sophisticated devices, by the combination of a CCD with a phosphor screen via fiber optics. Present versions of image intensifiers, similar to TV tubes and CCD cameras, are relatively slow devices making their fields of applications very restricted; mainly to military purposes and in research – such astrophysics, biology, and in some experimental medical devices.

''Fast'' hybrid vacuum devices that satisfy the requirements of modern high-energy physics experiments are a combination of an ''image intensifier'' with a silicon position-sensitive detector – see Figure 1.17.

In this device, photoelectrons accelerate in a high electric field and hit the Si matrix surface, penetrate inside the detector, and create a large number of electron–ion pairs. These charges are eventually detected in a solid-state position-sensitive detector.

The unique property of this type of detectors is the capability to resolve single photons. If the detector is irradiated by a few photons the pulse-height spectrum, as measured by the Si detector, will consist of several narrow peaks corresponding to one, two, three, and more photoelectrons [26]. This entails that such a

3) Vacuum image intensifiers are rather old devices routinely used in medical X-ray imaging – see, for example [24].

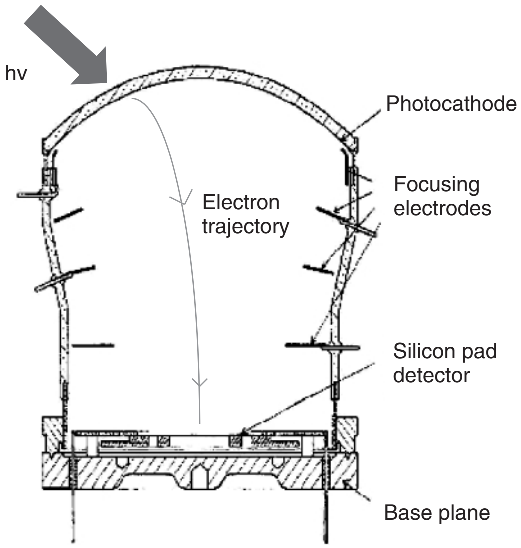


Figure 1.17 Schematic drawing of a fast hybrid detector (from Ref. [25]). (For a color version of this figure, please see the Color Plates at the beginning of the book.)

hybrid detector, combined with a scintillator, performs much better spectroscopic measurements (measurements of the absorbed radiation energy spectra) than any other vacuum photodetector. Another popular field of application of this hybrid device is in the detection of Cherenkov rings produced by fast charged particles crossing Cherenkov radiators: solid, liquid, gaseous, or aerogel (see [27]). The analysis of the resulting patterns allows the determination of the charged particle velocity.

The main disadvantage of vacuum hybrid detectors is their sensitivity to magnetic fields, more relevant when they are used in high-energy physics experiments.

1.2.6.2 **Gaseous Hybrid Detectors**

Besides the rather widely used gaseous detectors combined with solid and gaseous scintillators (see [28, 29] and Sections 7.1 and 7.3 for more details) there have been continuous efforts from various research groups to develop hybrid gaseous detectors made by combining solid convertors of photons (in which the radiation converts to primary electrons) with gas amplification structures. These detectors are still in their early developing stages, more details will be provided in Sections 9.3 and 9.4 [30, 31].

1.2.6.3 **Liquid Hybrid Detectors**

A type of liquid hybrid detector, the so-called ''double-phase noble-liquid detector,'' was already mentioned in Section 1.2.3. In this detector, hole-type structures are used to multiply primary electrons extracted from the liquid to the gaseous phase. They are still in the prototype phase, and they are used in few laboratories.

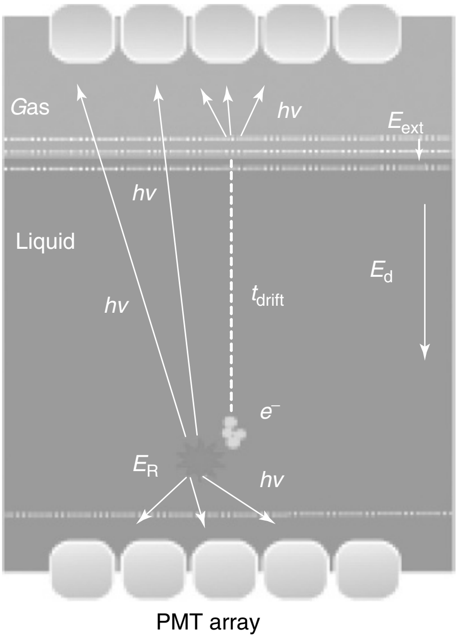


Figure 1.18 Schematic drawing of a dual-phase hybrid noble-liquid detector [32].

On a larger application scale, another type of hybrid gaseous detector is similar to the one described in Section 1.2.3: the radiation absorbed in noble liquids simultaneously produces a short burst of primary scintillation light and electron–ion pairs. Primary electrons are then extracted to the gaseous phase (vapors above the liquid). In the gaseous phase they drift to the gap between two parallel metallic meshes – see Figure 1.18.

The voltage applied between these meshes is not sufficient to start avalanche multiplication, but it is high enough to trigger an electroluminescence effect: electrons drifting in the gap excite atoms of the noble gas that emit ''secondary'' UV scintillation light. This light is detected by an array of vacuum or solid-state detectors. The analysis of the signals obtained from these detectors (produced by the primary and the secondary scintillation light) allows the determination of the radiation energy and the place where the absorption happened.

The main application of these hybrid detectors is for searching dark matter.

References

1. Kleinknecht, K. (1986) *Detectors for Particle Radiation*, Cambridge University Press, Cambridge.
2. Ferbel, T. *et al.* (1991) *Experimental Techniques in High-Energy Nuclear and Particle Physics*, 2nd edn, World Scientific, Singapore.
3. Grupen, C. *et al.* (1996) *Particle Detectors*, Cambridge University Press, New York.

4. Knoll, G. (2000) *Radiation Detection and Measurement*, 3rd edn, John Wiley & Sons, Inc., New York.
5. Leroy, C. *et al.* (2004) *Principles of Radiation Interaction in Matter and Detection*, World Scientific, Singapore.
6. Musienko, Y. (2008) SiPMs, Presentation at the 5th International Conference on New Developments in Photodetection, Aix-les-Bains, France, June 2008.
7. Tokanai, F. (2008) Development of capillary-based gaseous detectors, Presentation at the 5th International Conference on new Developments in Photodetection, Aix-les-Bains, France, June 2008.
8. Bellazzini, R. *et al.* (2008) *Nucl. Instrum. Methods Phys. Res. A*, **591**, 125.
9. Vertilon corporation products (see: *http://www.vertilon.com/mapmts.html*.)
10. Yoshiza, Y. *et al.* (1997) *Nucl. Instrum. Methods Phys. Res. A*, **387**, 33.
11. Townsend, J.S.E. *Philos. Mag.*, June 1901, April 1903, September 1903, November 1903.
12. Iacobaeus, I. *et al.* (2004) *IEEE. Nucl. Sci.*, **51**, 952.
13. Bellazzini, R. *et al.* (2007) *Nucl. Instrum. Methods Phys. Res. A*, **581**, 246.
14. Meertens, H. *et al.* (1985) *Phys. Med. Biol.*, **30**, 313.
15. Flyckt, S.O. and Marmonier, C. (2002) *Photomultiplier Tubes: Principles and Applications*, Philips Photonics, Brive.
16. Sala, P. *et al.* (2003) *Proceedings of the 28th International Cosmic Ray Conference, Tsukuba, Japan, July 31 – August 7, 2003*, Universal Academic Press, p. 1545.
17. Policarpo, A.P.L. *et al.* (1995) *Nucl. Instrum. Methods A*, **365**, 568.
18. Kim, J.G. *et al.* (2004) *Nucl. Instrum. Methods Phys. Res. A*, **534**, 376.
19. Seguinot, G. *et al.* (1977) *Nucl. Instrum. Methods Phys. Res. A*, **142**, 377.
20. Breskin, A. *et al.* (2009) *Nucl. Instrum. Methods Phys. Res. A*, **598**, 107.
21. Bondare, A.A. *et al.* (2008) *J. Instrum.*, **3**, P07001.
22. Bollozdynya, A.I. (1999) *Nucl. Instrum. Methods Phys. Res. A*, **422**, 314.
23. Habe, J. (2008) *Nucl. Instrum. Methods Phys. Res. A*, **595**, 154.
24. Flory, L.E. (2006) *Ann. N. Y. Acad. Sci.*, **157**, 38.
25. Seguinot, J. *et al.* (1999) *Nucl. Instrum. Methods Phys. Res. A*, **433**, 1.
26. De Salvo, R. (1997) *Nucl. Instrum. Methods Phys. Res. A*, **387**, 92.
27. Nappi, E. (2009) *Nucl. Instrum. Methods Phys. Res. A*, **604**, 190.
28. Bouclier, R. *et al.* (1988) *Nucl. Instrum. Methods Phys. Res. A*, **267**, 69.
29. (a) Charpak, G. *et al.*, Ethylferrocene: a possible alternative to tetrakis(dimethylamine)ethylene (TMAE) for the detection of BaF_2 scintillation Preprint CERN-EP-INT-88-02, CERN; (b) Charpak G. *et al.* (1989) *Nucl. Instrum. Methods Phys. Res. A*, **277**, 537.
30. Park, I.J. *et al.* (2000) *IEEE Nucl. Sci.*, **47**, 1820.
31. Ceron Zeballos, E. *et al.* (1997) *Nucl. Instrum. Methods Phys. Res. A*, **392**, 150.
32. Aprile, E., (2006) XENON and Other Cryogenic Noble Liquid Dark Matter Experiments Report at Fermilab, April 19, 2006.