SCIONIX scintillation detectors

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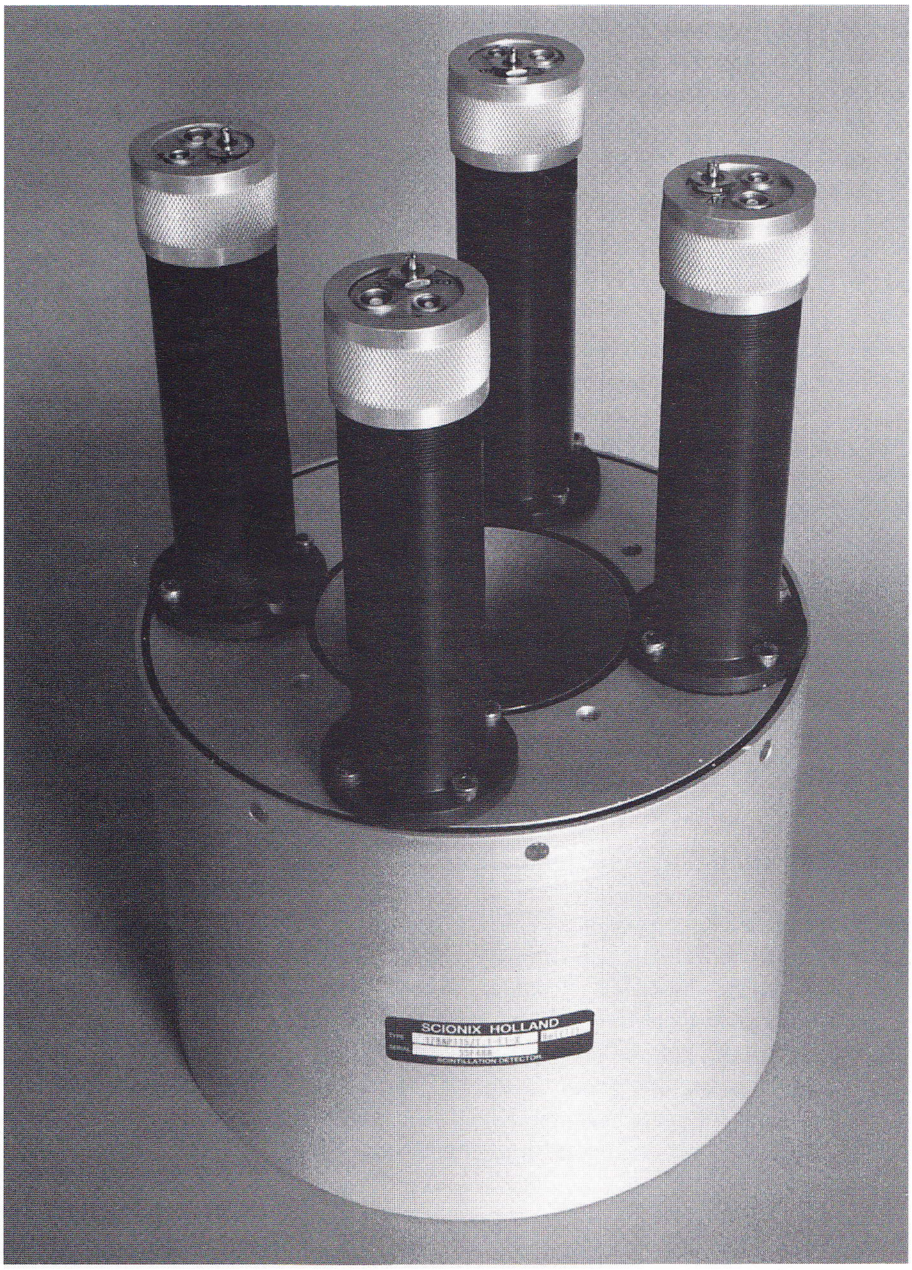
NOTE :

SCIONIX is not limited to manufacturing only the designs we present in this book.
The models illustrated only represent examples of types of detectors.
Many other options are possible.

The performance data we present in this handbook are typical and not necessarily guranteed. SCIONIX reserves te right to alter designs and specifications without notice.

Whilst every effort is made to ensure accuracy of published information, SCIONIX cannot be held responsible for errors or consequences arising therefrom.

Contents



SCIONIX HOLLAND
SCINTILLATION DETECTOR

1 Introduction, who we are...

This general catalog of SCIONIX scintillation detectors is meant for users of radiation detection instruments to select the instrument best suited for their specific application.

For the detection of radiation a great number of possibilities exist. Scintillators are often used for efficient detection of alpha- and beta-particles or electromagnetic radiation like gamma-rays or X-rays. For each application, a choice must be made for the type of scintillation material, its required size and the readout method. Also for the physical realization of the instrument numerous possibilities exist. The optimum choice often depends on the conditions in which your instrument should be used.

This catalog provides you with some basic information about the physical properties of different scintillation materials and their typical applications. A limited number of standard detector configurations is presented. In practice, a scintillation detector is often "tailor made" for a specific application and the presented range is only a selection.

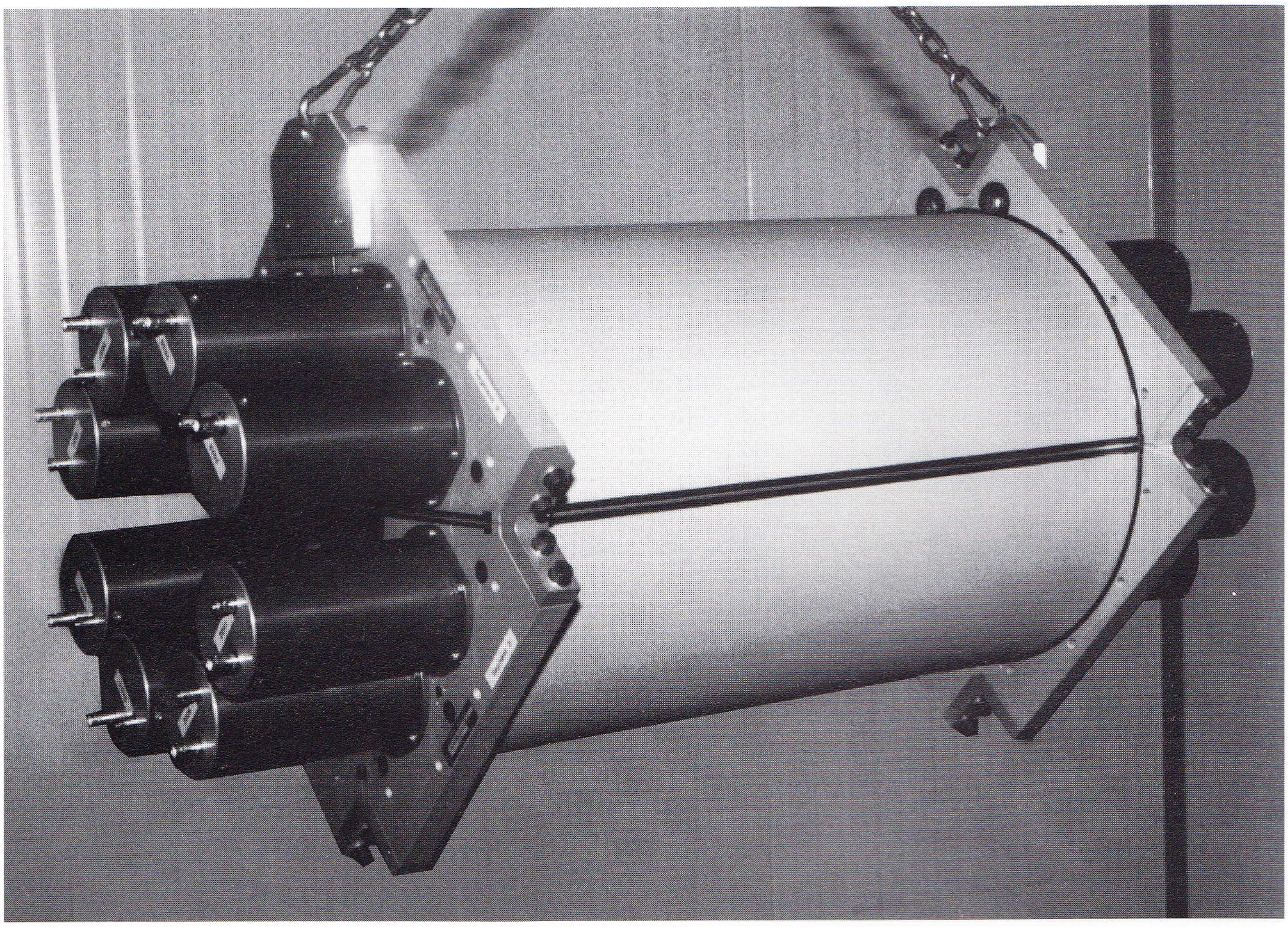
The SCIONIX philosophy is that the final detector is the result of close cooperation between us and you, the user of the instrument.

SCIONIX is a company producing equipment and components for radiation detection instruments employing **scintillation crystals and materials.** We are located near Utrecht in the center of the Netherlands, a 40 min drive from Amsterdam airport.

Scintillation detectors are being manufactured in the Netherlands since the 1960s. The design and fabrication of high quality scintillation detectors require a vast amount of expertise and experience. The long term presence of these qualities in the Netherlands form the foundation on which SCIONIX was established in 1992.

Our product range consists of scintillation detection instruments with associated front-end electronics, often incorporated into the detector assembly. Key themes are: quick interaction on new scientific developments regarding materials and detection techniques; and close collaboration with end users.

We would like to invite you to learn more about SCIONIX and our products. Please feel free to call us for additional information, prices, and our exact capabilities.



200 kg four-segment NaI(Tl) detector.

2 Scintillation detectors, general

In this section, a short overview of the use and general principle of scintillation detectors is presented. Scintillation crystal parameters in relation to the application are discussed.

A scintillator is a material that converts energy lost by ionizing radiation into pulses of light. In most scintillation counting applications, the ionizing radiation is in the form of X-rays, γ-rays and α- or β-particles ranging in energy from a few thousand electronvolts to several million electron volts (keVs to MeVs).

2.1 General

Pulses of light emitted by the scintillating material can be detected by a sensitive light detector, usually a photomultiplier tube (PMT). The photocathode of the PMT, which is situated on the backside of the entrance window, converts the light (photons) into so-called *photoelectrons.* The photoelectrons are then accelerated by an electric field towards the dynodes of the PMT where the multiplication process takes place. The result is that each light pulse (scintillation) produces a charge pulse on the anode of the PMT that can subsequently be detected by other electronic equipment, analyzed or counted with a scaler or a rate meter. The combination of a scintillator and a light detector is called a *scintillation detector.*

Since the intensity of the light pulse emitted by a scintillator is proportional to the energy of the absorbed radiation, the latter can be determined by measuring the pulse height spectrum. This is called spectroscopy. To detect nuclear radiation with a certain efficiency, the dimension of the scintillator should be chosen such that the desired fraction of the radiation is absorbed. For penetrating radiation, such as γ-rays, a material with a high density is required. Furthermore, the light pulses produced somewhere in the scintillator must pass the material to reach the light detector. This imposes constraints on the optical transparency of the scintillation material.

When increasing the diameter of the scintillator, the *solid angle* under which the detector "sees" the source increases. This increases detection efficiency. Ultimate detection efficiency is obtained with so-called *"well counters"* where the sample is placed inside a well in the actual scintillation crystal.

The *thickness of the scintillator* is the other important factor that determines detection efficiency. For electromagnetic radiation, the required thickness to stop say 90 % of the incoming radiation depends on the X-ray or γ-ray energy. For electrons (e.g. β-particles) the same is true but different dependencies apply. For larger particles (e.g. α-particles or heavy ions) a very thin layer of material already stops 100 % of the radiation.

The thickness of a scintillator can be used to create a *selected sensitivity* of the detector for a distinct type or energy of radiation. Thin (e.g. 1 mm thick) scintillation crystals have a good sensitivity for low energy X-rays but are almost insensitive to higher energy background radiation. Large volume scintillation crystals with relatively thick entrance windows do not detect low energy X-rays but measure high energy gamma rays efficiently.

2.2 Interactions in scintillation materials

Electromagnetic radiation can interact with matter via

- photoelectric effect,
- Compton effect or
- pair production.

The last effect only occurs at energies above 1.02 MeV. In practice, all effects have a chance to occur, this chance being proportional to the energy of the radiation and the atomic number (Z-value) of the absorber (the scintillation material).

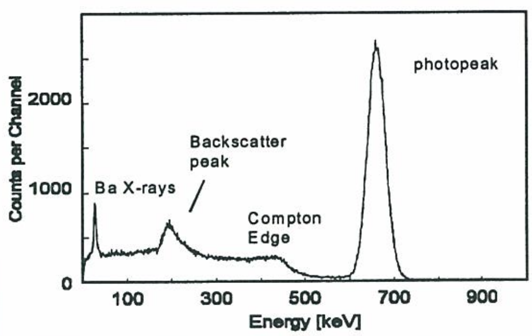


Fig. 2.1 ***Typical pulse height spectrum of radiation emitted generated by a ^{137}Cs source detected in a 76 x 76 mm NaI(Tl) scintillation crystal.***

In the photo(electric) effect, all energy of the radiation is converted into light. This effect is important when determining the actual energy of the impinging X-ray or gamma-ray photons. The lower the energy and the higher the Z-value, the larger the chance on photo effect.

Fig. 2.1 shows a *typical pulse height spectrum* measured with a 76 mm diameter, 76 mm high NaI(Tl) crystal in which the radiation emitted by a ^{137}Cs source is detected. The photopeak, Compton maximum and backscatter peak are indicated. The lines around 30 keV are Ba X-rays emitted by the source.

The total *detection efficiency* (counting efficiency) of a scintillator depends on the size, thickness and density of the scintillation material. However, the photopeak counting efficiency, important for e.g. gamma-ray spectroscopy, increases with the Z^{4-5} of the scintillator. At energies below 100 keV, electromagnetic interactions are dominated by the photoelectric effect.

The absorption can be calculated from the attenuation coefficient for a certain scintillator (or absorber). Consult the SCIONIX leaflet "Attenuation coefficients" for data on the most common materials.

Electrons (e.g. β-particles) can be *backscattered* from a material which implies that no energy is lost in the interaction process and the particle is not detected at all. The backscattering fraction is proportional to the Z of the material. For NaI(Tl) the backscatter fraction can be as high as 30 %! This implies that for efficient detection of electrons, low Z materials such as **plastic scintillators** or e.g. **CaF_2 (Eu)** are preferred. The window material is also of importance.

2.3 Scintillator response to γ-rays

2.3.1 Pulse height spectrometry

The basic principle of pulse height spectroscopy is that the light output of a scintillator is proportional to the energy deposited in a crystal. The standard way to detect scintillation light is to couple a scintillator to a photomultiplier. Furthermore, a γ-ray spectrometer usually consists of a preamplifier, a main (spectroscopy) amplifier and a multichannel analyzer (MCA). The electronics amplify the PMT charge pulse resulting in a voltage pulse suited to detect and analyze with the MCA. The schematic is shown in Fig. 2.2. For a typical pulse height spectrum see Fig. 2.1.

2.3.2 Energy resolution

An important aspect of a γ-ray spectrometer is the ability to discriminate between γ-rays with slightly different energy. This quality is characterized by the so-called *energy resolution* which is defined as the width (FWHM) of the photopeak at a certain energy.

Besides by the γ-ray energy, the energy resolution is influenced by :

- The light output of the scintillator,
- The size of the scintillator (light collection),
- Photomultiplier characteristics (quantum efficiency and photocathode homogeneity)

At low energies where photoelectron statistics dominate the energy resolution, the energy resolution is roughly inverse proportional to the square root of the γ-ray energy.

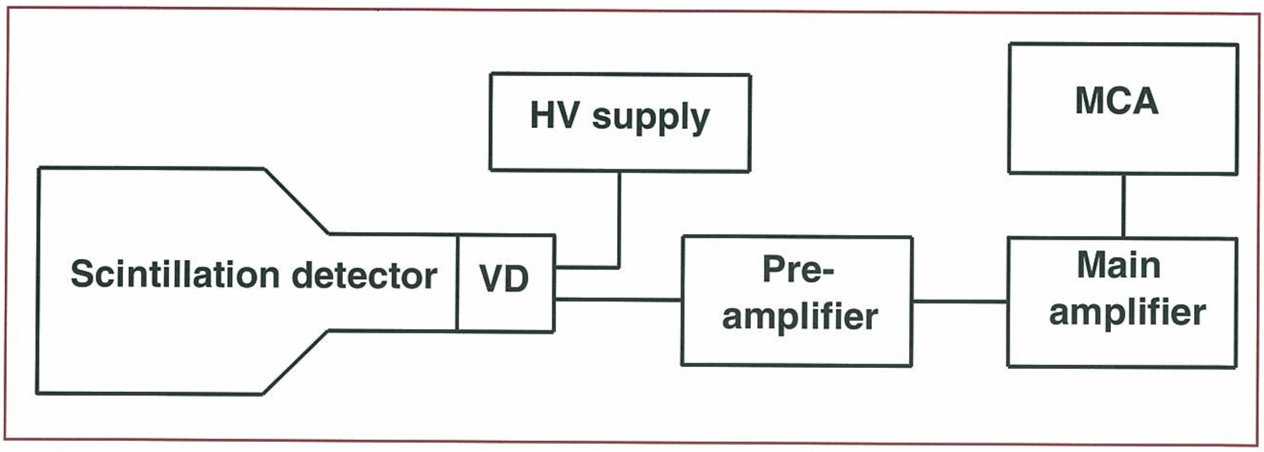


Fig. 2.2 Schematic of a standard scintillation spectrometer set-up.

The energy resolution of a scintillation detector is a true *detector property*, limited by the physical characteristics of the scintillator and the PMT or other readout device.

A typical energy resolution for 662 keV γ-rays absorbed in small NaI(Tl) detectors is 7.5 % FWHM. At low energies, e.g. at 5.9 keV, a typical value is 45 % FWHM. At these low energies, surface treatment of the scintillation crystal strongly influences the resolution. It may be clear that especially at low energies, scintillation detectors are low resolution devices unlike Si(Li) or HPGe detectors.

2.3.3 Time resolution

The time resolution of a scintillation detector reflects the ability to define precisely the moment of absorption of a radiation quantum in the detector.

The light pulse of a scintillator is characterized by a rise time and by a 1/e fall time τ (= *decay time* see section 3.1). It is obvious that the best time definition of an absorption event is obtained when the scintillation pulse is short (small decay time) and intense. Furthermore, the rise time and time jitter of the PMT and of the electronics are important.

Small cm size NaI(Tl) detectors have typical time resolutions of a few nanoseconds for ^{60}Co (1.2 MeV). Much better time resolutions can be obtained with plastic or **BaF_2** scintillation crystals. BaF_2 is presently the fastest known scintillator with detector time resolutions of a few hundred picoseconds.

2.3.4 Peak-to-valley ratio

A sensitive way to check the energy resolution of a scintillation detector is to define a so-called peak-to-valley (P/V) in the energy spectrum. This criterium does not depend on any possible offsets in the signal. Either the peak-to-valley between two gamma peaks is taken or the ratio between a low energy peak and the PMT / electronic's noise.

A good P/V ratio for a 76 x 76 mm NaI(Tl) crystal is 10 : 1. This is equivalent to an energy resolution of 7.0 % at 662 keV. At 5.9 keV, a high quality X-ray detector can have a P/V ratio of 40 : 1.

2.3.5 Spectrum stabilization

Extreme count rate changes, temperature variations or instable electronics may cause peak position variations in a spectrum. To compensate for these effects it is possible to calibrate the peak position with a so-called *Am-pulser.* This is a very small radioactive ^{241}Am source mounted inside a scintillation detector. The α-particles, emitted by the ^{241}Am, cause scintillations in the crystal that are detected by the PMT (or the photodiode) of the detector. For NaI(Tl), the *α-peak* is situated between a *Gamma Equivalent Energy (GEE)* of 1.5 and 3.5 MeV and can be specified. Count rates are 50, 200 and 1000 cps. The position of the pulser peak is used as a reference to compensate for the above mentioned variations in detector response. The above way of calibration is not ideal since the response of most scintillation crystals for γ-rays and α-particles is different. However, a second order compensation using e.g. a thermistor is only necessary for large temperature ranges.

Also other spot-activated scintillation crystals can be used for the above application. The best choice depends on the type of host crystal, the required GEE and required calibration accuracy.

For occasionally monitoring your system integrity, Light Emitting Diodes (LEDs) or laser ports can also be used. LEDs can be mounted inside scintillation detectors or a window for that purpose can be provided. Apart from these ways of pulse height stabilization, it is of course possible to stabilize electronically on the peak of an (always present) external source. Sometimes the ^{40}K background line can be used for this purpose.

2.4 Scintillator interaction with charged particles: α- and β-particle detection

Charged particles such as electrons, muons or atomic nuclei (e.g. α-particles) lose energy through Coulomb interactions with the atomic electrons in the surrounding matter. When selecting a detector for charged particles, the primary consideration is the type of particle to detect.

2.4.1 Weakly penetrating particles

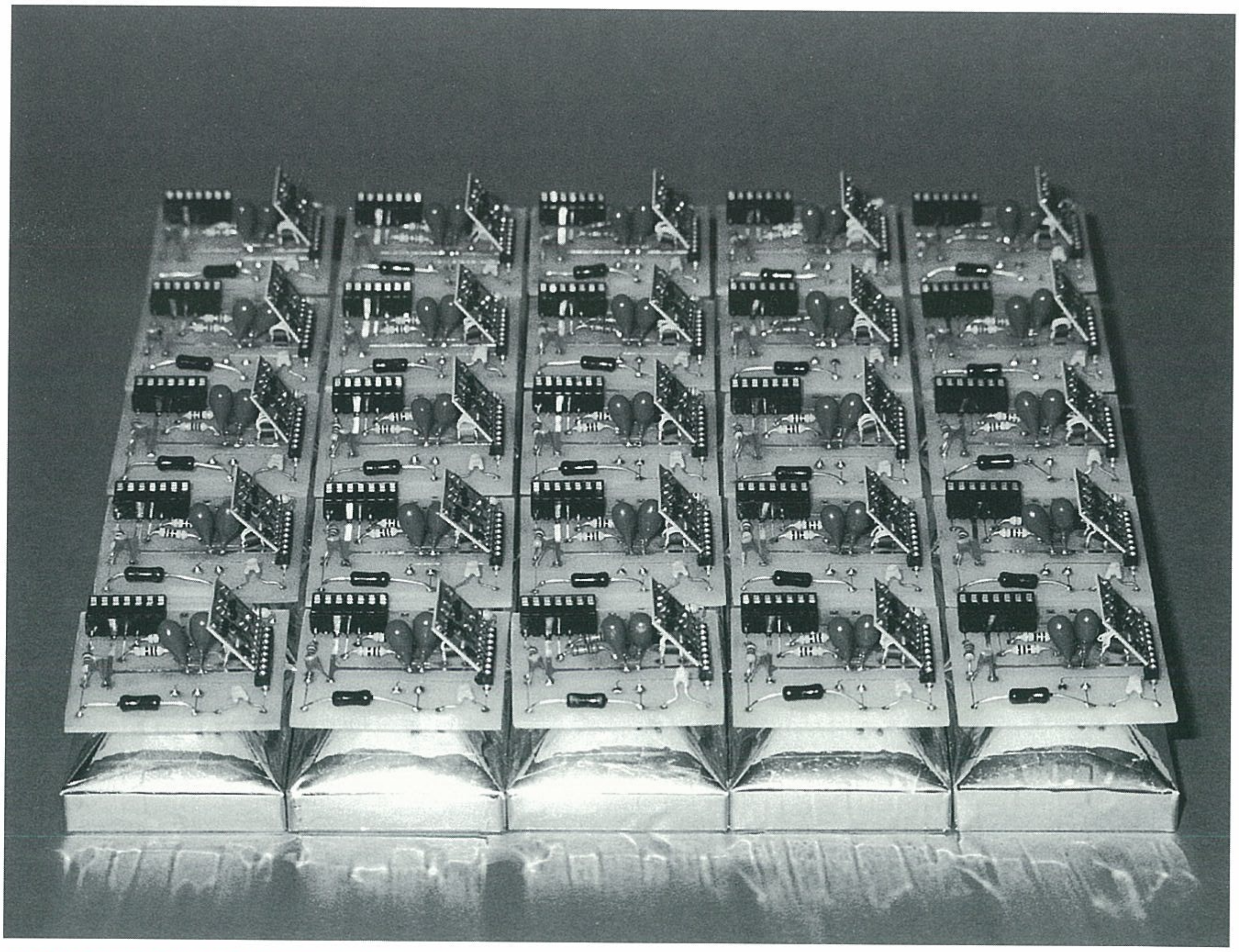
This includes low energy electrons, protons, α-particles and heavy ions. The rate of energy loss in matter increases as the charge and mass of the particle increase, but the conversion of particle energy in scintillation light decreases. The number of photons produced by an 5.4 MeV α-particle is only 70 - 80 % of a gamma photon with the same energy. Apart from the emitted energy and the specific scintillator, the energy resolution for particles also depends on the surface treatment of the material.

The following aspects should be considered. The entrance window of the detector should be very thin so that the incident radiation is not absorbed; aluminized mylar windows are normally used. For heavy ions, the detector is best operated in a light-tight environment without a window. The thickness of mylar windows can vary between 1.5 μm and 100 μm.

2.4.2 Minimum ionizing particles

Particles in this group are usually single charged with a low mass and a high energy. Their energy loss per unit path length is small. Common examples of minimum ionizing particles are cosmic muons and fast electrons. In a plastic scintillator, minimum ionizing particles lose several MeV per cm material. Applications include calorimetry and electron spectroscopy.

Entrance window material and thickness are usually not that important since the particles normally pass through the window and the entire scintillator.



CsI(Tl) photodiode detector array for heavy irons.

3 Properties and specific use of scintillation crystals

3.1 Scintillator properties

A large number of different scintillation crystals exists for a variety of applications. Some important characteristics of scintillators are:

- Density and atomic number (Z)
- Light output (wavelength + intensity)
- Decay time (duration of the scintillation light pulse)
- Mechanical and optical properties
- Cost

1. Density and Atomic number

It is clear that for an efficient detection of γ-rays, a material with a *high density* and *high Z* is required (see above). Inorganic scintillation crystals meet the requirements of stopping power and optical transparency, their densities ranging from roughly 3 to 9 g/cm^3 makes them very suitable to absorb penetrating radiation (γ-rays). Materials with high Z-values are used for γ-ray spectroscopy at high energies (> 1 MeV).

2. Light output

Since photoelectron statistics (or electron-hole pair statistics) plays a key role in the accurate determination of the energy of the radiation, the use of scintillation materials with a *high light output* is preferred for all spectroscopic applications. The scintillator emission wavelength should be matched to the sensitivity of the light detection device that is used (PMT of photodiode).

3. Decay time

Scintillation light pulses (flashes) are usually characterized by a fast increase of the intensity in time (pulse rise time) followed by an exponential decrease. The *decay time* of a scintillator is defined by the time after which the intensity of the light pulse has returned to 1/e of its maximum value. Most scintillators are characterized by more than one decay time and usually, the effective average decay time is mentioned. The decay time is of importance for fast counting and / or timing applications.

4. Mechanical and optical properties

The most important scintillation material NaI(Tl) is hygroscopic and is only used in hermetically sealed metal containers to preserve its properties. All water soluble scintillation materials should be packaged in such a way that they are not attacked by moisture. Some scintillation crystals may easily crack or cleave under mechanical pressure whereas others, like CsI, are plastic and only will deform. In table 3.1 below, the most important aspects of commonly used scintillation materials are listed. The list is not exhaustive and new materials are developed regularly.

Each scintillation crystal has its own specific application. For high resolution γ-ray spectroscopy, NaI(Tl), or CsI(Na) (high light output) are normally used. For high energy physics applications, the use of bismuth germanate $Bi_4Ge_3O_{12}$ (BGO) crystals (high density and Z) improves the lateral confinement of the shower. For the detection of β-particles, CaF_2(Eu) can be used instead of plastic scintillators (higher density).

Below a short description of the most commonly used scintillators is presented.

MATERIAL	DENSITY [g/cm³]	EMISSION MAXIMUM [nm]	DECAY CONSTANT (1)	REFRACTIVE INDEX (2)	CONVERSION EFFICIENCY (3)	HYGROS-SCOPIC
NaI(Tl)	3.67	415	0.23 μs	1.85	100	yes
CsI(Tl)	4.51	550	0.6 / 3.4 μs	1.79	45	no
CsI(Na)	4.51	420	0.63 μs	1.84	85	slightly
CsI(undoped)	4.51	315	16 ns	1.95	4 - 6	no
CaF_2(Eu)	3.18	435	0.84 μs	1.47	50	no
^{6}LiI(Eu)	4.08	470	1.4 μs	1.96	35	yes
^{6}Li - glass	2.6	390 - 430	60 ns	1.56	4 - 6	no
CsF	4.64	390	3 - 5 ns	1.48	5 - 7	yes
BaF_2	4.88	315 220	0.63 μs 0.8 ns	1.50 1.54	16 5	no
YAP(Ce)	5.55	350	27 ns	1.94	35 - 40	no
GSO(Ce)	6.71	440	30 - 60 ns	1.85	20 - 25	no
BGO	7.13	480	0.3 μs	2.15	15 - 20	no
$CdWO_4$	7.90	470 / 540	20 / 5 μs	2.3	25 - 30	no
Plastics	1.03	375 - 600	1- 3 ns	1.58	25 - 30	no

(1) EFFECTIVE AVERAGE DECAY TIME FOR γ - RAYS.
(2) AT THE WAVELENGTH OF THE EMISSION MAXIMUM.
(3) RELATIVE SCINTILLATION SIGNAL AT ROOM TEMPERATURE FOR γ - RAYS WHEN COUPLED TO A PHOTOMULTIPLIER TUBE WITH A Bi-ALKALI PHOTOCATHODE.

Table 3.1 Physical Properties of the most important scintillation materials.

NaI(Tl) scintillation crystals are used in most standard applications for detection of γ-radiation because of their unequalled high light output and the excellent match of the emission spectrum to the sensitivity of photomultiplier tubes, resulting in a good energy resolution.

CsI(Tl) has the advantage that it is non-hygroscopic, does not cleave and can be read out using silicon photodiodes instead of photomultiplier tubes. These so-called *Scintillator Photodiode Detectors* are compact, very stable, do not require any high voltage, are rugged, and can be operated in high magnetic fields. These detectors are frequently used in arrays or matrices in particle physics research.

CsI(Na) is a non-hygroscopic, high light output scintillator mainly used for applications where mechanical stability and good energy resolution are required. Below 120 °C it is an alternative to NaI(Tl).

BGO has the extreme high density of 7.13 g /cm^3 and has a high Z value which makes these crystals very suited for the detection of *natural radioactivity* (U, Th, K), for high energy physics applications (high photofraction) or in compact Compton suppression spectrometers.

YAP:Ce is a high density (5.5 g/cm^3) oxide crystal with a decay time about 10 times shorter than NaI(Tl). It is used in detectors for high count rate (up to several MHz) X-ray spectrometry. The non-hygroscopic nature of this material allows the use of thin mylar entrance windows and guarantees a long lifetime of the detector.

CaF_2(Eu), Europium doped calcium fluoride is a low density scintillation crystal with a high light output. Thanks to its low Z value it is well suited for the detection of electrons (beta particles) with a high efficiency (low backscatter fraction). CaF_2(Eu) is a crystal that is also used in *phoswich* scintillation detectors in combination with NaI(Tl) (see section 7.4).

Organic (plastic) scintillators consist of a transparent host material (a plastic) doped with a scintillating organic molecule (e.g. POPOP : p-bis [2-(5-phenyloxazolyl)] benzene). Radiation is absorbed by the host material, mostly via Compton effect because of the low density and Z- value of organic materials. Therefore, plastic scintillators are mostly used for the detection of β- and other particles. Furthermore plastic scintillators are mainly used when large detector volumes are required e.g. in security or health physics applications. The cost of large plastic scintillation detectors (per volume) is much lower than that of equivalent size NaI(Tl) detectors; plastic scintillators can be manufactured in meter long slabs.

3.2 Afterglow

To detect fast changes in transmitted intensity of X-ray beams, as e.g. in CT scanners or luggage X-ray detectors, crystals are required exhibiting extremely low afterglow. Afterglow is defined as the fraction of scintillation light still present for a certain time after the X-ray excitation stops. Afterglow originates from the presence of millisecond to even hour long decay time components. Afterglow in most halide scintillation crystals can be as high as a few percent after 3 ms. The long duration afterglow in e.g. CsI(Tl) can be a problem for many applications. Afterglow in halides is believed to be intrinsic and correlated to certain lattice defects. BGO and Cadmium Tungstate ($CdWO_4$) crystals are examples of low afterglow scintillation materials.

3.3 Neutron detection

Neutrons do not produce ionization directly in scintillation crystals, but can be detected through their interaction with the nuclei of a suitable element. In a ^{6}LiI(Eu) scintillation crystal for example, neutrons interact with ^{6}Li nuclei to produce an alpha particle and a triton (tritium nucleus), which both produce scintillation light that can be detected. For this purpose, also enriched ^{6}Li containing glasses can be used, doped with Ce as activator.

3.4 Radiation damage

Radiation damage is defined as the change in scintillation characteristics caused by prolonged exposure to intense radiation. This damage manifests itself by a decrease of the optical transmission of a crystal which causes a decrease in pulse height and deterioration of the energy resolution of the detector. Radiation damage other than radio-activation is usually partially reversible; i.e. the absorption bands disappear slowly in time. In general, doped alkali halide scintillators such as NaI(Tl) and CsI(Tl) are rather susceptible to radiation damage. All known scintillation materials show more or less damage when exposed to large radiation doses. The effects usually can only be observed clearly in thick (> 5 cm) crystals. A material is usually called radiation hard if no measurable effects occur at a dose of 10.000 Gray. Examples of radiation hard materials are $CdWO_4$ and GSO.

3.5 Emission spectra of scintillation crystals

Each scintillation material has a characteristic emission spectrum. The shape of this emission spectrum is sometimes dependent on the type of excitation (photons / particles). This emission spectrum is of importance when choosing the optimum readout device (PMT /

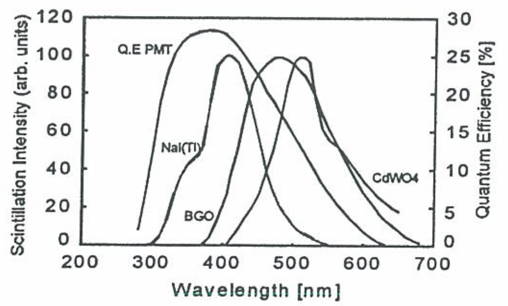


Fig. 3.1 ***Emission spectra of NaI(Tl), BGO and $CdWO_4$, scaled on maximum emission intensity.***

photodiode) and the required window material. Fig. 3.1 and 3.2 show the emission spectrum of some common scintillation materials.

3.6 Temperature influence on the scintillation response

The light output (number of photons per MeV gamma) of most scintillators is a function of temperature. This is caused by the fact that in scintillation crystals, radiative transitions, responsible for the production of scintillation light, compete with non-radiative transitions (no light production). In most scintillation crystals, the light output is quenched (decreased) at higher temperatures. An example of the contrary is the fast component of BaF_2 of which the emission intensity is essentially temperature independent.

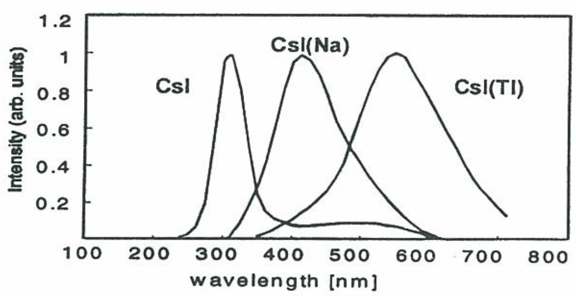


Fig. 3.2 ***Emission spectra of CsI, CsI(Na) and CsI(Tl) scaled on maximum emission intensity. Also a typical quantum efficiency curve of a bialkali photocathode is shown.***

The scintillation process usually involves as well production, transport and quenching centers. Competition between these three processes each behaving differently with temperature, causes a complex temperature dependence of the scintillation light output. Fig. 3.3 shows the temperature dependence of some common scintillation crystals.

For applications such as oil well logging and space research, where it is very difficult to control the temperature, this dependence should be taken into account. The doped scintillators NaI(Tl), CsI(Tl) and CsI(Na) show a distinct maximum in intensity whereas many undoped scintillators such as BGO show an increase in intensity with decreasing temperature.

From Fig. 3.3 it can be seen that at above 120 °C, NaI(Tl) has the highest light output followed by CsI(Na) and CsI(Tl). For lower temperatures CsI(Na) is a good alternative to NaI(Tl) because it has better mechanical characteristics.

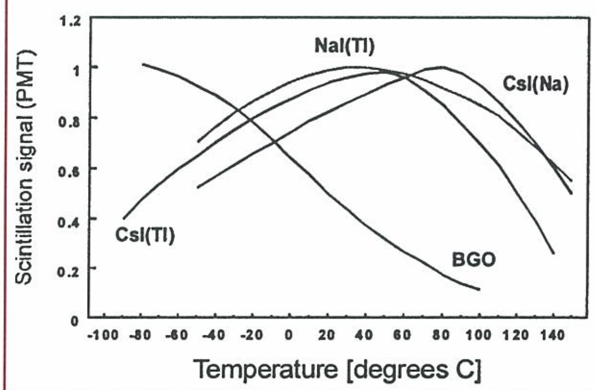


Fig. 3.3 ***Temperature dependence of the scintillation yield of NaI(Tl), CsI(Na), CsI(Tl) and BGO.***

3.7 Which scintillator for your application?

When we observe Table 3.1 carefully, it is clear that none of presently known scintillation crystals possesses all the above mentioned (ideal) characteristics such as high density, fast decay etc. The choice of a certain scintillation crystal in a radiation detector depends strongly on the application. Questions such as :

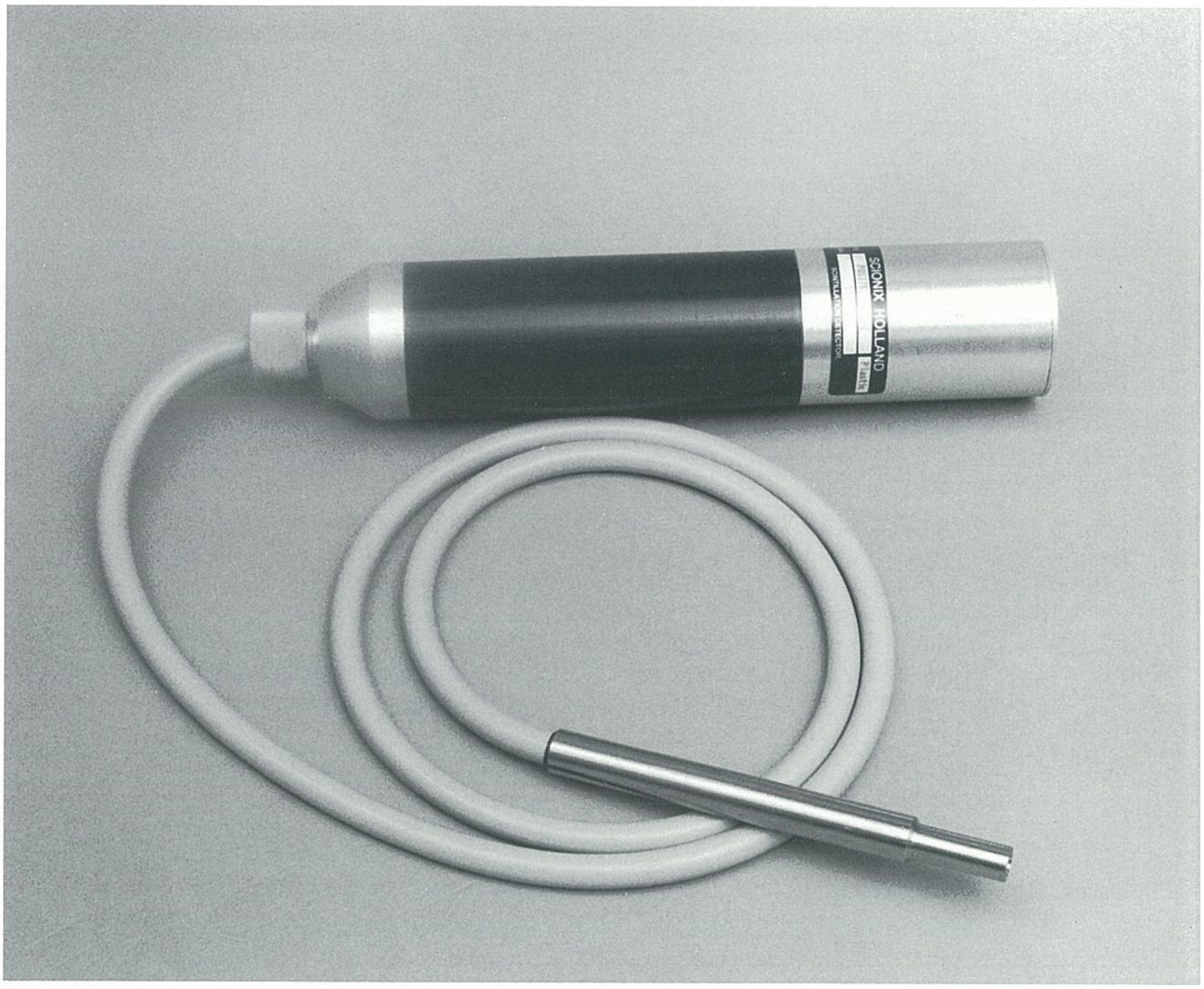
- What is the energy of the radiation to measure ?
- What is the expected count rate ?; and
- What are the experimental conditions (temperature, shock) ?

MATERIAL	IMPORTANT PROPERTIES	MAJOR APPLICATIONS
NaI(Tl)	Very high light output, good energy resolution	General scintillation counting, health physics, environmental monitoring, high temperature use
CsI(Tl)	Non-hygroscopic, rugged, long wavelength emission	Particle and high energy physics, general radiation detection, photodiode readout, phoswiches
CsI(Na)	High light output, rugged	Geophysical, general radiation detection
CsI(undoped)	Fast, non-hygroscopic, radiation hard, low light output	Physics (calorimetry)
CaF_2(Eu)	Low Z, high light output	β detection, α, β phoswiches
^{6}LiI(Eu)	High neutron cross-section, high light output	Thermal neutron detection and spectroscopy
^{6}Li - glass	High neutron cross-section, non-hygroscopic	Thermal neutron detection
BaF_2	Ultra-fast sub-ns UV emission	Positron life time studies, physics research, fast timing
YAP(Ce)	High light output, low Z, fast	MHz X-ray spectroscopy, synchrotron physics
GSO(Ce)	High density and Z, fast, radiation hard	Physics research
BGO	High density and Z	Particle physics, geophysical research, PET, anti-Compton spectrometers
$CdWO_4$	Very high density, low afterglow, radiation hard	DC measurement of X-rays (high intensity), readout with photodiodes, Computerized Tomography (CT)
Plastics	Fast, low density and Z, high light output	Particle detection, beta detection

Table 3.2 Scintillation materials and most common applications.

are very important in this respect to determine the optimum choice.

Table 3.2 presents an overview of the most commonly used scintillation materials with some of their specific applications.

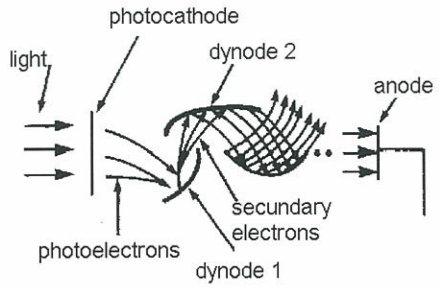


Medical probe with fiber optics light guide and built-in HV supply

4 Readout of scintillation crystals

The light emitted by a scintillation material must be detected using some kind of sensitive light detection device. Basically, there are two options :

- **Photomultiplier Tubes (PMTs)**
  Light (photons) is converted into *photoelectrons* by absorption in a thin photocathode layer inside a (glass) vacuum tube. Most often a photocathode is semi-transparent and usually consist of a thin layer of evaporated Cs, Sb, and K atoms or a mixture of these. Each photoelectron is pulled by an electric field towards a dynode and subsequentially amplified. In a 12 stage PMT, the net amplification is of the order of 10^6. Each scintillation pulse produces a charge pulse at the anode of the PMT. The process is illustrated below.



  Besides in the above described pulse mode, PMTs can also be operated in *current mode* in which case the anode current is a measure for the integral radiation intensity absorbed in the scintillator. This method is only used at high count rates.

- **Photodiodes**
  In a photodiode, the scintillation photons produce electron-hole pairs that are collected at respectively the anode and the cathode of the diode. Most frequently, reverse biased PIN photodiodes are used having a low capacitance and leakage current.

In the following section, the above detection mechanisms are discussed in more detail.

4.1 Photomultiplier tubes

The energy resolution, coincident resolving time and stability of a scintillation detector depend to a great extent upon the type of photomultiplier tube.
The selection of a proper type is fundamental to a good detector design.

The light conversion efficiency of a photomultiplier cathode is a function of the wavelength; the *Quantum Efficiency (Q.E.)* is defined as the chance that one photon produces one photoelectron. In the amplification process, one photoelectron produces per dynode step about 3 - 4 secondary electrons. With a 12 stage PMT, a typical gain in the order of 10^6 can be obtained.
Fig. 4.1 shows a schematic of a PMT. It should be noted that PMTs are sensitive to magnetic fields; a μ-metal shield provides adequate protection from the earth magnetic field. For operation in high magnetic fields, special PMTs are available.

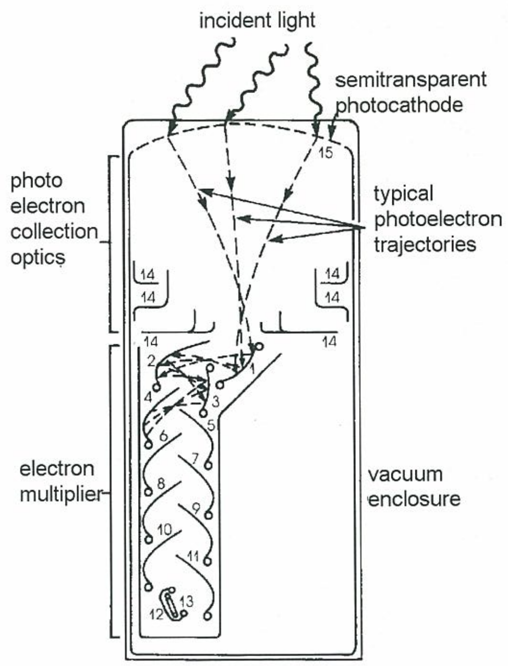


Fig. 4.1 Schematic of a photomultiplier tube.

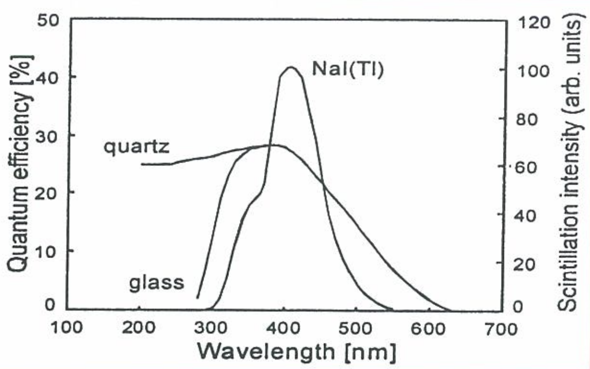


Fig. 4.2 ***Quantum efficiency curve of a standard bialkali photocathode together with the scintillation emission spectrum of NaI(Tl).***

There exist a number of PMT dynode structures, each with their typical characteristics. Important PMT parameters are :

- Amplification as a function of voltage
- Dark current
- Pulse rise time
- Physical size
- Gain stability
- Radiological background

Gain, stability and dark current depend on the used dynode materials and are a function of temperature. Pulse rise time depends on the dynode structure. For fast timing applications, so called *"linear focused"* PMTs are advised.

A very important factor is the sensitivity as a function of the position on the PMT entrance window. A large variation can cause a degradation of the energy resolution of a scintillation detector. This variation can be caused by a change in quantum efficiency of the photocathode or a non-uniform photoelectron collection efficiency from the cathode onto the first dynode. The above effects can be important for both small and large diameter PMTs.

From Table 3.1 it is clear that each type of scintillator has a different emission spectrum. It is important for a good performance that the emission spectrum of a scintillator is well matched to the quantum efficiency curve (for definition see above) of the PMT. To detect the fast scintillation component of BaF_2 for example, it is necessary to use a PMT with quartz window since glass absorbs all light below 280 nm. Fig. 4.2 shows the quantum efficiency (Q.E.) of a standard PMT with a bialkali photocathode. The emission spectrum of the most common scintillator NaI(Tl) is shown too. It can be seen that the overlap is very good. For other scintillation materials such as BGO, the match is less ideal.

The gain of a PMT is temperature sensitive. The variation in gain, which depends on the photocathode and dynode material, amounts to typically a few tenths of a percent per °C.

Due to their dynode stages, PMTs are usually quite bulky devices although some short versions and miniature types have been developed.

Care must be taken when PMTs are used inside *magnetic fields*. Although there are PMT types that have a high magnetic field immunity, this effect remains a problem.

The material of a PMT is usually glass. Glass has an intrinsic amount of ^{40}K which contributes to the *radiological background* of the scintillation detector. ^{40}K emits as well 1460 keV gamma rays as beta particles. The face-plate of the PMT can be constructed of special low-K glass. Furthermore, this background can be limited by using light guides absorbing the β-particles and creating a distance between the crystal and the PMT. The above techniques are used in so-called *"low background"* scintillation detectors.

Below we would like to summarize the advantages and disadvantages of PMTs in conjunction with scintillation crystals.

For more information regarding PMTs we refer to the PMT manufacturer's literature.

Photomultiplier Tubes

Advantages :
- Standard device
- Large signals
- Large active areas possible
- Fast rise times possible

Disadvantages :
- Large physical dimension
- High Voltage required
- Gain instability as function of temperature
- Sensitive to magnetic fields
- Background radiation

4.2 Photodiodes

An alternative way to detect the scintillation light from a crystal is the use of a silicon photodiode. This is a semiconductor device which consists of a thin layer of silicon in which the light is absorbed after which free charge carriers (electrons and holes) are created. Electron and holes are collected at the anode and cathode of the diode. Most frequently used are PIN diodes operated in reverse bias mode.

When these photodiodes (usually of the PIN type) are optically coupled to a scintillation crystal, each scintillation light pulse will generate a small *charge pulse* in the diode which can be measured with a charge sensitive preamplifier. Alternatively, the *current* produced in the diode can be measured.

The quantum efficiency of silicon photodiodes is typically 70 % between 500 and 900 nm but decreases rapidly below 500 nm as shown in Fig. 4.3. It is clear that the highest signals can be expected from scintillation crystals that have an intense emission above 500 nm. CsI(Tl) crystals, characterized by a large scintillation intensity with a maximum at 550 nm, are therefore well suited to couple to photodiodes.

In contrary to photomultiplier tubes, photodiodes do not require a high voltage (HV) power supply but only a bias voltage of about 30 V. Photodiodes are thin, rugged and insensitive to magnetic fields. Furthermore, the output signal from a crystal/photodiode detector is very stable due to the absence of drift of the diode gain since no charge amplification takes place in the device itself. Photodiodes are thin (several mm) which can be advantageous.

Due to the small signal generated by the photodiode, it is necessary to employ a high quality charge preamplifier in order to keep the noise level as low as possible. Noise is an intrinsic problem to standard photodiodes. In silicon PIN photodiodes, the created number of primary electron-hole pairs (e-h pairs) is not increased by amplification. The PIN photodiode is a *unity gain device*. The thickness of the silicon used is typically 200 - 500 µm. Coupled to a conventional (low noise) charge sensitive preamplifier, the substantial capacitance of the device (40 - 50 pF/cm² for 200 and 300 µm wafer devices) is mainly responsible for the noise which determines for a large part the energy resolution of the detector. Also the dark current of PIN photodiodes (1 - 3 nA/cm² at full depletion) may contribute significantly to the noise, especially at larger shaping times. The dark current increases as well with increasing surface area as with increasing temperature.

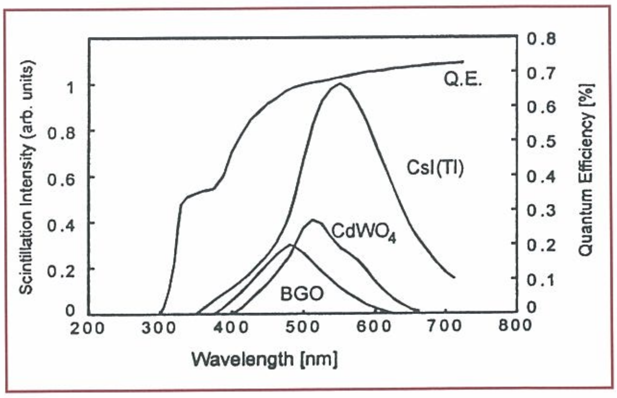


Fig. 4.3 Quantum efficiency curve of a silicon photodiode together with the emission spectrum of CsI(Tl), $CdWO_4$ and BGO.

Some typical noise numbers are:

Photodiode size	Noise	
10 x 10 mm	390	ENC
20 x 20 mm	550	ENC
30 x 30 mm	1050	ENC

As long as there is enough light per event available, every scintillation event can be detected using photodiodes. However, due to the intrinsic noise there is a lower limit on the energy of the radiation that can be detected. For a small (1 cm³) CsI(Tl) cube coupled to a 10 x 10 mm² photodiode the best lower energy limit reported amounts to 37 keV. From the above noise numbers and the electron-hole pair yield of the

Scintillator Photodiode Detectors

Advantages :

- Small dimension (thin)
- Low Voltage operation
- Very stable signal height
- Rugged
- Insensitive to magnetic fields

Disadvantages :

- Limited surface area
- Low energy noise threshold
- Increased noise at elevated temperatures

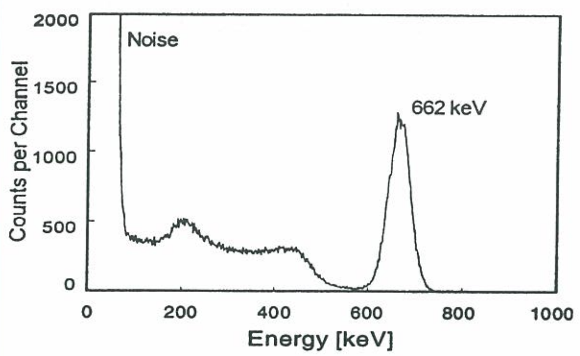


Fig. 4.4 Example of a pulse height spectrum of 662 keV gamma rays absorbed in a photodiode scintillation detector equipped with an 18x18x25 mm³ CsI(Tl) scintillation crystal.

scintillator / photodiode combination, the noise contribution to the energy resolution can be calculated. Fig. 4.4 shows a pulse height spectrum measured with a photodiode scintillation detector.

At increasing temperatures, the dark current of the photodiode increases. This limits the use of scintillation photodiode detectors to temperatures below 50 °C.

On the previous page we summarize the advantages and disadvantages of photodiode scintillation detectors in conjunction with scintillation crystals for pulse counting.

Photodiodes can also be used in *DC mode* to read out a scintillation crystal. Capacitance and leakage current are less important then since the diode is used unbiased. This mode of operation is used for applications where radiation intensities are high and close packing of arrays of scintillation crystals is required such as in medical CT scanners.

The low level noise limit can be overcome by using so called *"Avalanche Photodiodes"*, APDs. These devices can also detect X-rays of lower energy by using internal amplification. However, an external voltage of at least several hundred Volts is required and the amplification is a strong function of temperature (gain stability). Also, the leakage current of APDs at room temperature is relatively high. APDs are currently available in approx. 1 cm diameter size maximum. APD signals are much faster than signals from PIN diodes and are mostly used for fast timing with small scintillation crystals.

5 Detector configurations, general description

In this chapter some general aspects are mentioned regarding detector construction which may help you choosing the right detector for your application.

5.1 Scintillation crystals without photomultiplier tubes

A scintillation crystal can be supplied to fit user specifications. The scintillation crystal is usually supplied in a hermetically sealed metal container to protect the crystal from hydration (NaI(Tl)) or to protect the crystal from other environmental influences. In case of non-hygroscopic crystals this requirement is less stringent.

Because of statistics, it is always desirable to detect as much light as possible from a scintillation event in the light detection device. For this purpose, the scintillation crystal is covered on all sides, except the read-out side, with reflective material. This can be e.g. white reflective paper, teflon or reflective powder such as MgO or Al_2O_3. The surfaces in contact with the reflector can be optically polished or ground. The scintillation light is transmitted through a glass or quartz window to be optically coupled to the PMT entrance window.

Depending on the *shape of the scintillation crystal*, a certain surface treatment is required to obtain a large light output *and* a good uniformity. Both are important to achieve a good energy resolution. The optimization of scintillation crystal surfaces is based on experience with the material and not always obvious. In case of axial or transverse wells in the crystal (see chapter 7), different types of surface treatments are required to ensure a homogeneous response.

In general it is advisable to choose the diameter of the scintillator slightly smaller than the diameter of the PMT since the outer area of a PMT is often less sensitive that the center.

Optical coupling to the PMT can be achieved by using optical grease or a special optically transparent glue. In Fig. 5.1 the general construction of a canned scintillation crystal is shown. Flexible optical coupling allows for different expansion coefficients between materials.

Standard high temperature crystal assembly

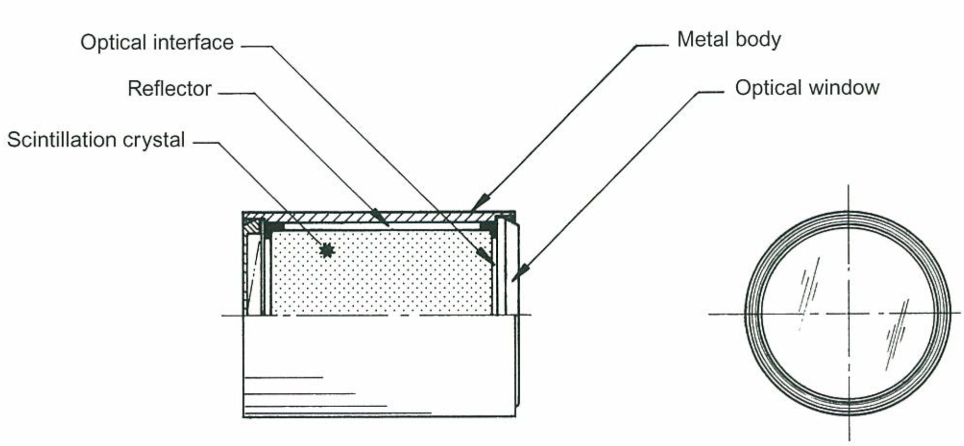


Fig. 5.1 Construction of a canned scintillation crystal.

5.2 Scintillation crystals with photomultiplier tubes

The most frequently used scintillation detector consists of a scintillation material integrally coupled to a PMT. The entire assembly is mounted in a metal housing with μ-metal shielding against the influence of magnetic fields. For conditions where strong fields are expected, this shield can be increased in thickness for additional protection.

Standard scintillation detectors read out with PMTs can be provided with either an external so called "plug-on" *Voltage Divider (VD)* for the PMT or with a built-in one. In the first case, the detector itself ends in a 12, 14, 20 or 21 pins connector that should be plugged into the socket of the VD. This allows quick exchange of detectors and electronics but it makes the detector considerably longer (about 5 cm). For more details regarding detector electronics we refer to chapter 8. For low background applications, a built-in VD is always advised since this avoids the use of connector materials which are often a source of background. Fig. 5.2 shows a detector with integrally connected PMT and built-in voltage divider/emitter follower.

5.3 Detector entrance windows

The density and thickness of the detector entrance window determine the transmission of the radiation. For high energy gamma-rays say > 300 keV, the absorption of a mm or so entrance window can be neglected and the choice for a window is dictated by practical considerations.

For *lower energy X-rays* this choice is more critical. In Fig. 5.3 the transmission of a range of standard detector windows is presented from which you can determine the optimum window for your application. The thinnest Aluminum window normally used has a thickness of 25 -30 μm. This window can be used down to 10 keV X-ray energy. Below this energy, 0.2 or 0.3 mm thick Beryllium is required. The advantage of a Be window above a thin aluminum one is that is it less fragile.

For the detection of low energy *electrons* (beta particles), a thin aluminized (light tight) mylar window is used. Mylar windows however can only be applied for non-hygroscopic scintillation materials (see chapter 3). Standard thickness is 25 or 100 μm.

Standard scintillation detector assembly with built-in electronics

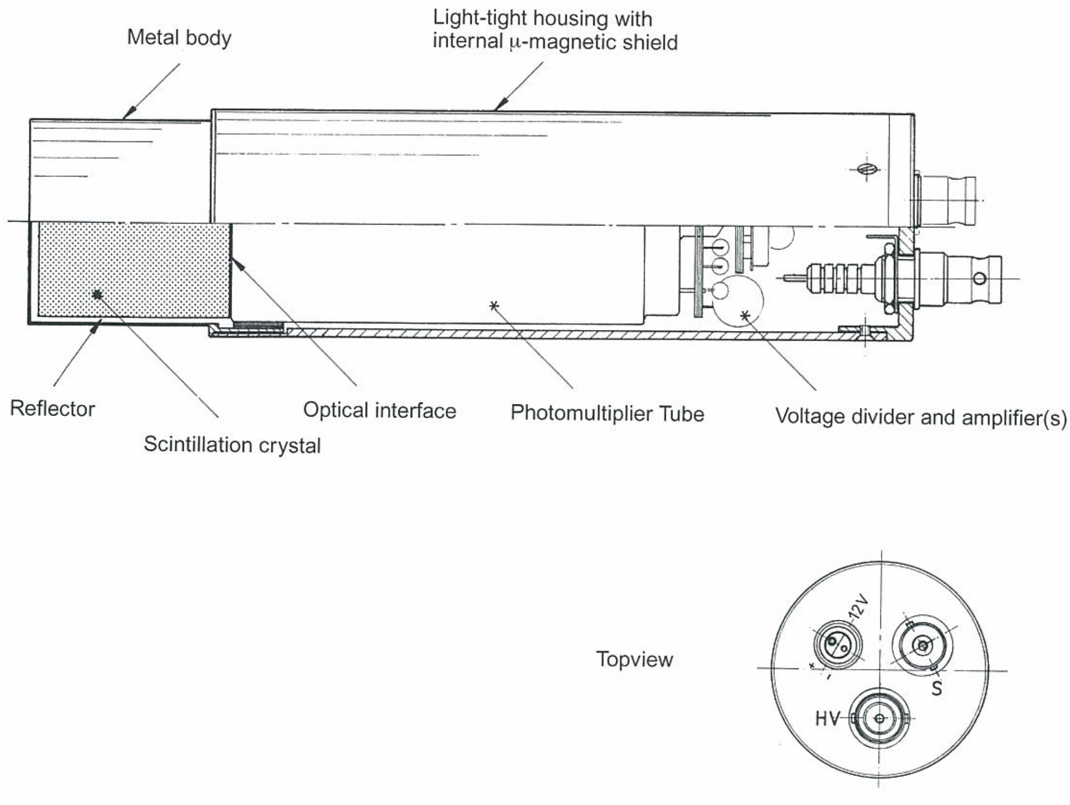
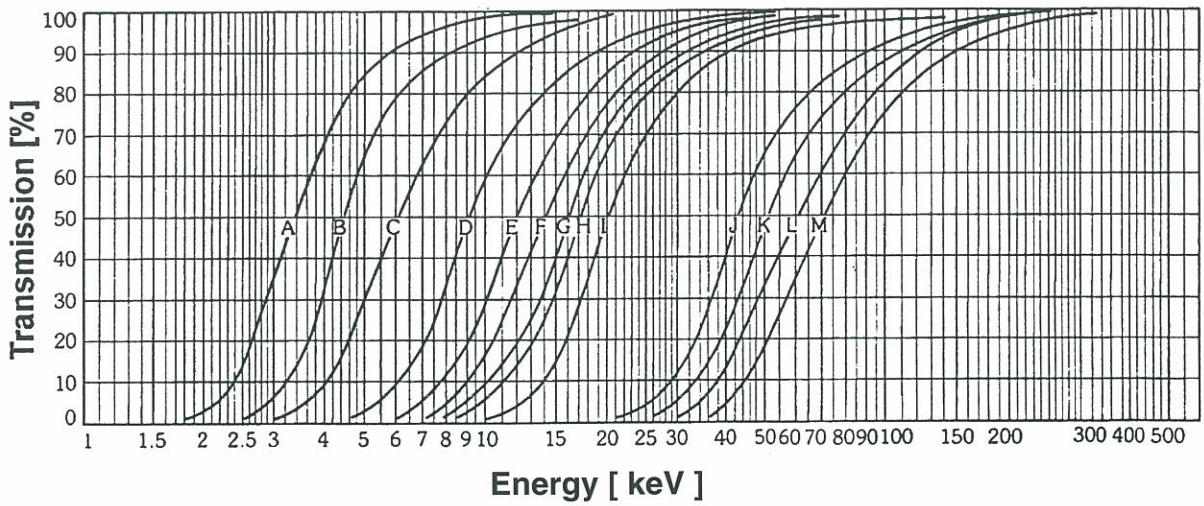


Fig. 5.2 Construction of a scintillation detector with built-in PMT& electronics.



A = 0.2 mm Be
B = 0.5 mm Be
C = 0.03 mm Al
D = 0.1 mm Al
E = 0.2 mm Al
F = 0.3 mm Al
G = 0.4 mm Al
H = 0.5 mm Al
I = 0.8 mm Al
J = 0.3 mm Fe
K = 0.5 mm Fe
L = 0.5 mm Cu
M = 0.8 mm Cu

***Fig. 5.3** Parallel beam transmission of frequently used entrance windows.*

For the detection of *alpha particles* or *heavy ions*, a windowless detector (used in absolute dark, e.g. a vacuum vessel) or a very thin aluminized mylar window is used (typical thickness 2 μm). Some crystals are suitable to coat with several hundreds of nm evaporated aluminum for the detection of very low energy beta particles (e.g. from Tritium).

5.4 Crystal dimensions and housing materials

As discussed in section 2.1, the surface area (solid angle) and the thickness of a scintillation crystal determine its detection efficiency. Normally, a scintillation crystal is read out with a PMT or a photodiode in dimension equal to one of its sides. However it is possible to use light guides or to taper a crystal without much loss of performance. This can save space and cost, especially when resolution is not of prime importance.

The maximum size of a scintillation crystal varies very much between different materials. NaI(Tl) crystals can be manufactured up to around 0.5 m in diameter whereas e.g. the limit for good quality BGO crystals is around 15 cm. This has to do with crystal growing physics related to the physical properties of the material. The limit for Ce doped crystals like YAP:Ce is even smaller, 5 cm in diameter. Sometimes it is easier and less expensive to construct a large detector surface area by combining smaller detectors.

We always advise to consult us for the optimum detector configuration for your application.

Detectors can be supplied with cylindrical housings made of e.g. *plastics* (only non-hygroscopic crystals), *aluminum, (chrome plated) steel, stainless steel or copper.* More complicated geometries are possible but add to cost. Aluminum has excellent radiation transmission properties but is relatively soft and can corrode, even when anodized. For aggressive or rough environments (shocks), stainless steel is advised. Copper is useful for low background applications (see section 5.7).

All detectors can be provided with customer defined mounting flanges or other means to support the instrument.

5.5 Light pulsers

The light yield of a scintillation material and the gain of a PMT is a function of temperature. As discussed in 2.3.5, it is possible to calibrate a scintillation detector on a light pulse emitted by e.g. a stabilized LED or by the light emitted by a *radioactive pulser.* This can be :

- A low activity built-in gamma source producing a line outside the region of interest; the energy is usually < 1 MeV.
- An alpha particle emitting nuclide like ^{241}Am in contact with the primary scintillation crystal producing a line between 1 and 3.5 MeV.
- A small (few mm diameter) built-in spot activated pulser crystal like YAP:Ce in optical contact with the primary scintillation crystal.

The advantage of method 1 is that one calibrates on the true response of the primary crystal. However, many gamma sources have more than one line and Compton background adds to the spectrum.

The advantages of alpha sources is the absence of Compton background and their high energy (usually around 5 MeV) which implies narrow lines. The disadvantage is that the temperature response of many scintillation crystals is different for gammas and alphas. The optimum choice depends on the energy of interest and on the temperature region in which the detector should be stabilized.

5.6 Photodiode detectors

The advantages and limitations of photodiode detectors were already discussed in detail in 4.2. In general, the required size of the scintillation crystal determines the possibility to use this readout technique. Small crystals perform best with good energy resolution and noise levels around 50 keV or slightly less. For medical applications these devices are well suited for measurement of 140 keV gamma-rays in which case the CsI(Tl) scintillation crystal is chosen with 15 x 15 or 10 x 10 mm surface area.

Photodiode detectors are also widely used for heavy ion detection in combination with thin Si detectors for E / ΔE measurements applied to particle identification. Compact size, good energy resolution and immunity to magnetic fields are pro's.

A totally different application is the measurement of high intensity X-ray beams. In this case, the photodiode is used in DC current mode (no pulse height discrimination). Low afterglow scintillation crystals like $CdWO_4$ are used in arrays coupled to photodiodes. Advantages are the good signal reproducibility, the absence of gain drift and the compact size. Examples of photodiode detectors are shown in section 7.

5.7 Low background detectors

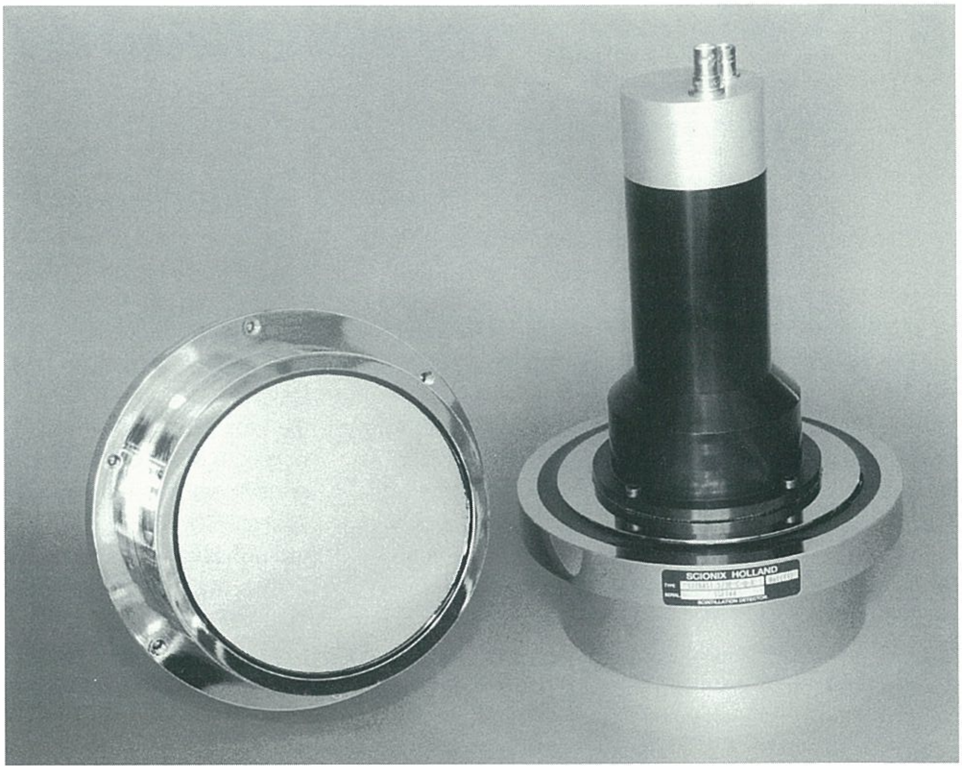
The term low background in itself needs to be specified in detail. A proper definition is the number of counts within a certain energy window with a well-defined shielding around the instrument (Pb, Fe and Cu).

Sources of background from within the detector are the photomultiplier tube, the detector housing and the crystal. The main contributing nuclides are ^{40}K (mainly from the PMT glass) and U and Th which are present in small quantities in the housing and window materials. Special PMTs can be selected with a ultra-low K content and all other materials can be pretested prior to assembly. Plastics should be avoided because these often contain K. Aluminum has a larger U and Th content than steel so for low background applications, steel housings are the best choice.

In low background detectors special precautions are taken to reduce the internal background. Between PMT and crystal quartz or undoped NaI light guides are used to absorb the beta radiation from ^{40}K and to increase the distance between the PMT and the scintillation crystal.

The scintillation crystal is a source of internal contamination too. Standard NaI(Tl) crystals have a low background since their ^{40}K content is less than 1 ppm. However, BGO crystals have an internal background that can be considerable and is approx 7 c/s/cc total (0 - 3 MeV). This background is caused by traces of ^{206}Pb that are transmuted by cosmic radiation into ^{207}Bi, resulting in gamma lines at 570, 1060, 1630 (sum peak) and 2400 keV. All BGO has this property. BaF_2 crystals have an intrinsic background of Radium causing a set of alpha lines with a typical count rate of 0.2 c/s/cc. The best scintillation crystal for low background applications is NaI(Tl).

127 mm diameter NaI(Tl) / CsI(Tl) phoswich.

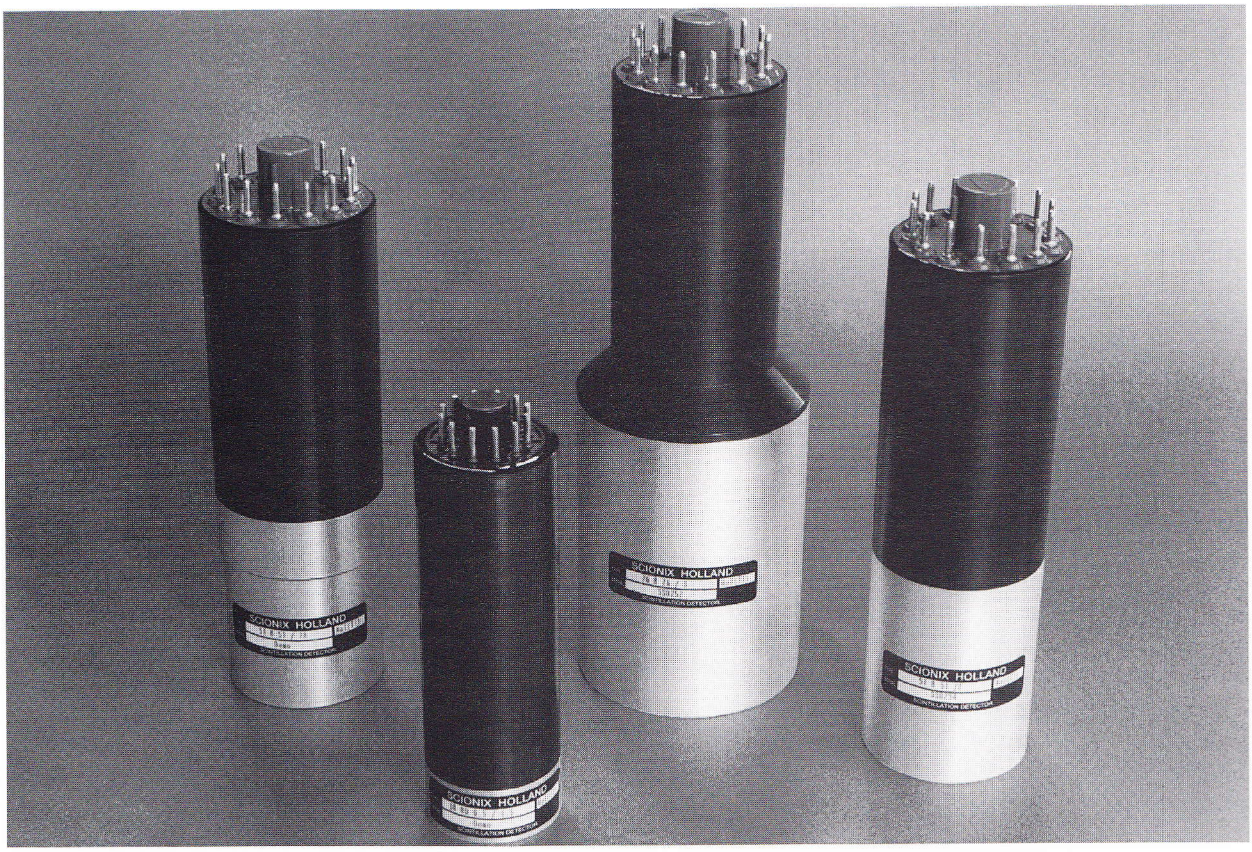


Low background detector.

6 Detector nomenclature / type numbering

SCIONIX scintillation detectors are characterized by a type number in which most of the properties of the instrument can be found. However, there remain features that are not "captured" in the type number (e.g. special geometries or electronic features) since there is a large number of ways a scintillation detector can be constructed. In this case the *suffix -X* is added to the type number which refers to "special". Note that for some of the nine features below, more than one option may apply.

The following example, type number **V 50 BD 5 / 2 ME1 - C - X** indicates a 50 mm square CsI(Tl) crystal, 5 mm high, integrally coupled to a 51 mm diameter (2") photomultiplier tube, provided with a beryllium entrance window, solid Mu-metal detector housing and built-in voltage divider. It is a customer special. Standard "off the shelf" scintillation detectors are provided with silver anodized aluminum housings, bialkali photocathode PMTs and positive (+) high voltage operation.



Standard B-style assemblies

V 50 B D 5 / 2 - ME1 - C - X

1. **Geometry of scintillator**
   - V = Square
   - R = Rectangular
   - C = Spherical
   - Z = Hexagonal
   - \- = Circular

2. **Actual scintillation diameter in mm**

3. **Type of crystal / light detector coupling**
   - A = Demountable photomultiplier
   - B = Integrally mounted photomultiplier
   - C = Crystal without photomultiplier
   - K = Gamma camera crystal
   - P = Photodiode readout
   - T = High temperature detector
   - H = Crystal readout side perpendicular to PMT
   - F = Fiber optics light guide
   - Q = Quartz light guide or window
   - NaI = Undoped NaI light guide

4. **Type of window / housing**
   - A = Thin window aluminum entrance window
   - D = Beryllium entrance window
   - M = Mylar entrance window
   - S = Steel housing (chrome plated or stainless)
   - C = Copper housing
   - P = Axial well in crystal
   - R = Ruggedized construction
   - \- = Standard 0.5 mm thick aluminum housing

5. **Height of crystal in mm**
   In case of *phoswiches,* the height of the primary crystal precedes the letters *PH* followed by the height of the secondary (guard) crystal.

6. **Diameter of photomultiplier tube in inches**
   In case of more than one PMT, the number is indicated in brackets after the diameter; e.g. / 3(3) indicates three 76 mm PMTs. In case of photodiode readout, the size of the photodiode is indicated in mm.

7. **Electronics/ features of PMT**
   - M = External solid μ-metal shield
   - L = Version with flying PMT leads
   - E1 = Built-in Voltage Divider (VD)
   - E2 = Voltage divider / preamplifier
   - E3 = Customer electronics special
   - HV = Built-in high voltage generator
   - -NEG = Negative high voltage

8. **Scintillation material**
   - C = CsI(Tl)
   - CN = CsI(Na)
   - BGO = BGO
   - BAF = BaF_2
   - YAP = YAP:Ce
   - CaF = CaF_2
   - P = Plastic scintillator
   - ZnS = ZnS(Ag)
   - \- = NaI(Tl)

9. **Extra features**
   - Am= Am light pulser
   - T = Built-in thermistor
   - O = Fiber optic for gain monitoring PMT
   - L = Built-in Led or laser port
   - X = Non standard or custom configuration
   - LB = Low background selected materials

B-style assemblies with built-in VD / preamp.

Standard C-style assemblies.

7 Standard detector configurations

In this section some standard scintillation detector assemblies are presented. Sometimes the drawings are such that one can fill in the desired diameter and height of the scintillator to calculate the actual dimensions of the assembly. Only some examples are given; many other options are possible.

7.1 Assemblies without photomultiplier tubes

7.1.1 C-styles and CP-styles

FEATURES

SCIONIX C-style detector assemblies basically consist of a scintillation crystal which is machined and mounted in a housing of aluminum, stainless steel or copper. In case of hygroscopic crystals the assembly is sealed by a glass or quartz window for optical coupling to a photomultiplier tube or other light detection device. C-style assemblies can be manufactured from low background materials (LB steel or copper).

The standard housing thickness is 0.8 mm. C-style assemblies can be provided in a ruggedized version (CR-styles) or designed for use at elevated temperatures.

The optical window can be extended in height or tapered to form an optical light guide to a different diameter than that of the crystal. For optimum energy resolution, the diameter of the crystal is chosen equal or slightly smaller than the diameter of the PMT.

C-style assemblies are intended for use in combination with customer's photomultiplier tube in demountable assemblies. The optical contact to the PMT is accomplished by using optical coupling compound or customer's own optical glue.

Housings can be equipped with flanges or grooves for O-rings in order to facilitate a demountable coupling to the PMT and its housing.

C-style assemblies can be provided with an *axial well* and are then called CP-styles, or with thin (30 µm thick)

Standard crystal assembly: C-style

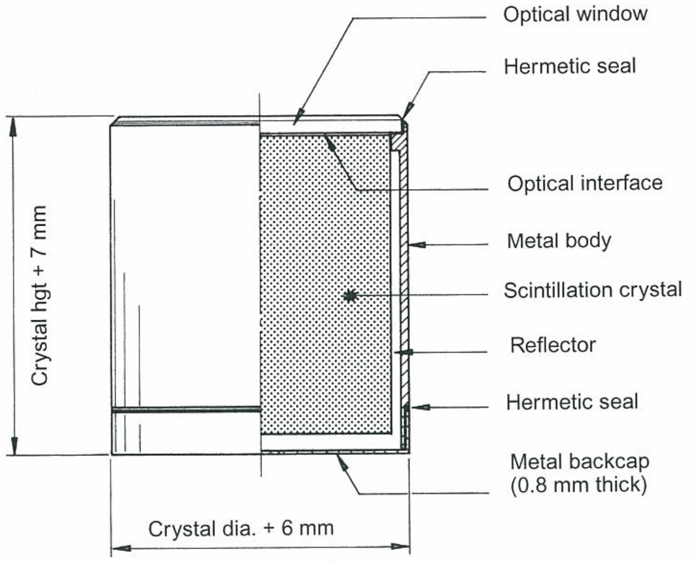


fig. 7.1 ***Example of C-style assembly: .. C ..***

Standard well-type crystal assembly: CP-style

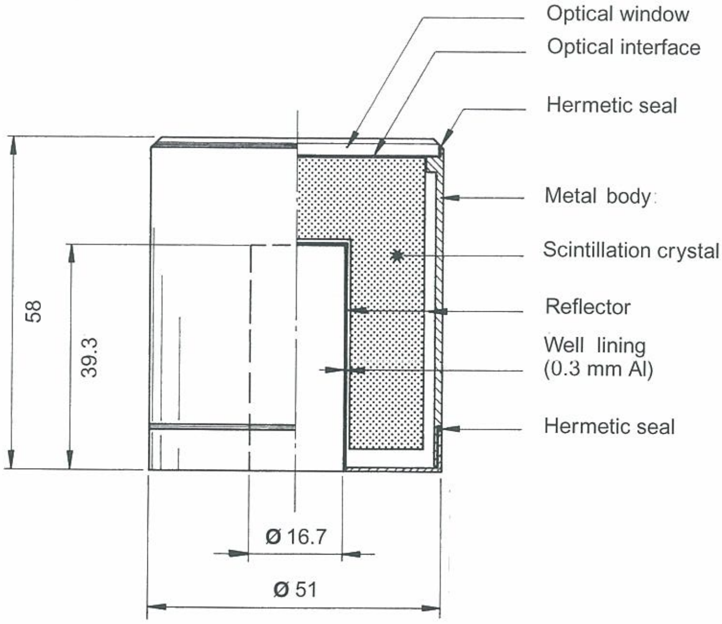


fig. 7.2 Example of CP-style assembly: 51 CP 51.

Al entrance windows at the flat side of the crystal, then called CA-styles.

Standard inner well dimensions for CP-style assemblies are :

51 CP 51 : 25.4 mm diameter, 39.3 mm deep,
16.6 mm diameter, 39.3 mm deep.

76 CP 76 : 25.4 mm diameter, 52 mm deep.

The standard well thickness is 0.3 mm (Aluminium).

APPLICATION

Standard C-style assemblies are used for detection of gamma-rays and X-rays between 30 keV and 2 MeV. For higher energies, BGO can be chosen as the scintillator of choice in which case the optical window is omitted. CP-styles are used in *well counters* for e.g. medical applications or wipe test detectors.

7.1.2 Thin window crystal assemblies: CA-styles, CD-styles

For the detection of low energy X-ray radiation, a detector can be made intrinsically insensitive to higher

Standard thin window crystal assembly: CA / CD-style

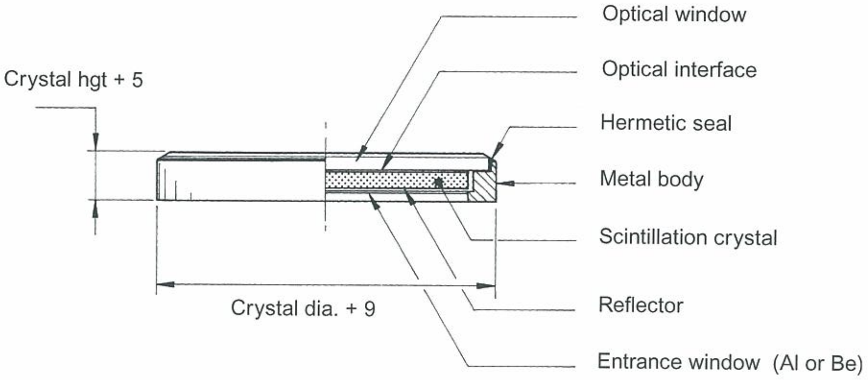


fig. 7.3 Example of thin-window CD-style assembly: .. CA/CD ..

energy radiation by choosing the scintillation crystal only a few mm thick. For optimum energy resolution, also at very low (several keV) energies, NaI(Tl) scintillation crystals are often used.

For transmission of the radiation of interest, 30 μm thin Aluminum (Al) windows or 0.2 - 0.3 mm thick Beryllium (Be) windows are used. Al windows are suitable for energies down to 10 keV whereas Be windows can be used down to 3 keV (see Fig. 5.3). The advantage of Al windows is their low cost but Be windows are less easily damaged. For non-hygroscopic crystals, aluminized mylar entrance windows can also be used.

For fast X-ray spectroscopy, thin (0.5 - 1 mm thick) YAP:Ce CA- or CD-styles can be used. Thanks to the decay time of YAP:Ce of only 27 ns (see Table 3.1), count rates of several MHz can be achieved.

7.2 Assemblies with photomultiplier tube(s)

Detectors with photomultiplier tubes exist basically in two versions: a demountable version called A-style and an integrated one called B-style.

7.2.1 Assemblies with integrated photomultiplier tubes: B-styles

FEATURES

Scintillation detectors with integrated photomultiplier tube(s) consist of a scintillation crystal, coupled directly to a photomultiplier tube with a slightly flexible, high refractive index optical coupling medium. The crystal and PMT are hermetically sealed (gas tight) in a light-tight housing with an aluminium or beryllium entrance window. Detectors have an internal μ-magnetic shielding or a solid μ-metal housing (special option) around the PMT and can be supplied as plug-in units to connect to a Voltage Divider (VD) or with a built-in VD (see section 8).

The advantages of this construction are :

- Permanent light sealing
- Improved energy resolution due to direct coupling to the PMT
- Guaranteed energy resolution
- Simplification of detector design by eliminating support hardware to maintain contact between crystal and PMT
- No problems with degradation of optical contact between crystal and PMT.

APPLICATION

One of the most widely used scintillation detectors world-wide is the 76 x 76 mm NaI(Tl) detector (SCIONIX type 76 B 76 / 3) which is *the* scintillation detector standard for general gamma spectroscopy having excellent efficiency and energy resolution.

For low background (LB) applications, B-style assemblies can be supplied in low background steel or electrolytic copper housings. All detector components can be selected on their lowest possible radioactive background. In LB units, quartz or undoped NaI light guides are used to reduce the background from the PMT (see section 5.7).

On the next pages some standard B-style detectors are presented as well as an example of an assembly equipped with an axial well *(BP-style).*

Beside the above shown, many other PMT diameters are possible. Standard PMT diameters are : 13, 19, 25, 28, 38, 51, 76, 90, and 127 mm.

7.2.2 Thin window B-style assemblies : BA-, BD- and BM-styles

FEATURES

For the detection of low energy radiation, thin scintillation crystals are combined with PMTs in a thin-window assembly. For the detection of X-rays > 10 keV, 30 μm thick Aluminum windows (*BA-styles*) are used. For lower energies, the *BD-style* with a 0.2 or 0.3 mm thick Be window is the detector of choice. *BM* is the notation for a thin mylar entrance window for the detection of heavy ions or low energy β-particles with non-hygroscopic crystals. The thickness of the above materials is not fixed and can be modified to your application.

NOTE

Thin window B-style assemblies are often constructed with light guides to compensate for local inhomogeneities in the response of the photocathode of the PMT.

TYPE: 38 B 38 / 1.5

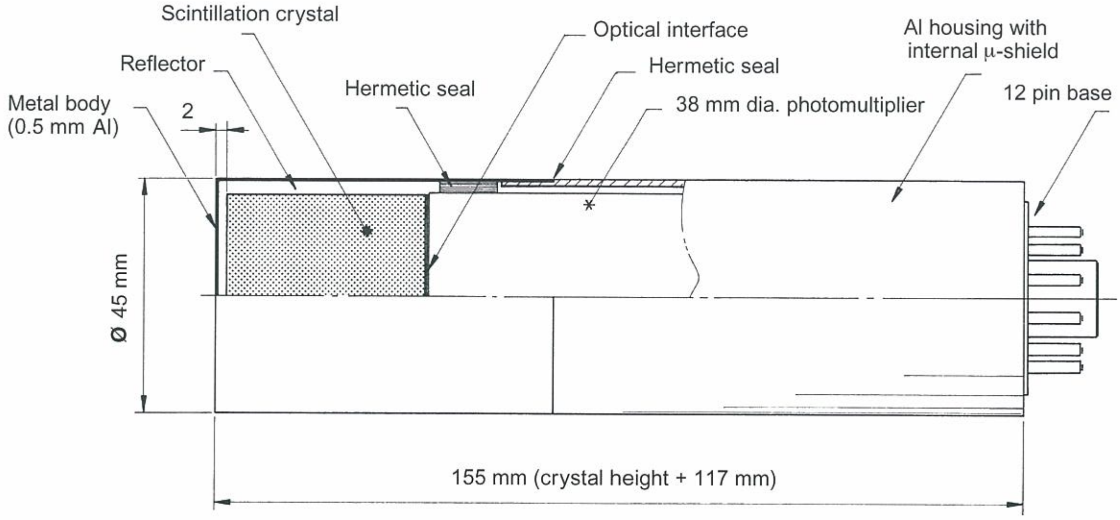


fig. 7.4 ***Example of standard B-style detector with 38 mm diameter PMT: 38 B 38 / 1.5.***

TYPE: 51 B 51 / 2

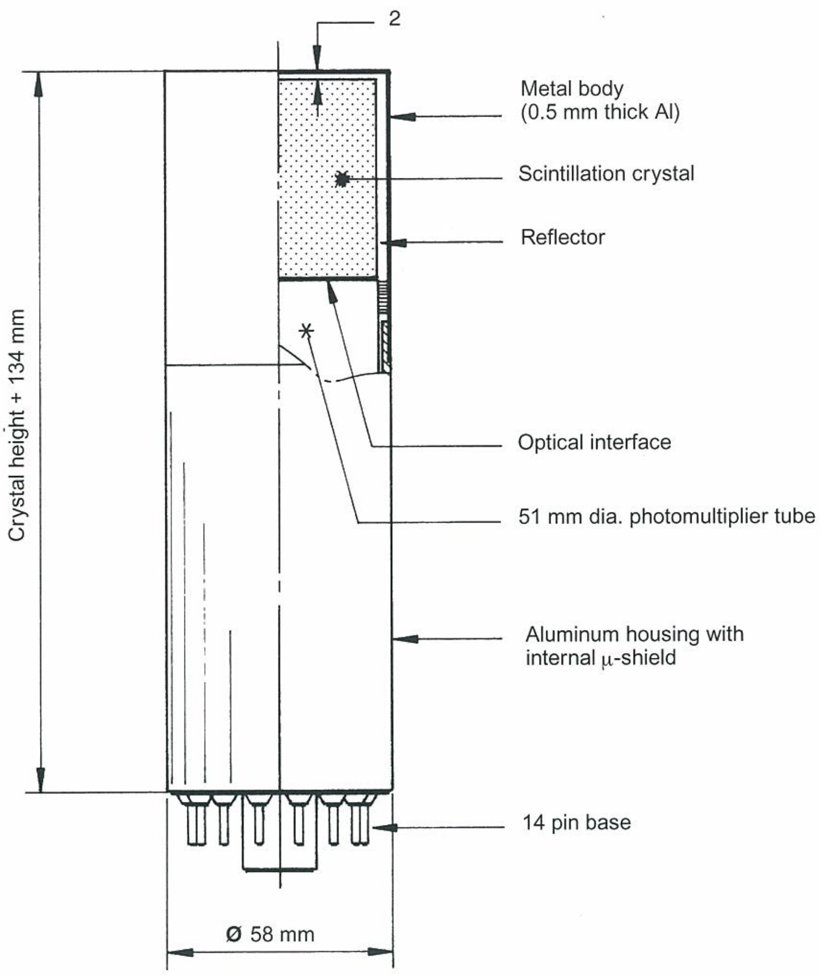


fig. 7.5 ***Example of standard B-style detector with 51 mm diameter PMT: 51 B 51 / 2.***

TYPE: 76 B 76 / 3

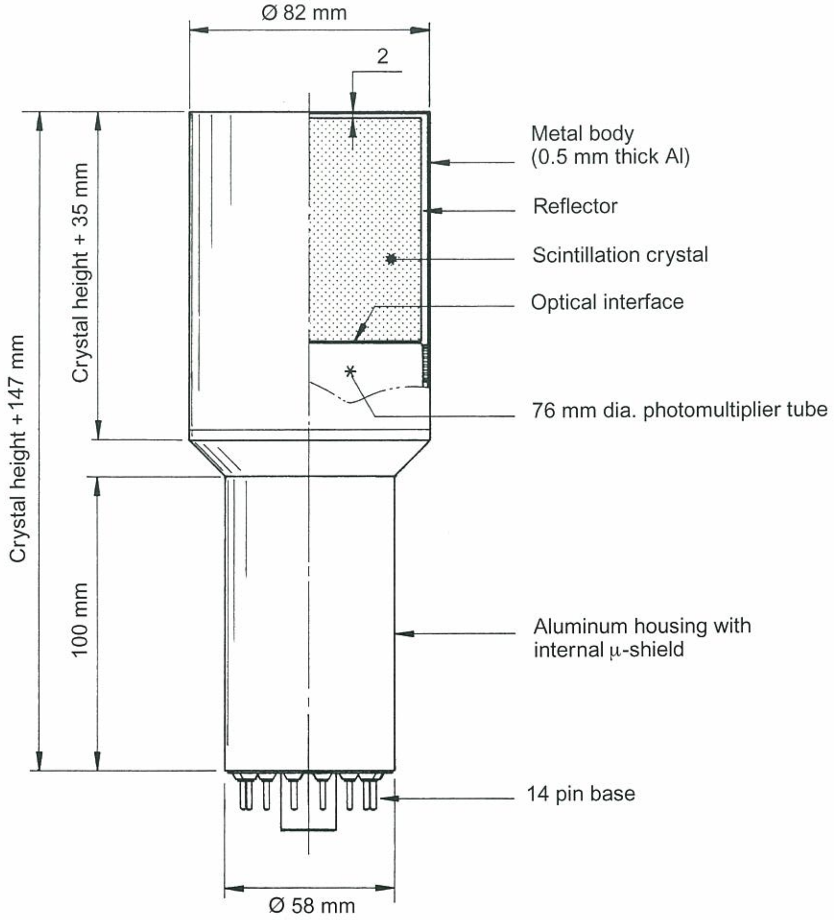


fig. 7.6 Example of standard B-style detector with 76 mm diameter PMT: 76 B 76 / 3.

detector configurations

TYPE: 32 BP 32 / 1.5 - X

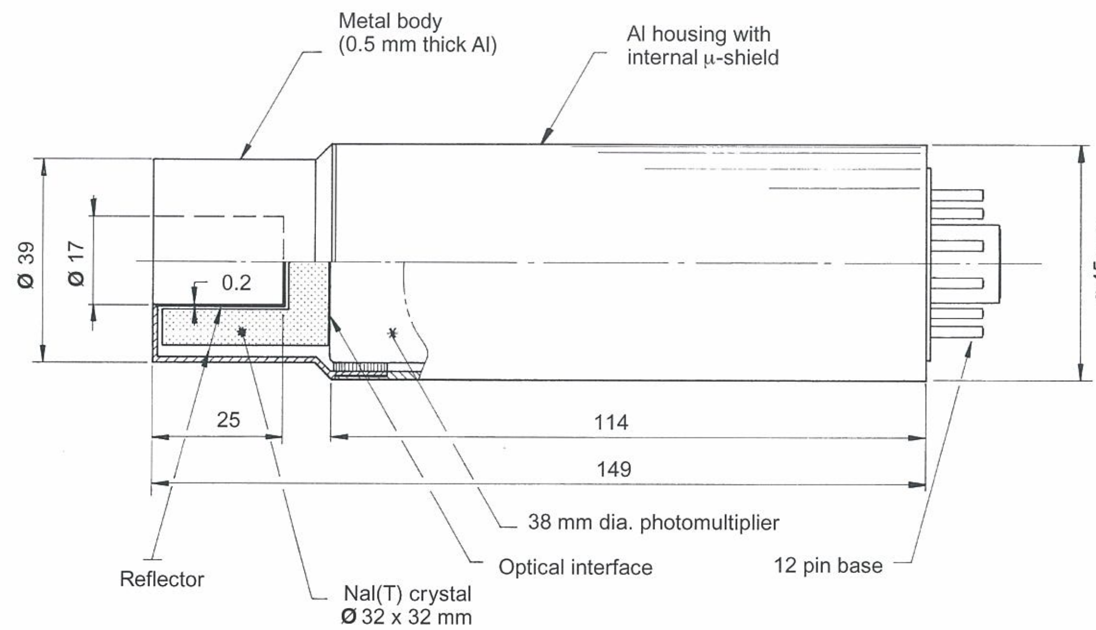


fig. 7.7 ***Example of BP-style assembly with 38 mm diameter PMT: 32 BP 32 / 1.5 - X.***

TYPE: 76 BP 76 / 3

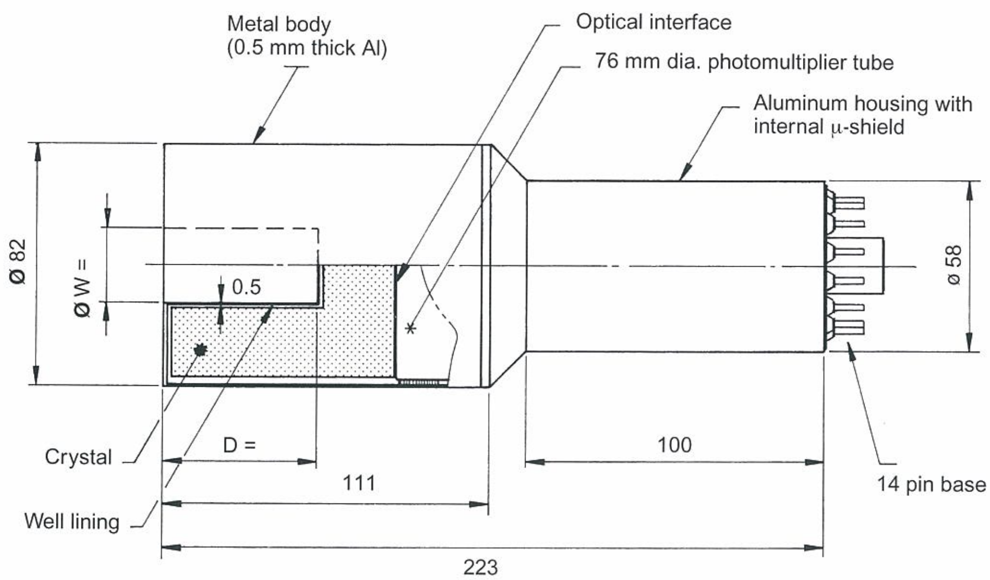


fig. 7.8 ***Example of standard BP-style with 76 mm diameter PMT: 76 BP 76 / 3.***

TYPE: 25 BA 1 / 1.5 - E1

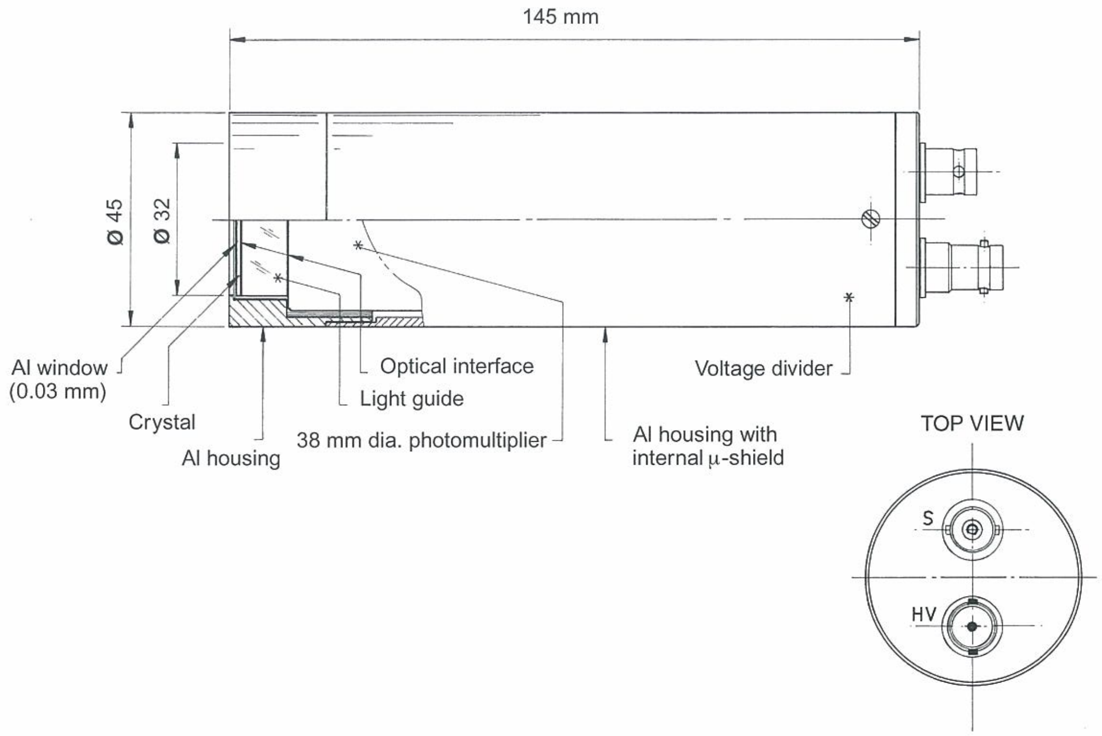


fig. 7.9 ***Example of standard BA-style assembly with 38 mm diameter PMT and built-in voltage divider: 25 BA 1 / 1.5 - E1.***

TYPE: 152 A 102 / 5 - E2
"Whole body counter"

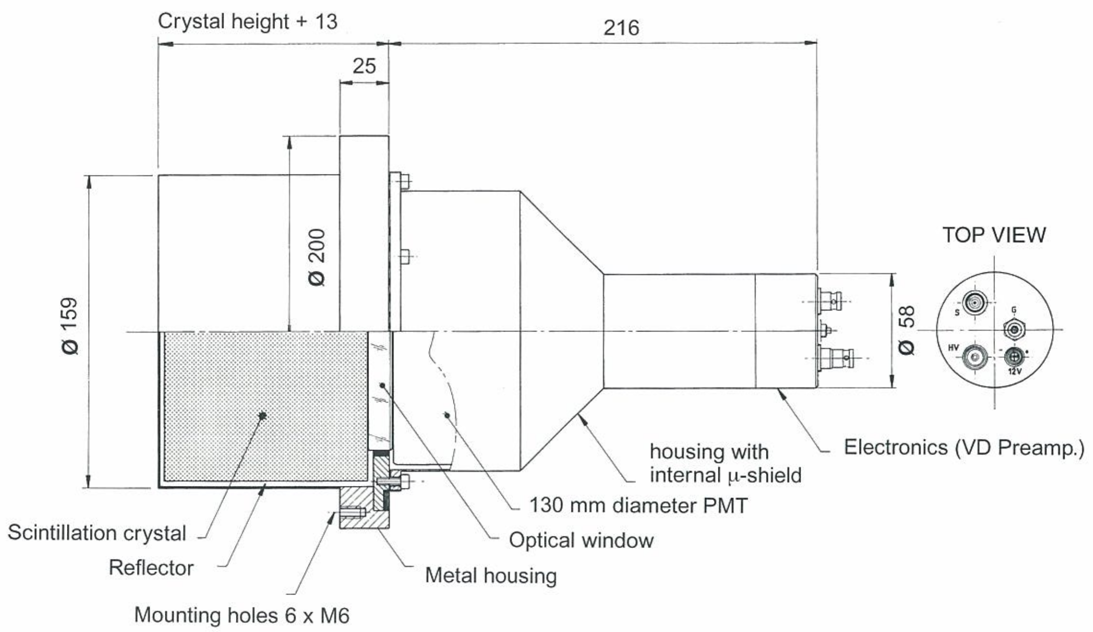


fig. 7.10 ***Example of A-style assembly with 127 mm diameter PMT and built-in voltage divider preamplifier: 152 A 102 / 5 - E2.***

7.2.3 Assemblies with demountable photomultiplier tubes: A-styles

Detectors with more than one PMT are often constructed as demountable assemblies. The advantage is that in case of break-down of one PMT, it can be replaced easily by the user without having to take apart the entire crystal assembly. Especially for complicated detectors such as Anti-Compton shields or large whole body counters, this is the normal approach. A-styles are also available with axial well (AP-style) or thin entrance window (AA-styles).

7.3 Photodiode detectors

The advantages and limitations of photodiode detectors were discussed in section 4.2. In general, photodiode scintillation detectors consist of a small PIN photodiode, integrally coupled to a scintillation crystal, often CsI(Tl). As a standard rule, a charge sensitive preamplifier is incorporated in the assembly.

FEATURES

The *intrinsic noise* of the photodiode/preamplifier combination *prohibits* the use of *large* scintillation crystals for detection of low energy (< 1 MeV) gamma-rays. This noise determines the lowest energy that can be detected with the device. CsI(Tl) crystals of 1 cm^3 coupled to 10x10 mm^2 PIN photodiodes can be used down to 40 keV; for larger crystals (e.g. for 2x2x2.5 cm^3 coupled to 18x18 mm^2 diodes), this energy is about 70 keV.

APPLICATION

Photodiode scintillation detectors can be used e.g. in applications where:

- No high voltage is available or desired (medical applications)
- Stable gain is essential (long term environmental monitoring)
- High magnetic fields are present (physics research)
- A rugged detector is required.

CsI(Tl) crystals do not crack or cleave and photodiodes are shock resistant. Many configurations are possible. The noise level and energy resolution of the detector depend very much on the crystal/diode configuration. Contact SCIONIX for your specific requirement. The noise of photodiode scintillation detectors increases with temperature. Above 50 °C these instruments are not advised.

An important application of photodiode detectors is in physics research for the detection of *charged particles*. A thin silicon detector is placed in front of a CsI(Tl) crystal read out with a photodiode to perform an E / ΔE measurement.

TYPE: 20 P 25 / 18 - E2 - C - X

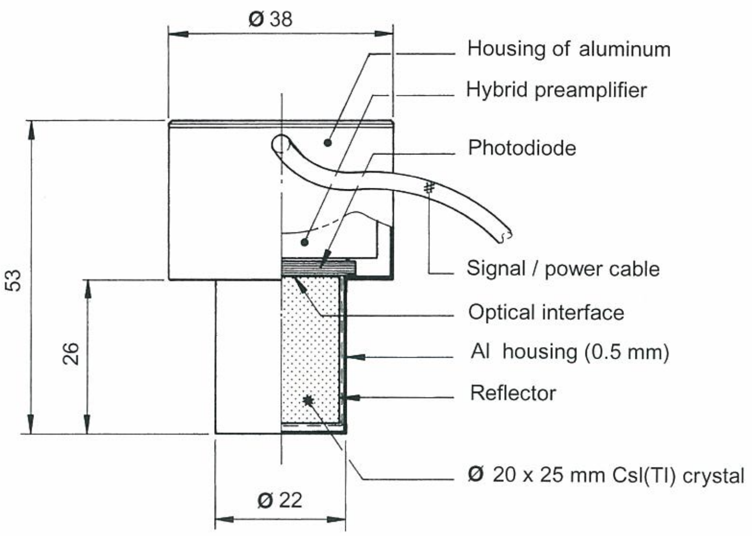


fig. 7.11 ***Photodiode detector for general radiation monitoring: 20 P 25 / 18 - E2 - C - X.***

TYPE: V50 PM 25 / 18 - E2 - C - X

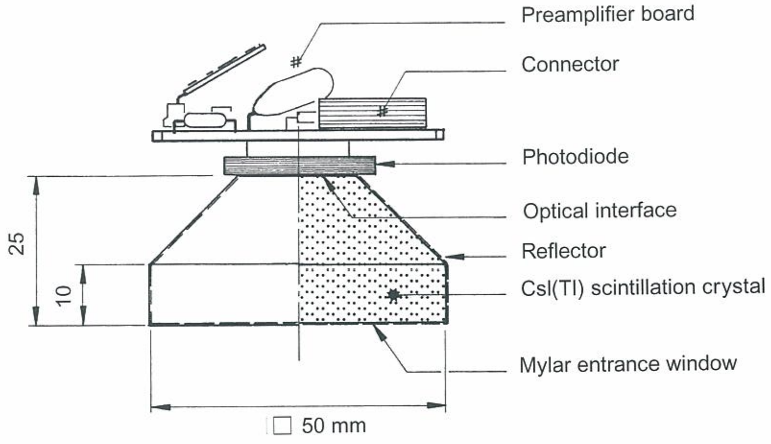


fig. 7.12 ***Photodiode detector for heavy ion detection: V50 PM 25 / 18 - E2 - C - X.***

SPECIAL

To avoid the necessity for extra pulse shaping electronics, the *SPD2000* was developed. This special photodiode detector includes a shaping amplifier with a maximal output of 10 V and line driving capabilities of 40 m. The output from the SPD2000 can be directly fed into an MCA or counter. For more information we refer to the special technical information leaflet of this instrument.

For the detection of low energy X-rays, a bare photodiode *without a scintillation crystal* can be used in an assembly essentially the same as above but without the crystal. These assemblies are only useful below 50 keV since the standard thickness of PIN photodiodes is only 0.2 - 0.3 mm.

7.4 Specials

In fact, many SCIONIX scintillation detectors are custom-made with detector configuration and materials adapted to the specific requirements of the user. Regarding the special applications we would like to mention here *anti-Compton shields, scintillation detectors with miniature PMTs* and *phoswiches.*

ANTI-COMPTON SHIELDS

Anti-Compton (AC) systems are scintillation detector assemblies mounted around a *High Purity Ge-detector (HPGe)* that detect the gamma rays Compton scattered by the Ge crystal and generate a *veto signal* when such a Compton event occurs. This improves the peak-to-total ratio in the pulse height spectrum of the Ge detector significantly.

Crucial parameters are a large solid angle coverage around the HPGe detector and high stopping power. The use of segmented well-type BGO detectors is the generally accepted optimum approach, except for *low background systems* where the intrinsic high background of BGO is prohibitive and NaI(Tl) is normally used. Below some examples are shown.

AC-shields can be provided with *special backcatcher detectors* around the cryostat arm for optimum solid angle coverage. To save cost, BGO AC-shields are often equipped with a NaI(Tl) "nose" since at these angles scattered energies are low and a high stopping power is not required.

Many options are possible and we advise to contact SCIONIX to discuss the optimum AC shield configuration for your Ge detector assembly.

BGO / NaI(Tl) anti-Compton shield

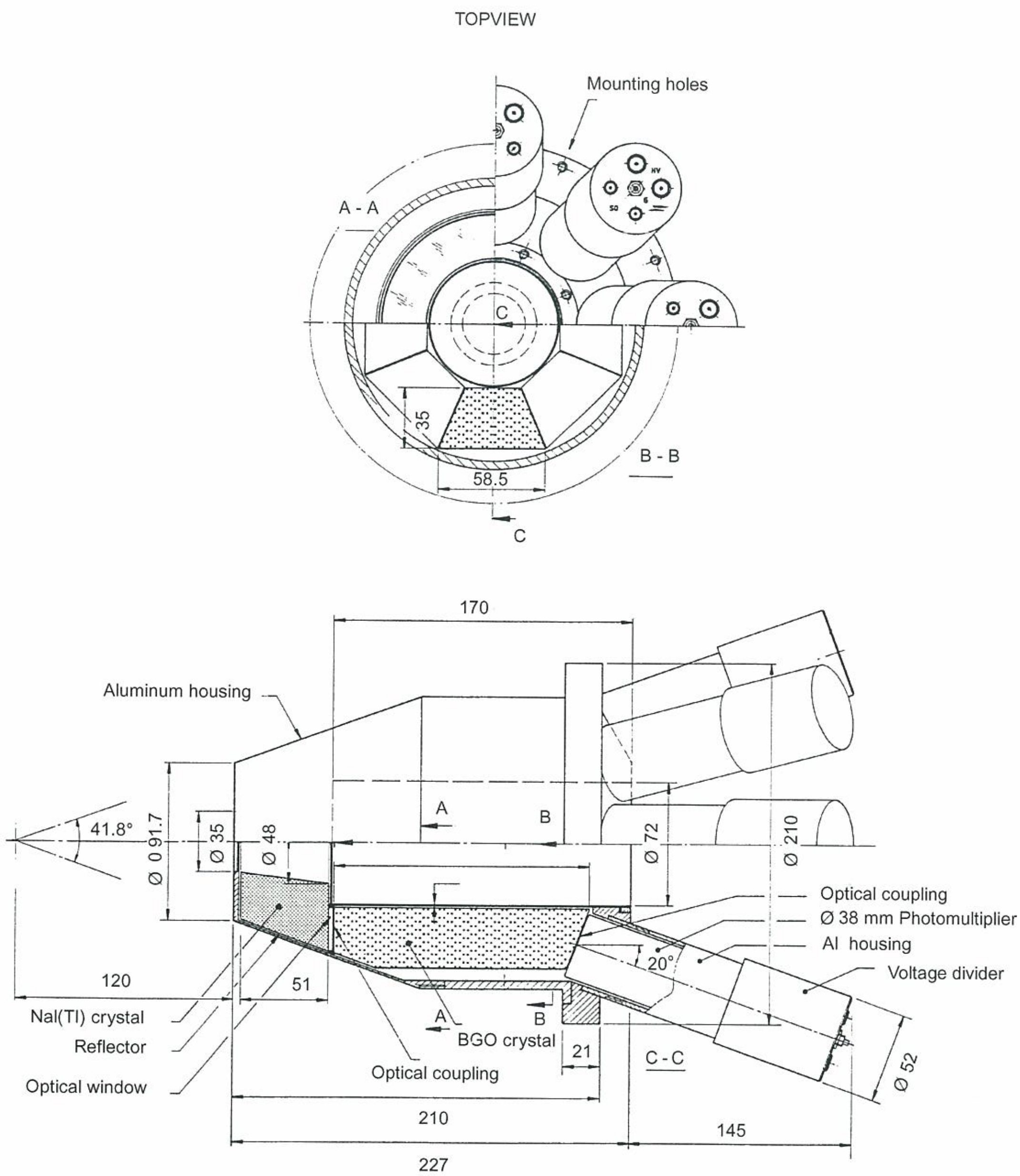


fig. 7.13 ***Standard BGO anti-Compton shield suited to fit around a 70 mm diameter HPGe detector assembly.***

TYPE 178 AP 115 / 1.1 (4) - E1

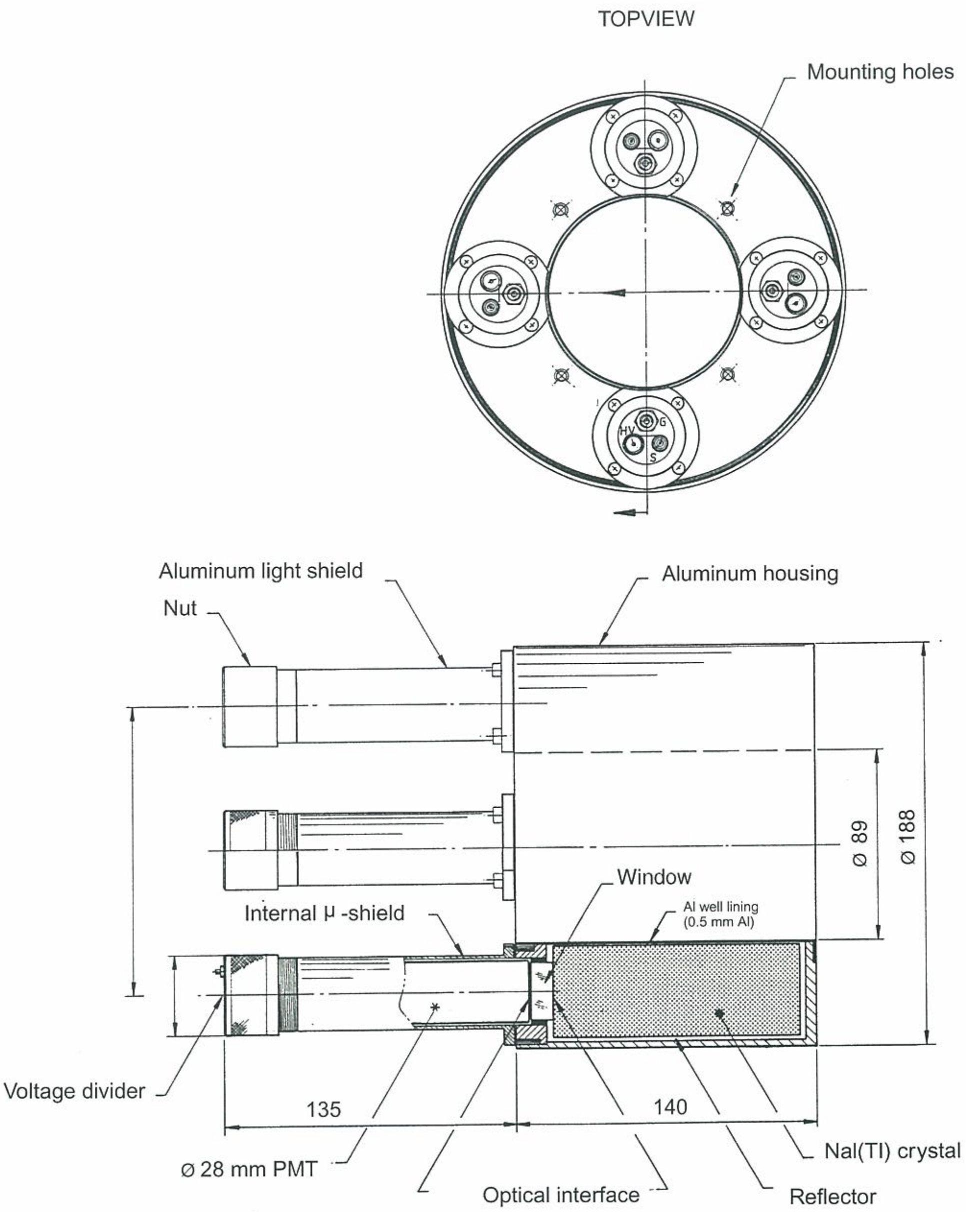


fig. 7.14 ***Ring-type NaI(Tl) anti-Compton shield, specially designed for portable HPGe systems.***

TYPE: 12.7 B 12.7 / 0.3 - E1

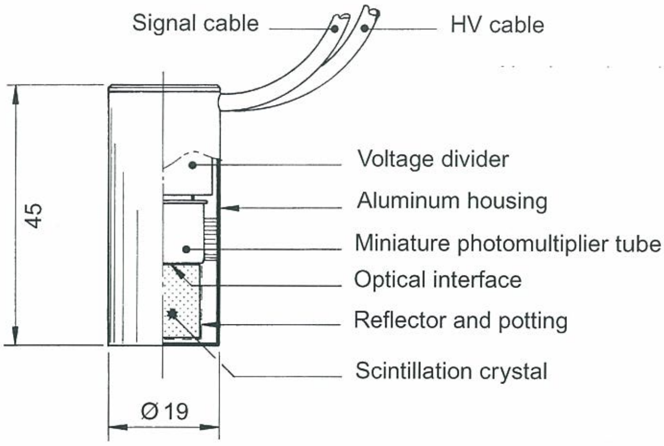


fig. 7.15 ***Small scintillation detector with miniature PMT.***

MINIATURE DETECTORS

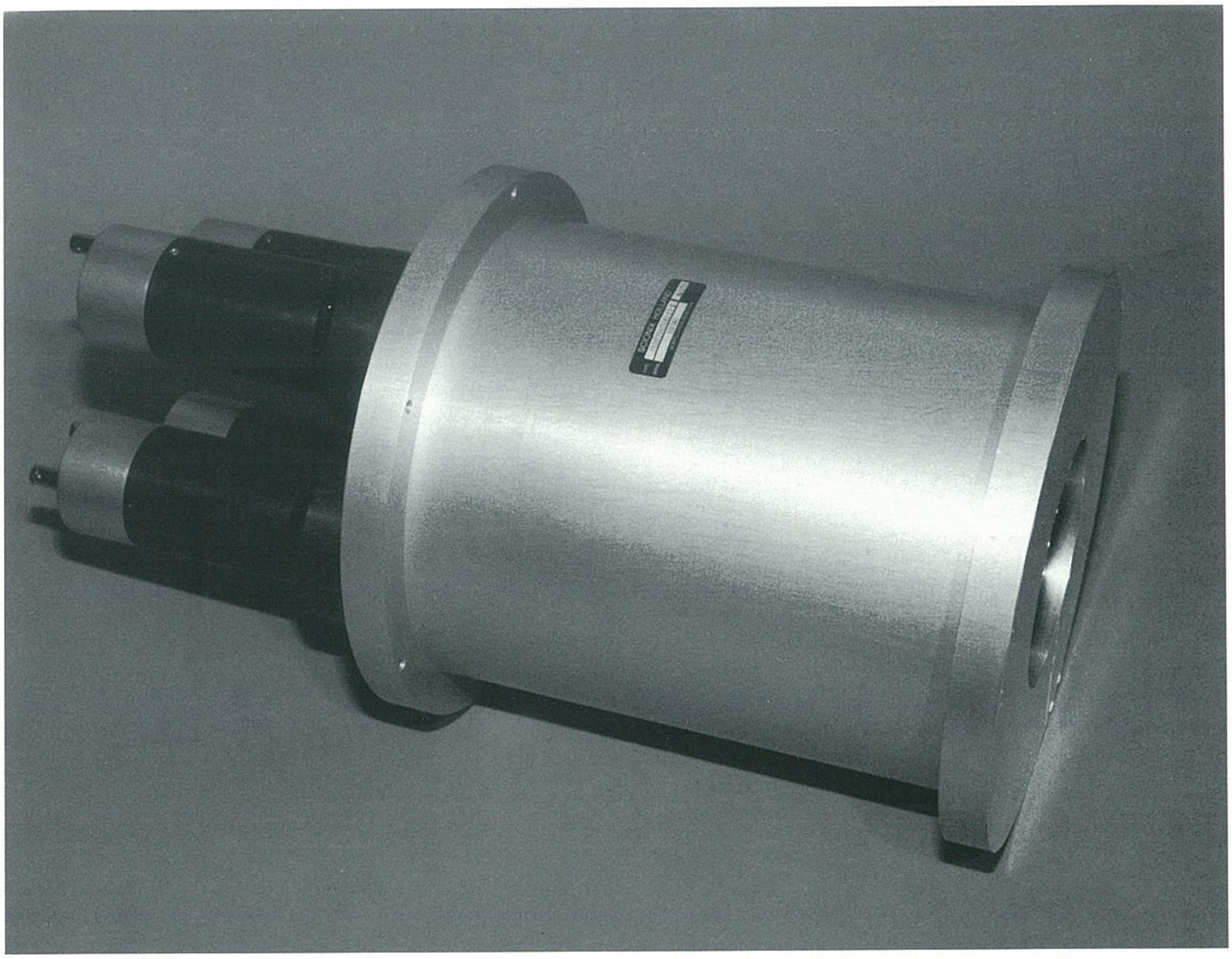
The recent development of miniature mesh-type dynode photomultiplier tubes has opened up some possibilities to construct short small diameter detector assemblies. The active area of these devices is around 1 - 2 cm which limits the diameter of scintillation crystals that can be used. The detectors are equipped with built-in voltage dividers. Miniature scintillation detectors are useful in applications where space is limited. Miniature PMTs are rugged and quite insensitive to magnetic fields. Below an example is presented. As an option, assemblies with built-in high voltage generator are available.

PHOSWICHES

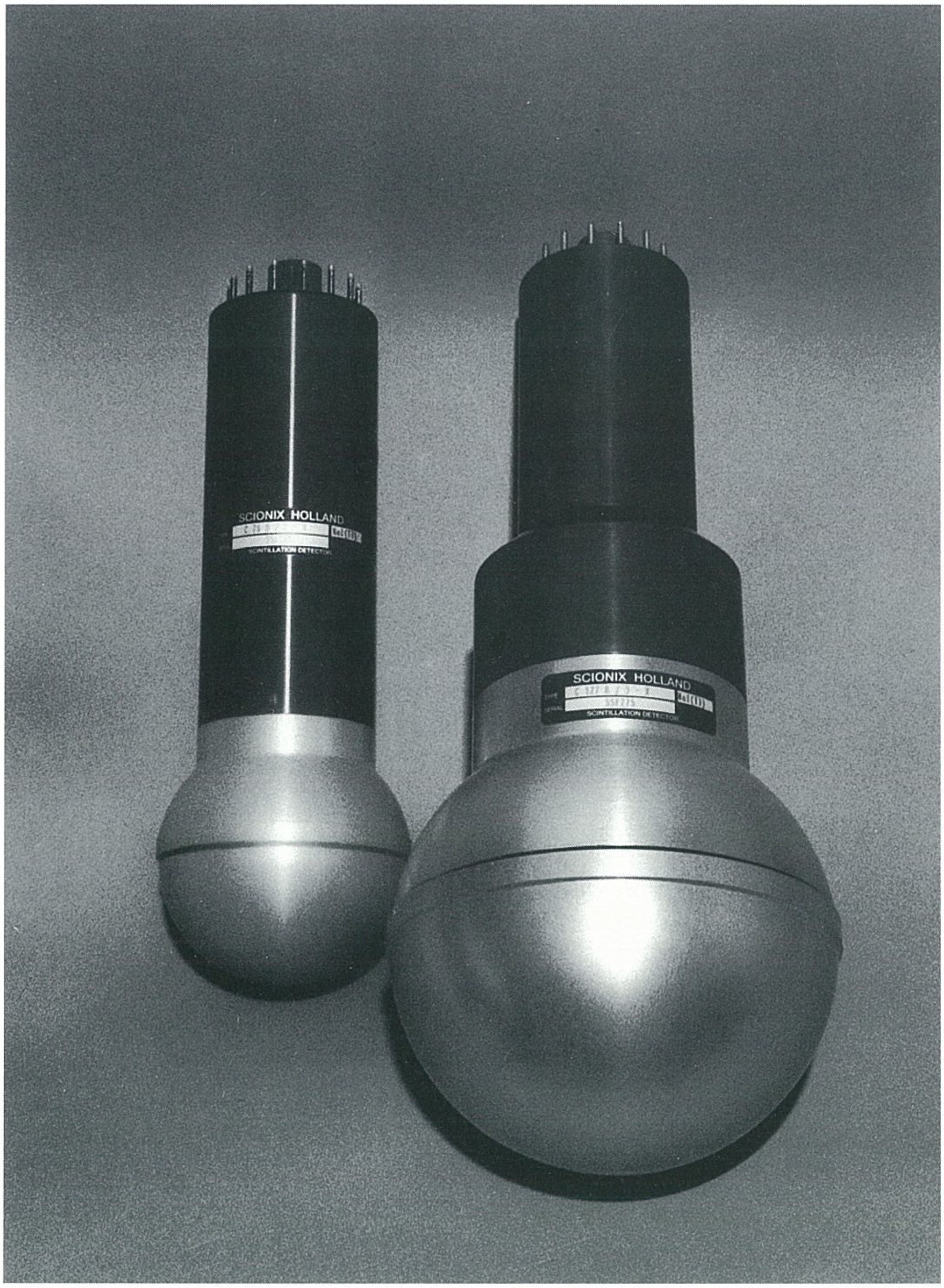
Phoswiches are detectors employing a combination of two different scintillation materials. The application is low intensity detection of X-rays and α- or β-particles in the presence of a γ-ray background. The (thin) primary scintillation crystal detects the radiation of interest and the secondary (guard) crystal detects background absorptions in the guard crystal and radiation that is scattered by the primary crystal and is absorbed in the guard crystal. This last aspect implies that by setting a *veto* in case of a *time coincidence* in signals between primary and guard crystal, the background contribution from the primary crystal can be reduced.

Both primary and guard crystal are read out with the same PMT. Whether a signal in the PMT originated from the primary or the guard crystal is determined by choosing scintillation materials having *different decay times*.
The most frequent combination is a NaI(Tl) and CsI(Tl) phoswhich (effective decay time 0.25 μs and 1 μs) for low energy X-ray detection or a CaF_2(Eu) / NaI(Tl) phoswich for low background α- and β-particle detection.

Signal separation is done by pulse shape analysis for which it is important that the decay times of the two scintillators are sufficiently different.



Large well detector (10 cm diameter x 20 cm deep well).



76 and 127 mm diameter spherical NaI(TI) detectors for optimal uniform sensitivity.

8 Voltage dividers and electronics

Scintillation detectors usually employ a Voltage Divider (VD) network to operate the PMT. This sometimes called "bleeder network" defines a potential (voltage) difference between the cathode, dynodes and anode of the PMT. The exact design of this network is of influence for proper working of the scintillation detector. Some details of voltage divider networks are discussed below. The descriptions below are not exhaustive; for more details we refer to the photomultiplier manufacturer's literature.

8.1 Positive or Negative High Voltage ?

It is possible to operate a photomultiplier tube in two ways:

A. anode at positive potential (cathode at ground)

B. anode at ground (cathode at negative potential).

For measurements of DC anode current such as in some X-ray applications, option B is the only choice since in the first option the anode must be separated from the follow-up electronics by means of a high voltage capacitor.

On the other hand, option A is used for most standard applications since the μ-metal shield should be preferably at cathode potential. Option A implies that cathode, detector mass (ground) and shield are all connected together. In option B, the shield must be very well insulated from the detector mass and special construction requirements apply.

In all cases, a detector designed for POSITIVE high voltage operation, should NEVER be connected to a Plug-in Voltage divider wired for negative High Voltage since this will cause a dangerous situation with the detector housing at LIVE POTENTIAL !

All standard SCIONIX detectors are designed for POSITIVE high voltage. A detector designed for NEGATIVE High Voltage has the suffix -NEG at the end of the type number.

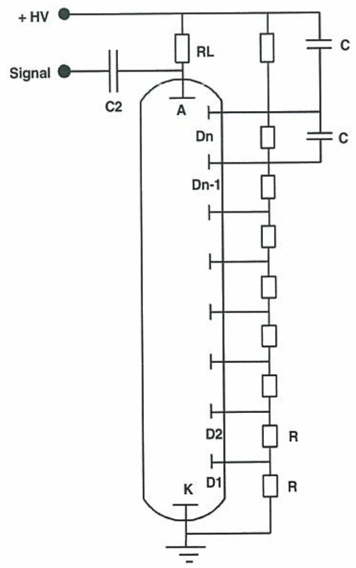


Fig. 8.1. Example of VD for positive high voltage.

Negative high voltage is required for some fast timing applications where the possibility of discharges between the cathode of the PMT and the μ-shield are to be avoided. These PMTs are operated at more than 2 kV for fast response.

Voltage dividers for detectors operated at positive high voltage can be wired with a *single connector* for signal and HV. At the electronic's side, these can be separated using a simple splitter, as illustrated in fig. 8.2.

8.2 Design of voltage dividers

The design of the voltage divider influences the performance of a detector. At high count rates, the voltage across dynodes may drop and the average bleeder current should always be defined as at least 10 times larger than the average anode current in the detector. A standard resistor value between dynodes is 470 kΩ. This is a compromise between bleeder current and gain stability which is sufficient for count rates up to approx. 50.000 c/s.

Voltage dividers may be linear (most common), tapered or specially stabilized with Zener dynodes or transistors.

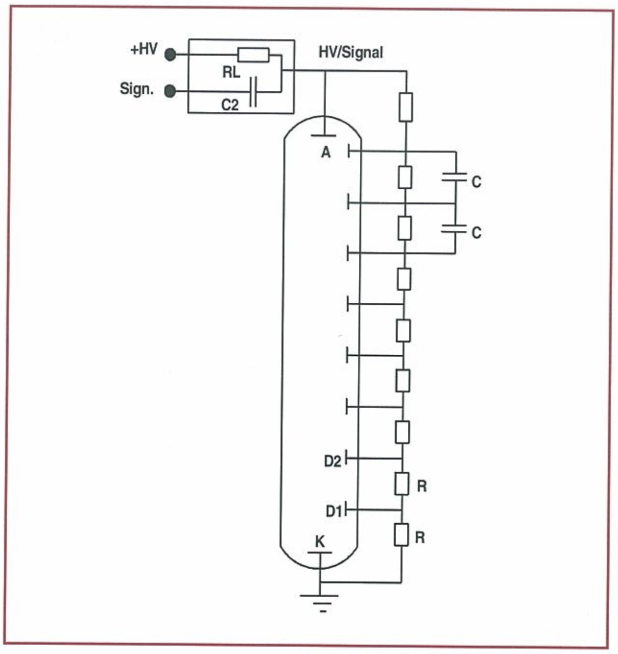


Fig. 8.2 ***Example of VD with single connector and signal/HV splitter.***

The number of possibilities is large. A very important aspect is the potential (electric field) between the cathode and the first dynode of the PMT. In any case, this potential should be sufficient to ensure a good photoelectron collection efficiency. Usually, this voltage is prescribed by the PMT manufacturer.

The *gain* of a scintillation detector varies with each PMT and is also strongly influenced by the exact design of the voltage divider. If the absolute detector gain is of importance, it can be defined as: ***the output voltage (in e.g. 1 MΩ) at a specific operating voltage of the PMT for a certain energy absorbed in the detector.***

PMTs can be *selected* on gain but adjustment of the gain of the detector by varying the voltage in the VD by means of a precision potentiometer is much more convenient. *Extra options* on voltage dividers are e.g. a gain potentiometer, an extra dynode output or a focus potentiometer.

SCIONIX can design the voltage divider best suited for your application without any additional cost.

8.3 Plug-on or integrated ?

Voltage Dividers and other electronics can be *incorporated* into the scintillation detector. In this case, the resistor network is *directly* soldered onto the pins of the PMT which implies a minimal length of the assembly. For low background applications this is the preferable option. The connector(s) for high voltage and signal are located at the back of the assembly. Also flying leads is an option.

When it is expected that detectors have to be interchanged often it may be preferable to use a so-called *"plug-on"* option in which case the voltage divider and associated electronics are mounted in a small housing with the same diameter as the detector which is plugged on the pins of the base of the PMT. Most frequently used PMT bases in this respect are the 12 pin JEDEC B12-43 base for 38 mm diameter PMTs and the 14 pin JEDEC B14-38 base for 51, 76 and 127 mm diameter PMTs. These are also the standard bases for scintillation detectors supplied without voltage divider. Below some examples are presented.

8.4 Voltage dividers and preamplifiers

A PMT signal will be attenuated in a long cable and when signals have to be transported over more than say 10 m of cable this effect cannot be neglected. Signals even may become deformed and signal differences between a set of detectors having different cable lengths can be a problem.

Furthermore, the signal that is to be fed into a main amplifier (also called shaping amplifier or spectroscopic amplifier) needs to have a certain pulse fall time (typically 50 μs) in order to allow proper pole-zero and base-line correction. This effect is especially important at high count rates.

To solve the above problems, scintillation detectors can be supplied with a built-in (or plug-on) *voltage divider / preamplifier*. This amplifier has an output impedance of 50 Ω for proper matching to the most frequently used cable impedance (reflections). Usually, the end stage of this amplifier is based on the principle of an emitter follower.

The standard SCIONIX voltage divider/ preamplifier the VD (12) 14 / E2 is an example of this suited for a wide variety of PMTs. This amplifier operates with a wide variety of voltages, is very fast (rise time < 50 ns) and can drive cable lengths of 100 m or more. Varieties for ultra low power consumption exist. The amplifier is very small so that it will fit in almost every scintillation detector.

Please consult SCIONIX for your specific requirements regarding signal shape, power consumption etc.

TYPE VD 14 - E2

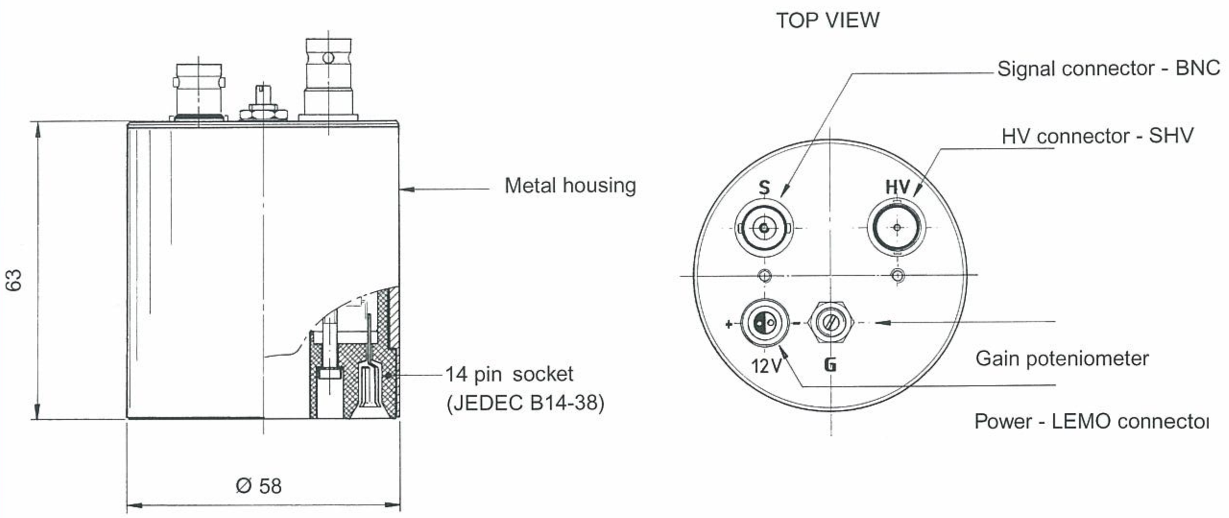
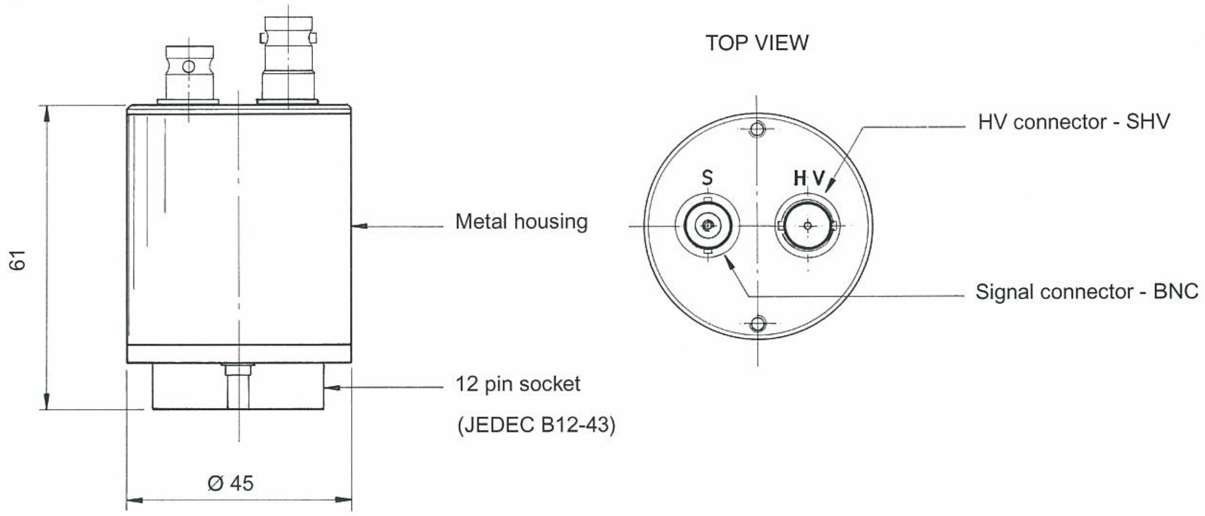


fig. 8.3 ***Standard plug-on voltage divider / preamplifier for 14 pin PMT bases.***

TYPE VD 12 - E1



NOTE: E2 option available

fig. 8.4 ***Standard plug-on voltage divider for 12 pin PMT bases.***

8.5 Connectors

Often, high voltage, signal and preamplifier power are fed in via separate connectors. The SCIONIX standard connector for high voltage is the *SHV* (Super High Voltage) connector, the most frequently used standard in nuclear electronics. For signals, *BNC* connectors are the standard and for preamplifier power signals, the *dual LEMO type 0* and the *9 pin sub-D* connector are normally used.

Other possibilities are e.g. flying leads options, water-tight connectors, MHV, TNC, PET-100 and different types of LEMO or FISHER connectors.

Power HV and signal can also be fed in (out) via a single large multipole connector.

8.6 Built-in High Voltage generators and other electronics

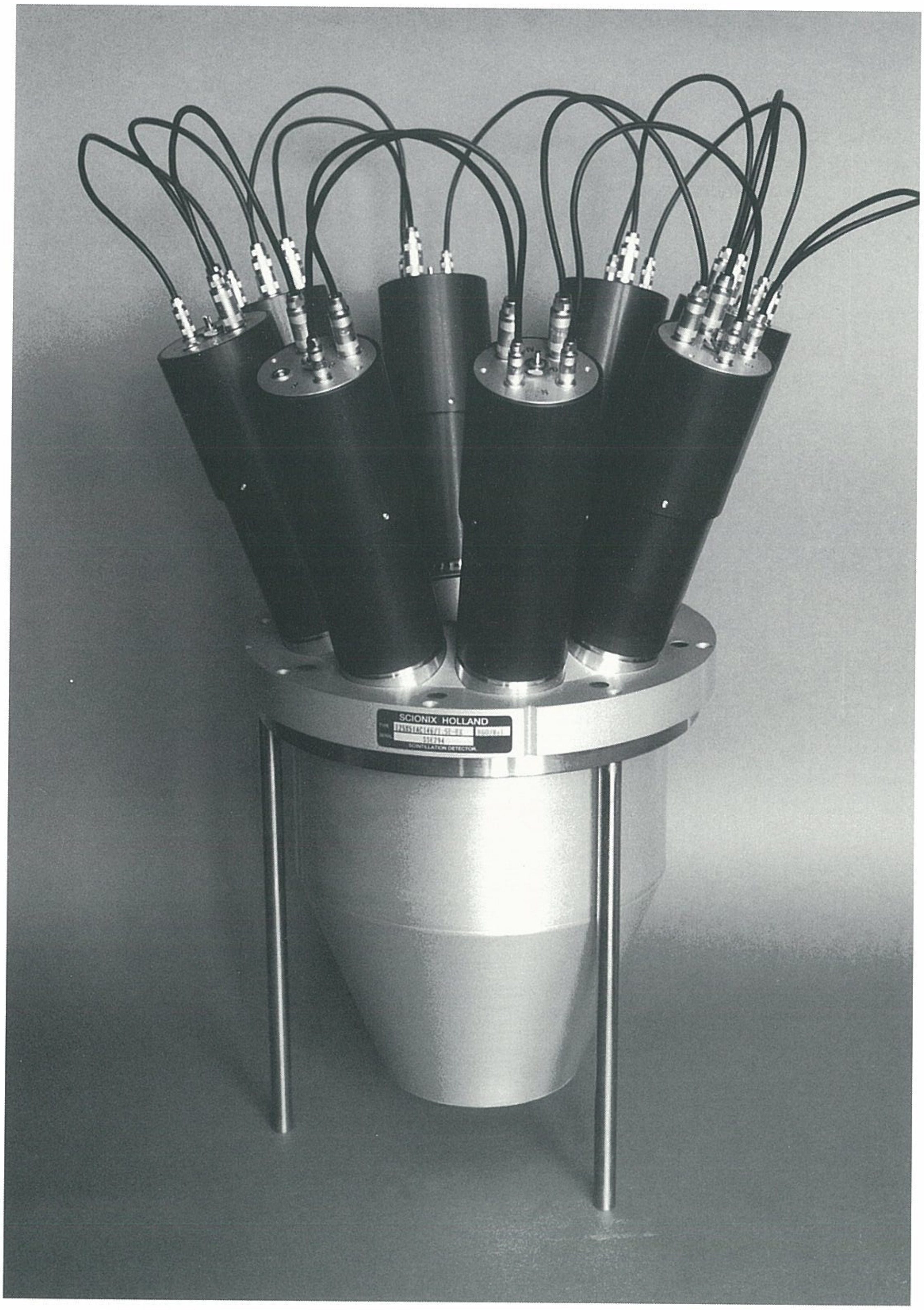
Recent developments in hybrid circuitry have allowed to incorporate a number of other electronic components *into* the scintillation detector assembly which eliminates in some applications the necessity of NIM based electronics.

An example of the above is the scintillation detector with a *built-in High Voltage Generator* (- HV option, see section 6). This is a small Cockroft - Walton generator which produces the high voltage required to operate a PMT. This unit only requires a DC voltage of + 5 V or + 12 V and uses only 100 mW of power. The unit is fully integrated with the PMT so there are no high voltage leads anywhere in the assembly. The gain of the PMT is maintained even at high anode currents (up to 100 μA) and the unit adds only 50 mm to the length of the PMT. The high voltage can be factory set, precision potentiometer adjustable or set by a 0 - 1 V regulating voltage. Below the advantages are summarized.

Advantages built-in high voltage generators :

- Compact
- Low power consumption
- Sealed
- High gain stability versus count rate

Besides the above mentioned preamplifiers it is also possible to incorporate e.g. *shaping amplifiers (spectroscopic amplifiers)* or *Single Channel Analyzers (SCAs)* into a detector assembly. All these components, constructed as small SMD or hybrid circuits, are very small in dimension. Specific parameters of these devices can be defined by the user since the standard models can be easily adapted. Please consult SCIONIX for more details.



BGO / NAI(Tl) anti-Compton shield

Index

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