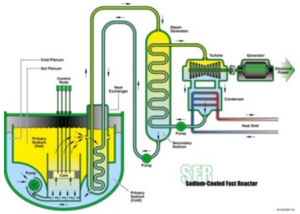
DE LA RECHERCHE À L'INDUSTRIE

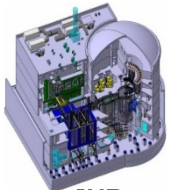


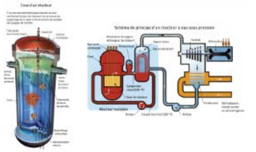

ANIMMA
PISA-LUCCA 2023
REAL COLLEGIO di LUCCA

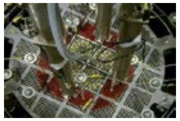
The 8th International Conference on
Advancements in Nuclear Instrumentation Measurement Methods and their Applications

APPLICATION FIELDS

COMMITTEE CHAIRS







Nuclear radiation detection : Basics and physical principles

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IEEE Distinguish Lecturer
Cape Town Instrumentation School (Virtual)
August 24th, 2023

IEEE NPSS
NUCLEAR & PLASMA SCIENCES SOCIETY

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The Menu…

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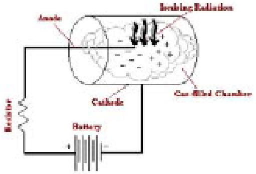
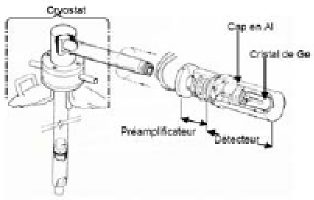
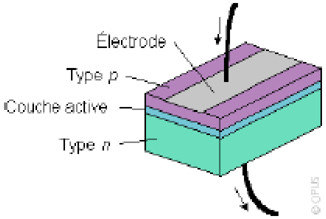
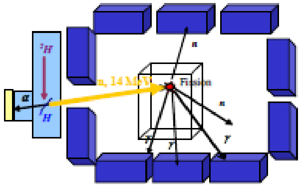
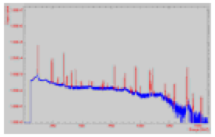
2. **Gas-filled detectors**
3. **Scintillation detectors**
4. **Semiconductor detectors**
5. **Activation detectors**
6. **Examples of applications**



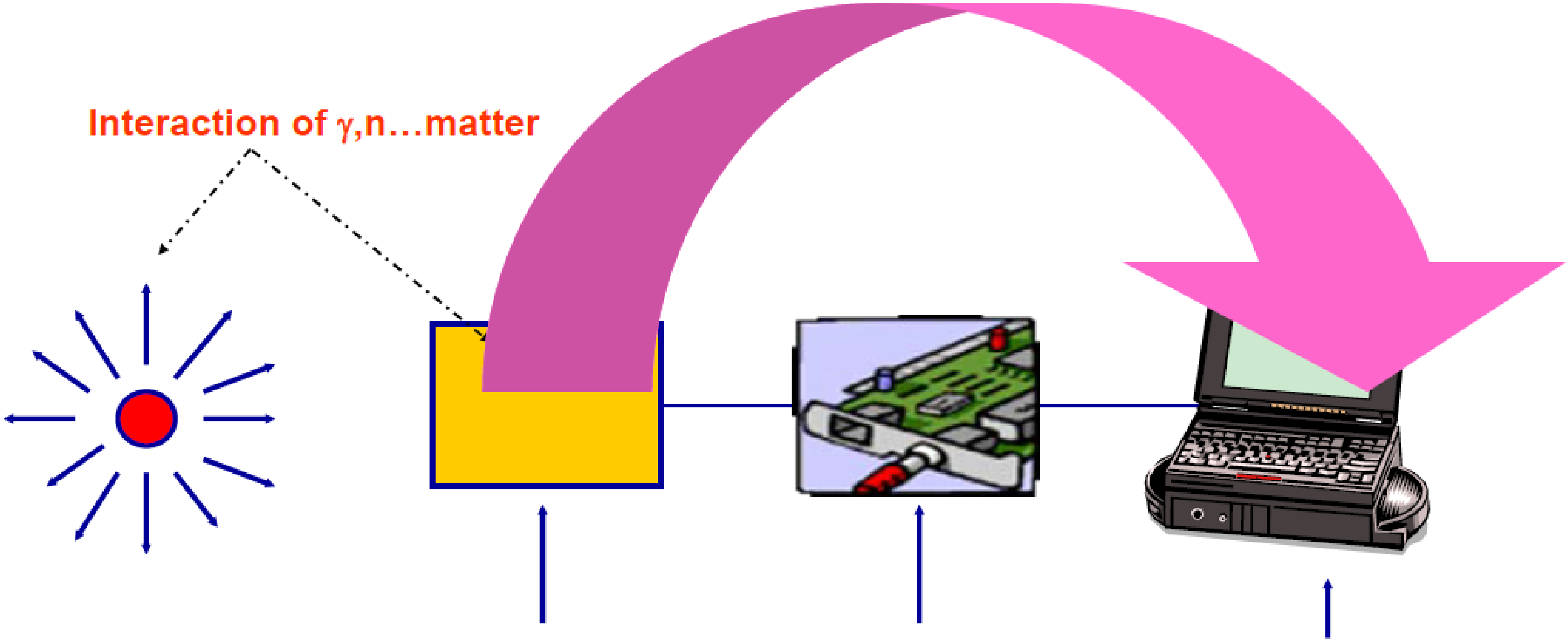








What about Radiation Detection ?



Interaction of γ,n…matter

Parameter to be directly measured

Sensor

Electronics and Signal Processing Units

Data treatement, anlysis to extract Final Parameter

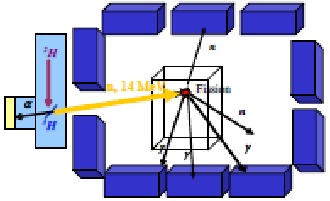
- **How it works?**

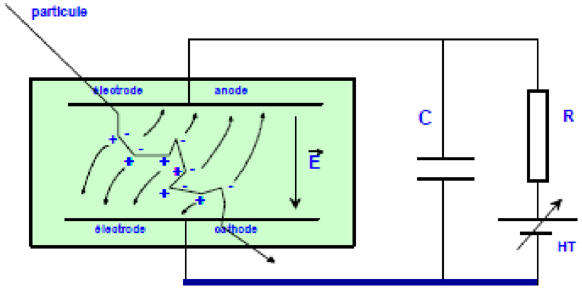
Introduction

Radiation carries energy and whenever it interacts with a detection medium it may deposit some or all of it to the particles in the medium.

This interaction can form a basis of signal formation that can be detected and measured by the processing electronics. Some of these interaction consequences are :

- Excitation
- Ionization
- Scintillation
- Excitation of lattice vibrations
- Excitation of optical states
- Nuclear reactions / Activation, fission…





Types of detectors

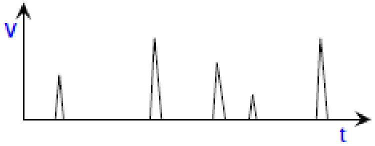
- ***Gas-filled detectors*** consist of a volume of gas between two electrodes.
- ***Scintillation detectors***, the interaction of ionizing radiation produces UV and/or visible light.
- ***Semiconductor detectors*** are generally pure crystals of silicon, germanium, or other materials to which trace amounts of impurity atoms have been added so that they behave as diodes.

Types of detector systems

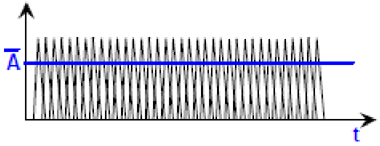
- Detector systems may also be classified by the type of information produced:
  - Detectors, such as Geiger-Mueller (GM) detectors, that indicate only the number of interactions occurring in the detector are called *counters*
  - Detectors that yield information about the energy distribution of the incident radiation, such as scintillation or SC detectors are called *spectrometers*
  - Detectors that indicate the net amount of energy deposited in the detector by multiple interactions are called *dosimeters*

Modes of operation of detector system

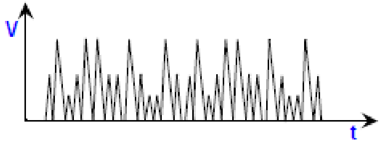
- In ***pulse mode***, the signal from each interaction is processed individually.



- In ***current mode***, the electrical signals from individual interactions are averaged together, forming a net current signal.



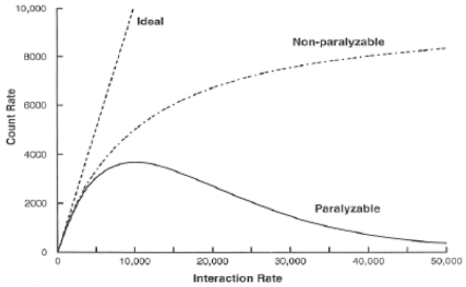
- Campbell mode (Fluctuation)



$$\overline{\sigma_I^2(t)} = \frac{rQ^2}{T}$$

Interaction Rate

- Main problem with detectors in pulse mode is that two interactions must be separated by a finite amount of time to produce distinct signals
- This interval is called the ***dead time*** of the system
- If a **second** interaction occurs in this interval, its signal **will be lost**; if it occurs **close enough** to the first interaction, it may distort the signal from the first interaction

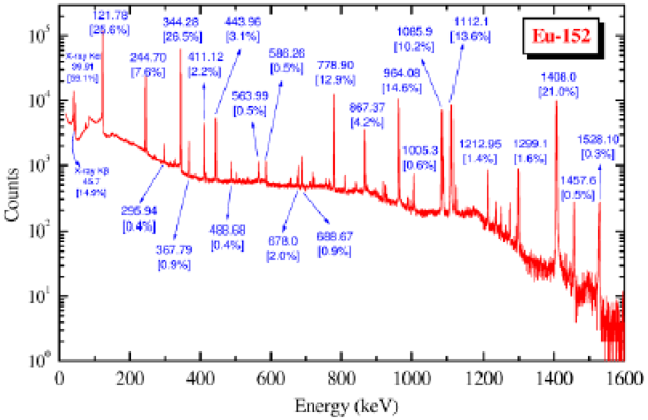


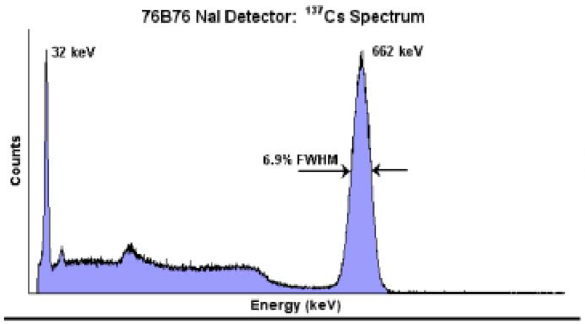
Dead time of detector system

- Dead time of a detector system largely determined by the component in the series with the longest dead time
  - Detector has longest dead time in GM counter systems
  - In multichannel analyzer systems the analog-to-digital converter often has the longest dead time
- GM counters have dead times ranging from tens to hundreds of microseconds, most other systems have dead times of less than a few microseconds

Energy resolution

- Energy resolution of a spectrometer is a measure of its ability to differentiate between particles (or photons) of different energies
- Determined by irradiating detector with monoenergetic particles or photons and measuring width of resulting peak in the pulse height spectrum
- Statistical effects in the detection process cause the amplitudes of pulses from detector to randomly vary about the mean pulse height, giving the peak a Gaussian shape

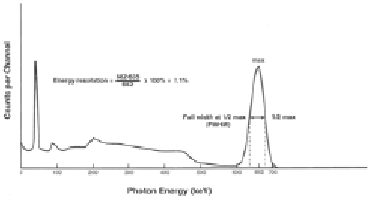


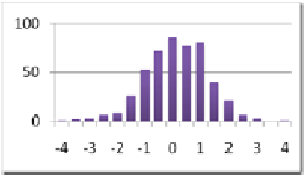


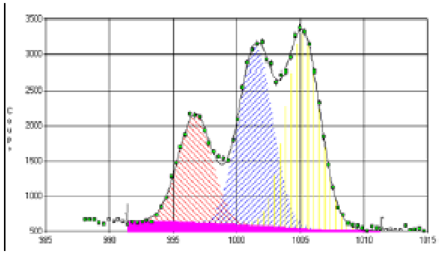
Energy resolution (cont.)

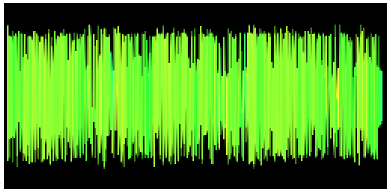
- Width is usually measured at half of maximal height of the peak – called the full width at half-maximum (FWHM)

$$\text{Energy resolution} = \frac{\text{FWHM}}{\text{Pulse height at center of peak}} \times 100\%$$









While the **statistical uncertainty** contributes notably to the broadening of the photopeaks observed in gamma-ray spectrometry, it is not the only source of peak broadening. **Electronic noise** and various fluctuations in responses of all associated electronic components may also impact resolution. **Noise effects often impact low-energy results more than high energy**, making resolution worse at the lower energies.

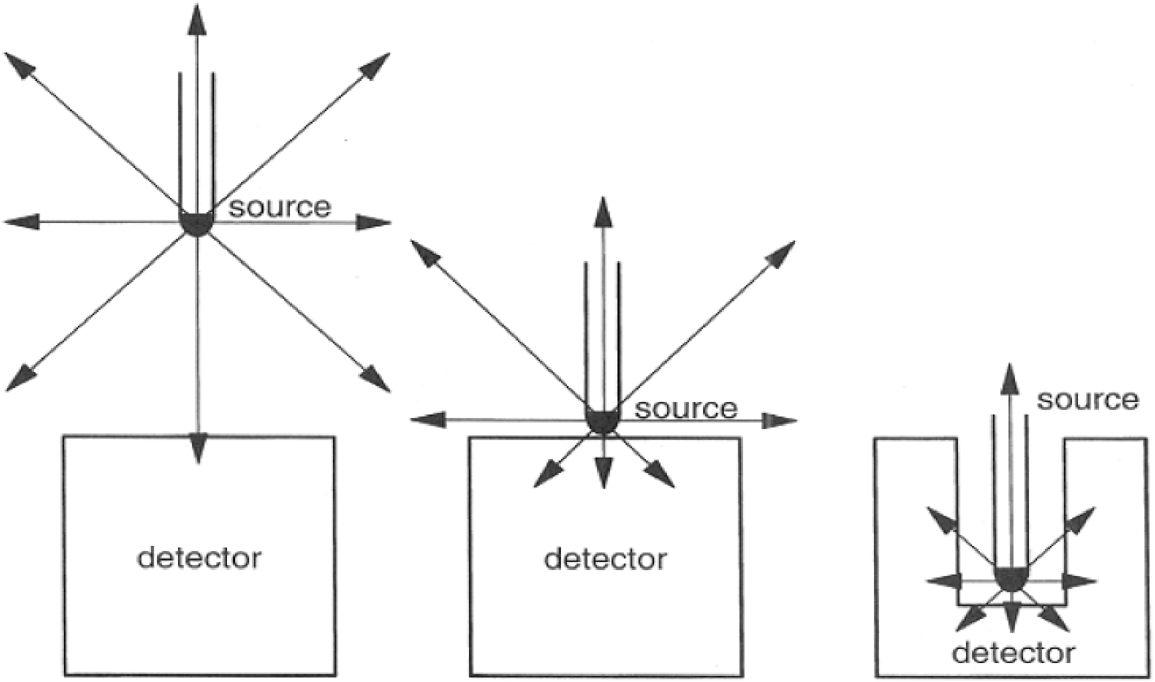
Detection efficiency

- The *efficiency (sensitivity)* of a detector represents its ability to detect radiation.
- Efficiency of a detection system operated in pulse mode is defined as the probability that a particle/radiation emitted by a source will be detected.

$$Efficiency = \frac{Number\ Detected}{Number\ Emitted} = \frac{Number\ reaching\ Detector}{Number\ Emitted}\ X\ \frac{Number\ Detected}{Number\ reaching\ Detector}$$

$$Efficiency = [Geometric\ Efficiency] x [Intrinsic\ Efficiency]$$

Detection efficiency (cont.)



$$Efficiency = \frac{Number\ Detected}{Number\ Emitted} = \frac{Number\ reaching\ Detector}{Number\ Emitted} X \frac{Number\ Detected}{Number\ reaching\ Detector}$$

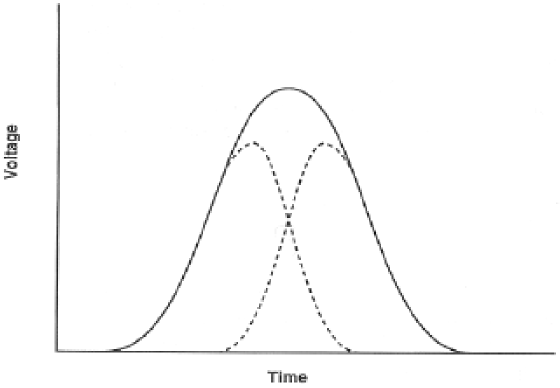
$$Efficiency = [Geometric\ Efficiency\ ] x [Intrinsic\ Efficiency\ ]$$

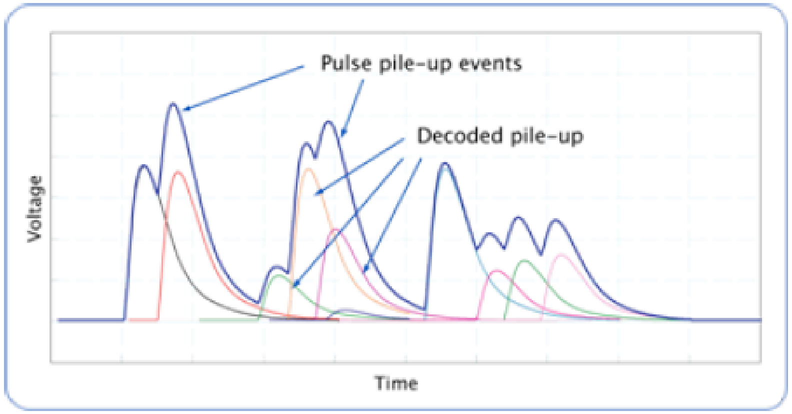
Selectivity of radiations

- Capacity of detector system to discriminate between different kind of radiations .
- For example : neutron/γ; α/β; β/γ
- Very important characteristic/specification for neutron detector systems (sensitivity to gamma rays)

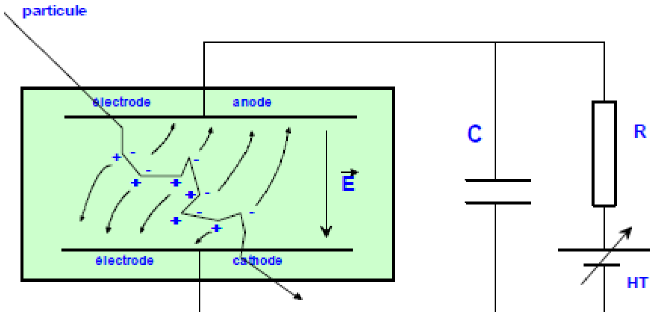
High count-rate effects

- **If two interactions occur in a detector, separated by a very short time interval, the detector produces a single pulse.**
  - Sum of the individual signals from the two interactions
  - Higher amplitude than the signal from either individual interaction
- **Operating a pulse height spectrometer at a high count rate causes loss of counts and misplacement of counts in the spectrum.**



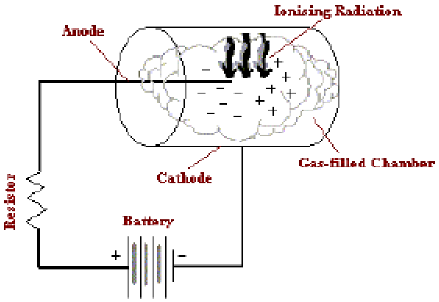


Gas-filled detectors



Gas-filled detectors

- A gas-filled detector consists of a volume of gas between two electrodes, with an electrical potential difference (voltage) applied between the electrodes
- Ionizing radiation produces ion pairs in the gas
- Positive ions (cations) attracted to negative electrode (cathode); electrons or anions attracted to positive electrode (anode)
- In most detectors, cathode is the wall of the container that holds the gas and anode is a wire inside the container

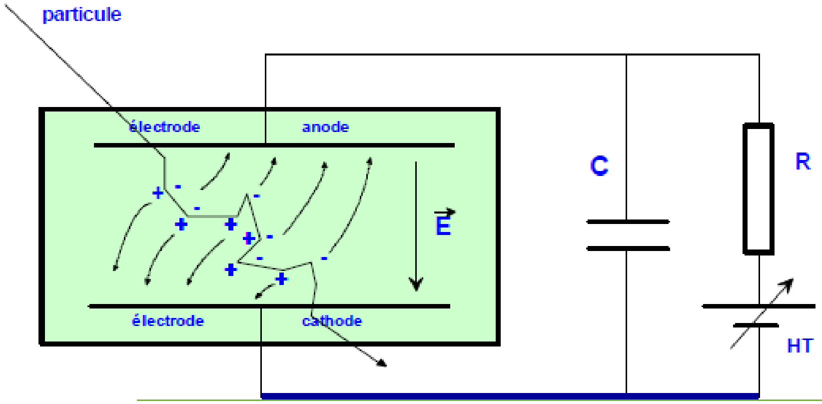


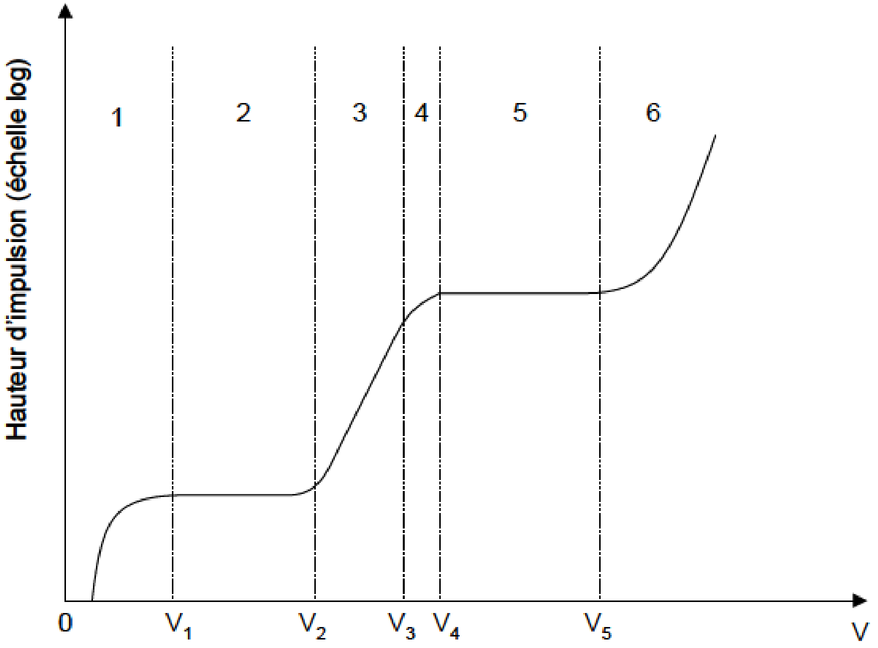
Types of gas-filled detectors

- Three types of gas-filled detectors in common use:
  - Ionization chambers
  - Proportional counters
  - Geiger-Mueller (GM) counters
- Type determined primarily by the voltage applied between the two electrodes.
- Ionization chambers have wider range of physical shape (parallel plates, concentric cylinders, etc.)
- Proportional counters and GM counters must have thin wire anode

Regions of Operation of G.F.D.

- Based on the applied bias voltage, a detector can be operated in a number of modes which differ from one another by the amount of charges produced and their movement inside the detector volume. Choice of particular mode depends on the application and generally detectors are optimized to work in the range of the applied voltage that is typical of that particular mode only.

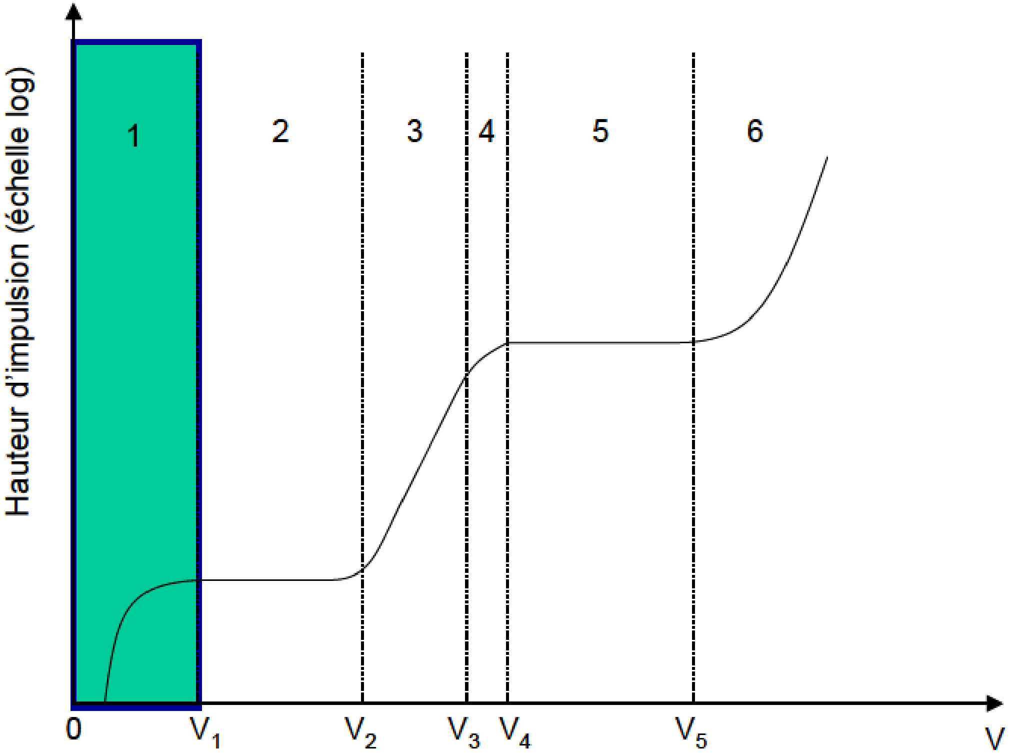




Regions of Operation of G.F.D.

Recombination Region

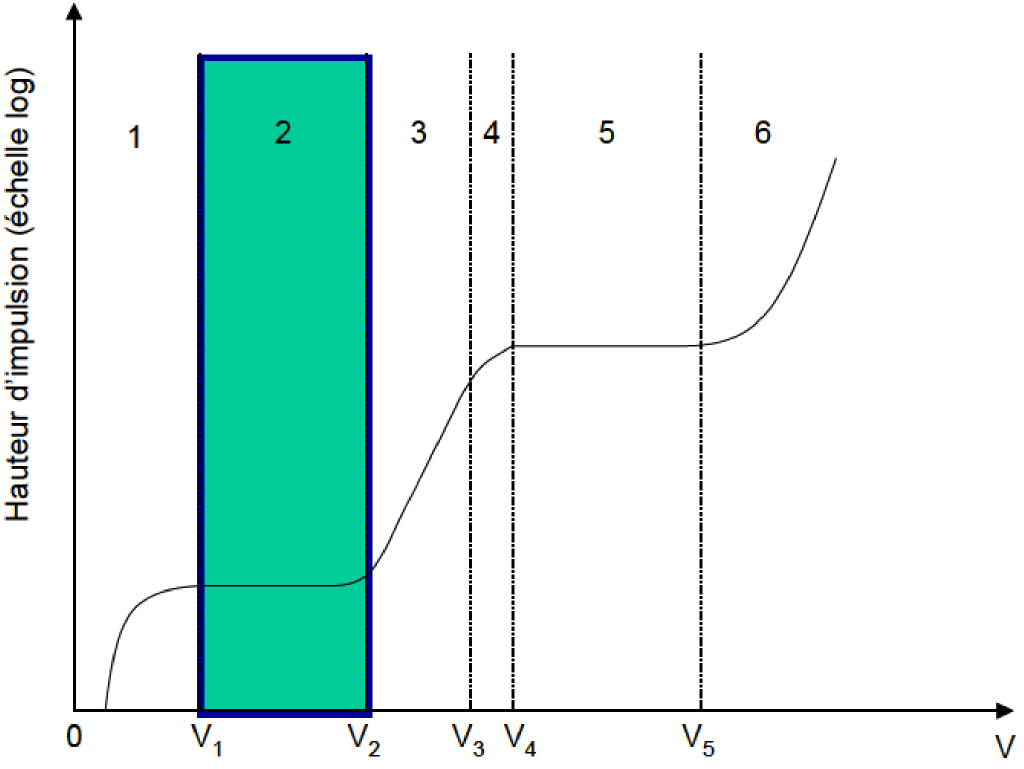
- In the absence of an electric field the charges produced by the passage of radiation quickly recombine to form neutral molecules. At the application of the bias voltage some of the charges begin to drift towards the opposite electrodes. As this voltage is raised the recombination rate decreases and the current flowing through the detector increases. In terms of measuring the properties of radiation e.g. energy deposit, it is useless to operate the detector in this region. .



Regions of Operation of G.F.D.

Ion Chamber Region

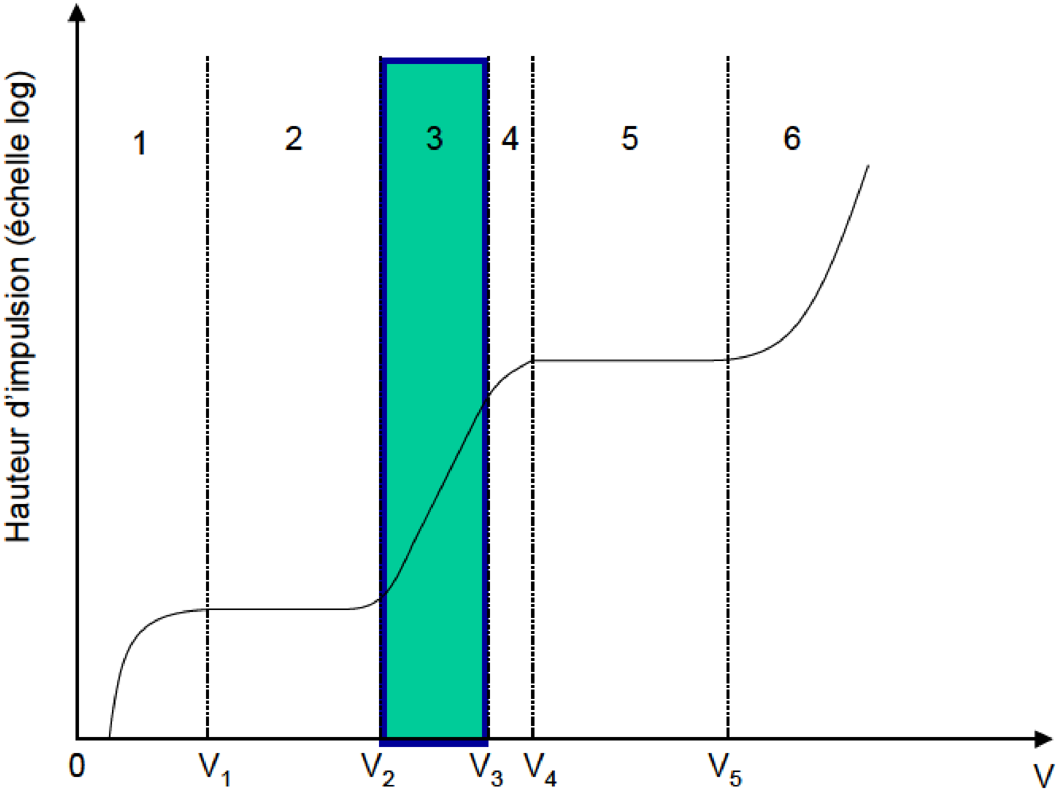
- The collection efficiency of electron-ion pairs in the recombination region increases with applied voltage until all the charges that are being produced get collected. This is the onset of the so called ion chamber region. In this region further increasing the high voltage does not affect the measured current since all the charges being produced get collected efficiently by the electrodes. The current measured by the associated electronics in this region is called saturation current an is proportional to the energy deposited by the incident radiation. The detectors designed to work in this region are called **ionization chambers**.



Regions of Operation of G.F.D.

Proportional Region

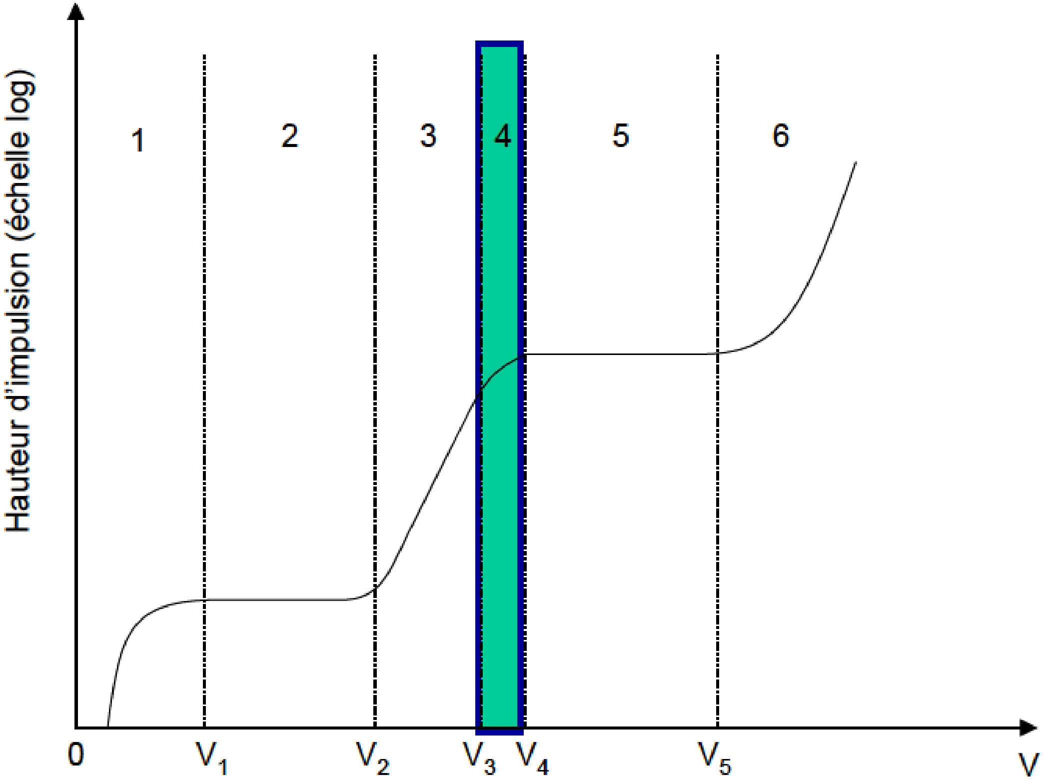
- If the charges produced during primary ionization have enough energy they themselves can produce additional electron-ion pairs, a process called **secondary ionization**. Further ionization from these charges is also possible provided they have enough energy. Obviously this process can occur only if a high enough electric potential exists between the electrodes so that the charges could attain very high velocities. Although the energy gained by the ions also increases as the bias voltage is increased, the electrons, owing to their very small mass, are the ones that cause most of the subsequent ionizations. The multiplication of charges occurs in such a way that the **output pulse remains proportional to the deposited energy**. That is why these detectors are called **proportional detectors**.



Regions of Operation of G.F.D.

Region of Limited Proportionality

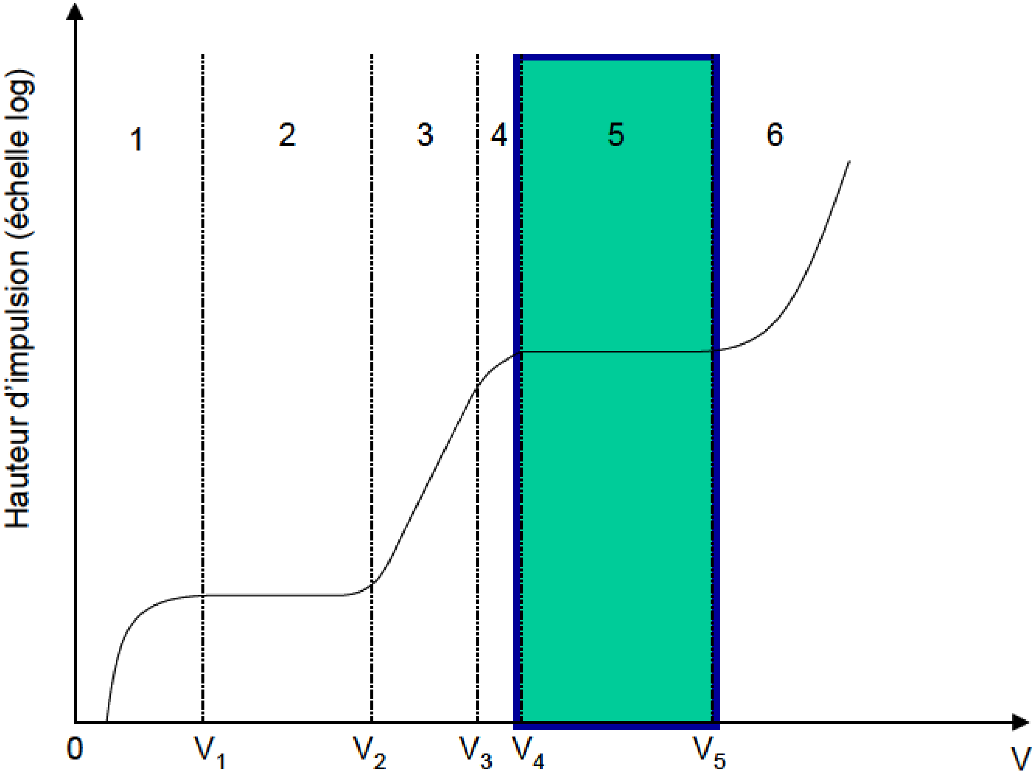
- As we increase the bias voltage, more and more charges are produced inside the active volume of the detector. Since heavy positive charges move much slower than the electrons, they tend to form a cloud of positive charges between the electrodes. This cloud acts as a shield to the electric field and reduces the effective field seen by the charges. As consequence the proportionality of the total number of charges produces to the initial number of charges is not guaranteed. Since the loss of proportionality means loss of linearity, radiation detectors are not operated in this region.



Regions of Operation of G.F.D.

Geiger-Mueller Region

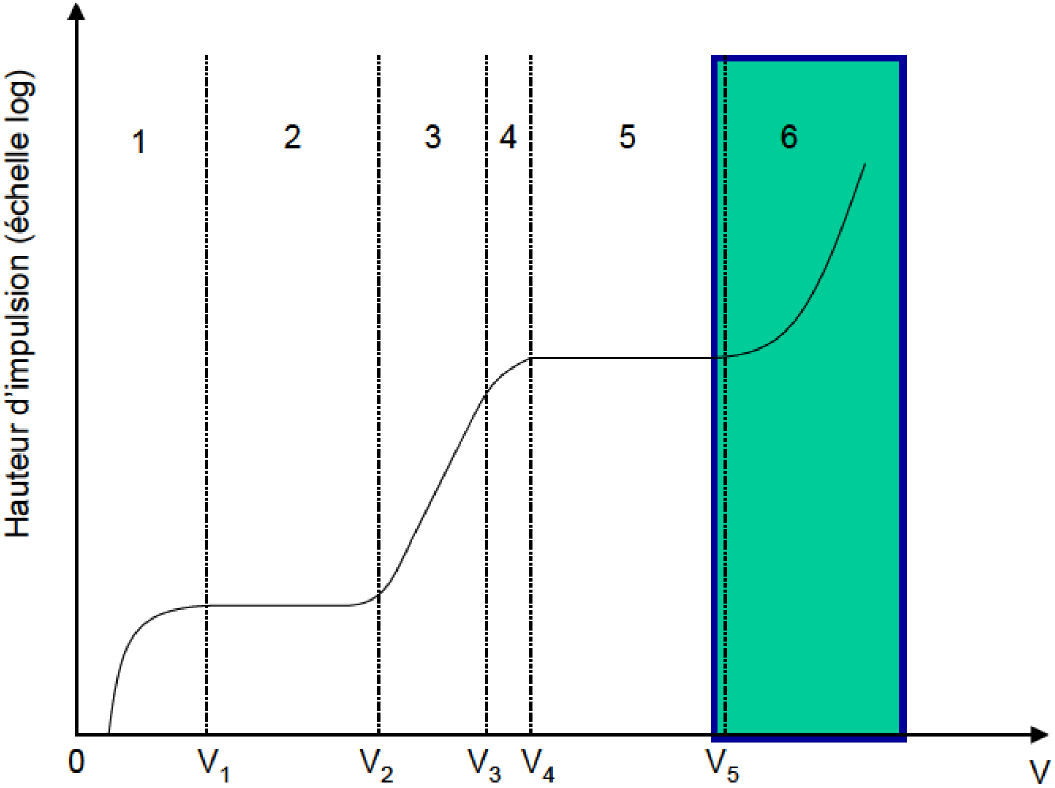
- Increasing the voltage further may increase the local electric field to such high values that an extremely severe avalanche occurs in the gas, producing very large number of charge pairs. Consequently a very large pulse of several volts is seen in the readout electronics. This is the onset of the so called Geiger-Mueller region. In this region, it is possible to count individual incident particles since each particle causes a breakdown and a large pulse. Since the output pulse is neither proportional to the deposited energy nor dependent on the type of radiation, the detectors operated in this region are not appropriate for spectroscopy. The multiplication of charges in a GM detector is so intense that sometimes it is termed as *breakdown* of the gas.



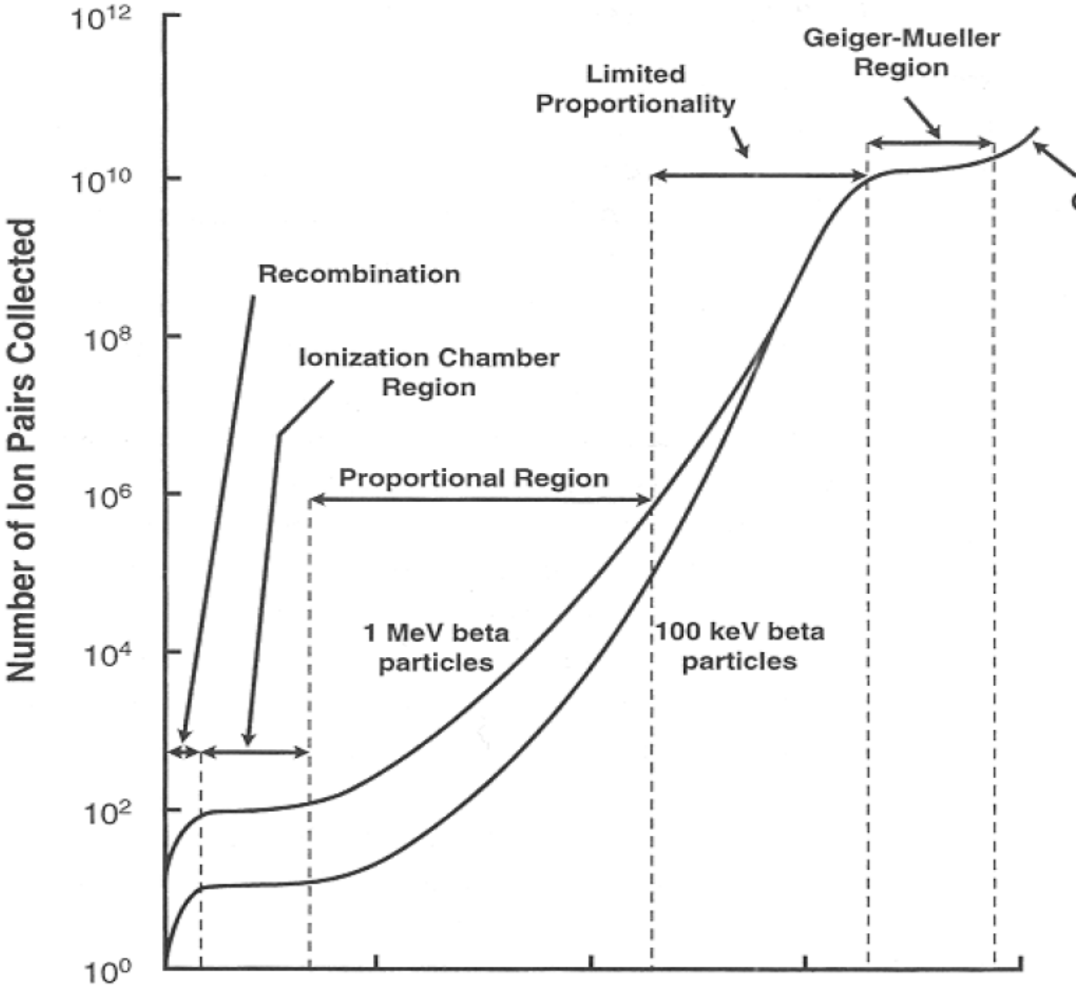
Regions of Operation of G.F.D.

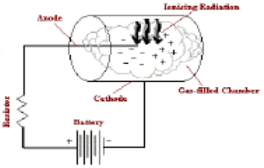
Continuous Discharge

- This continuous discharge starts as soon as a single ionization takes place and can not be controlled unless the voltage is lowered. In this region, electric arcs can be produced between the electrodes, which may eventually damage the detector. It is apparent that radiation detectors can not be operated at such high voltages and therefore one must make sure that it remains below the threshold of this process.



Radiation Detection & Measurement

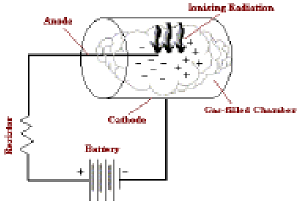




Ionization chambers

Ionization chambers

- If gas is air and walls of chamber are of a material whose effective atomic number is similar to air, the amount of current produced is proportional to the exposure rate
- Ionization chambers contain gas with specific properties (Ar, N, F) to perform and answer to specific needs.
- Air-filled ion chambers are used in portable survey meters, for performing QA testing of diagnostic and therapeutic x-ray machines, and are the detectors in most x-ray machine photo-timers.
- Low intrinsic efficiencies because of low densities of gases and low atomic numbers of most gases



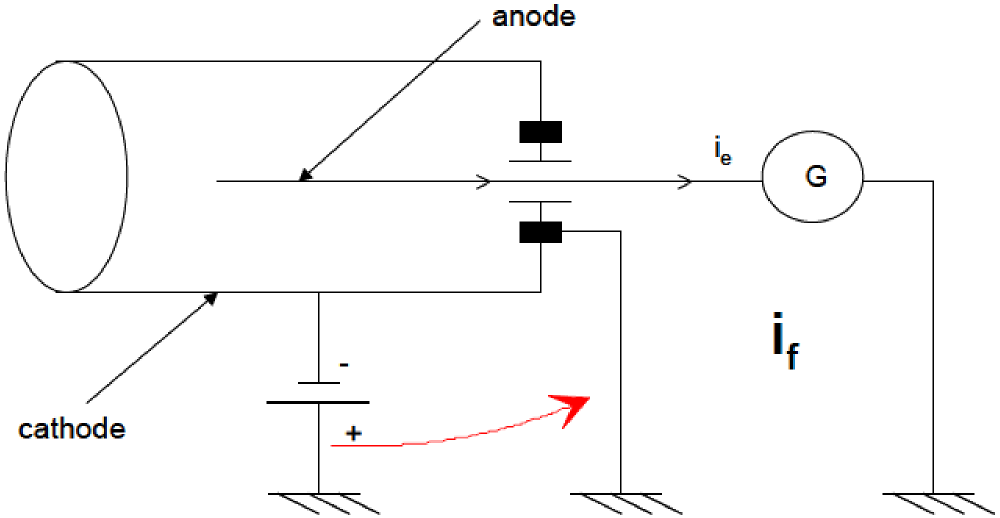
The Choice of gas is highly application dependent

Ionization chambers are perhaps the most widely used radiation detectors.

Ionization chambers

Current Mode Operation

To Avoid Leakage Current we perform specific grid



⇒ **The main part of voltage tension is between Anode and «Garde Circle »**

⇒ **Leakage Current do not pass any more through measurement apparatus.**

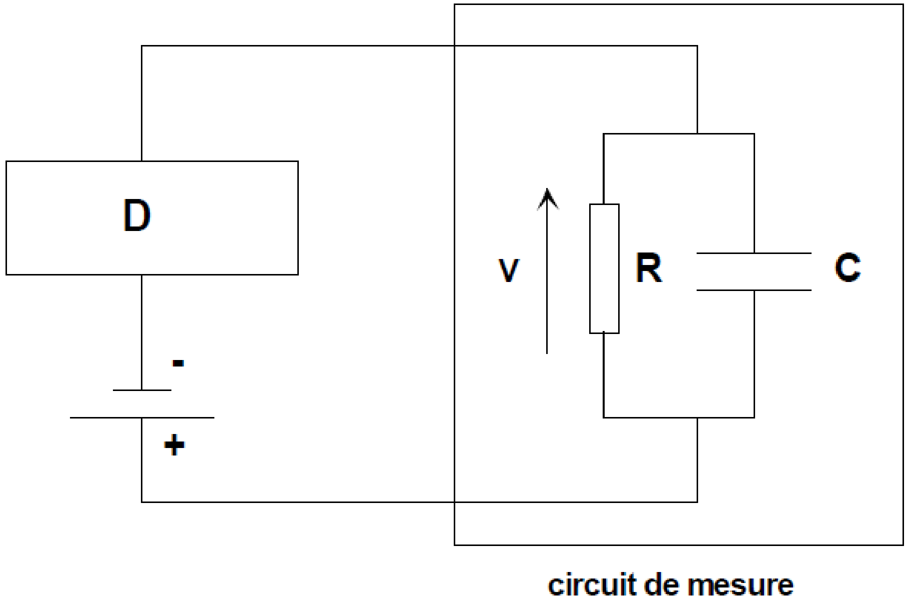
Ionization chambers

PULSE MODE

(Basic Scheme)

- Each pulse is individually treated ⇒ study particle/particle
- Output voltage is measured through resistance R and capacitance C of the circuit.

(intrinsic capacitance of detector , cable capacitance)



R : Equivalent Resistance of the circuit
C :Capacitance of the circuit

⇓

Signal Pulse output V(t) is RC

⇓

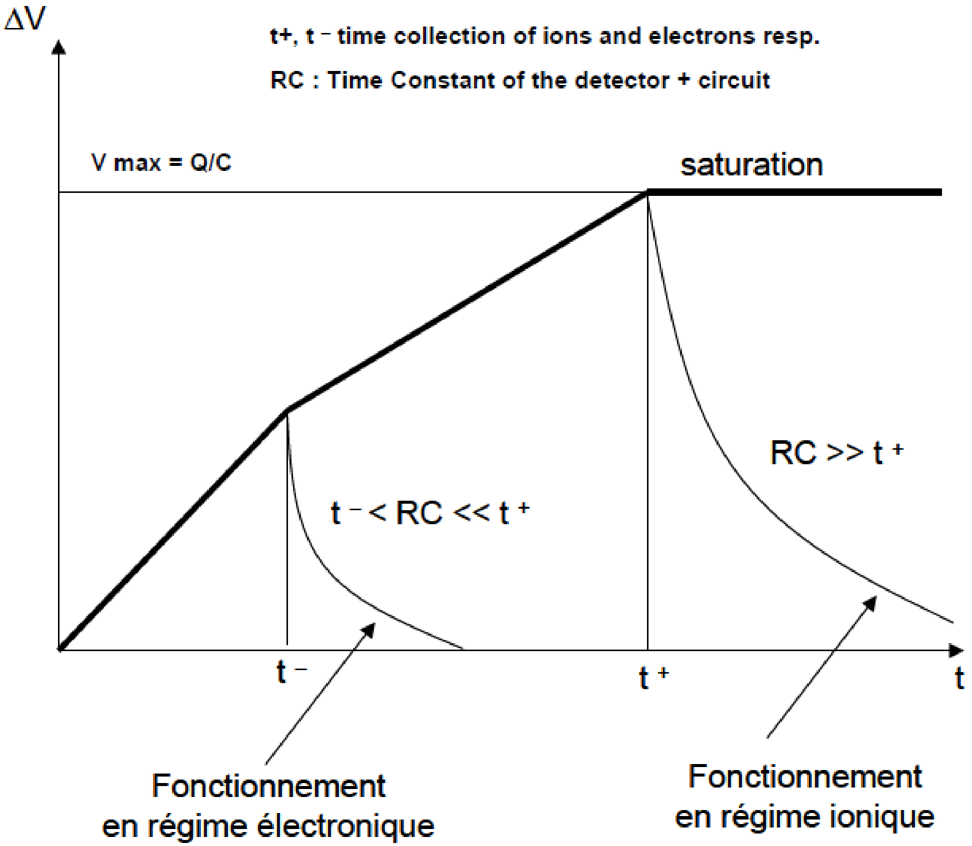
Shape of output depends on time constant value RC

Dynamic response of circuit

A. Lyoussi, Instrumentation School at iThemba LABS in Cape Town, August 24th 2023

Ionization chambers

PULSE MODE



- Since the electrons move much faster than ions ($t^- \ll t^+$), therefore initial pulse shape is almost exclusively due to electron motion. This will inhibit a sharp increase in pulse height with the maximum value attained when all the electrons have been collected by the anode. The ions, owing to their heavier mass, will keep on moving slowly toward cathode increasing the pulse height further, however at a much lower rate. The maximum voltage is reached when all the charges have been collected.
- Every detector has some intrinsic capacitance as well as the cable capacitance. These capacitances together with the installed capacitor (if any) and load resistance of the output make up the effective time constant of the circuit. The difference between this time constant and the charge collection time characterizes the shape of the output pulse. It is apparent that the quicker the pulse decays, the easier it will be to distinguish it from the subsequent pulse. On the other hand very small time constant may amount to loss of information and even non-linearity. Therefore considerable effort is warranted to tune the effective time constant according to the requirements.

Ionization chambers

Application of ionization chambers

- Neutron detection

(often uses converter material (nucleus))

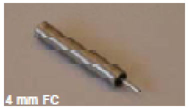
« Bakélite » chambers wrapped with Cadmium

Neutron conversion reaction used : $^{113}Cd\ (n, \gamma)\ ^{114}Cd$
Emission of capture gamma rays of (7.5 MeV) that will be detected

Boron-lined Ion Chamber

Detection of thermal neutrons by using reaction $^{10}B\ (n, \alpha)\ ^{7}Li$
α and/or Li are detected
Boron is coated on the inside of the cylindrical chamber, which is filled with conventional gas.
Boron lined detectors could be or not gamma compensated.
Generally used in current mode
⇒ often used as power/experimental reactor control instrumentation

Ionization chambers



Application of ionization chambers

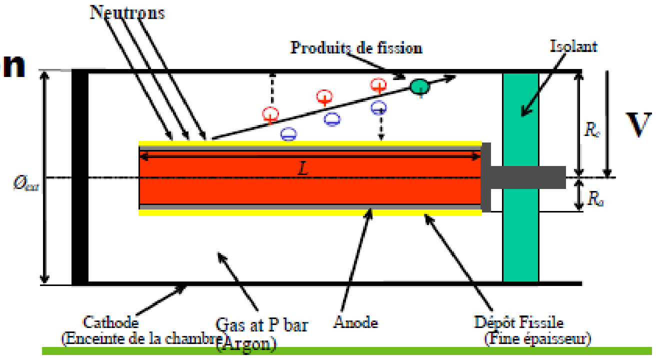
Fission ionization chamber

Fission reaction for neutron conversion ^{235}U (n , f) ⇒ thermal neutrons
^{237}Np (n , f) ; ^{242}PU (n , f) …. ⇒ fast neutrons

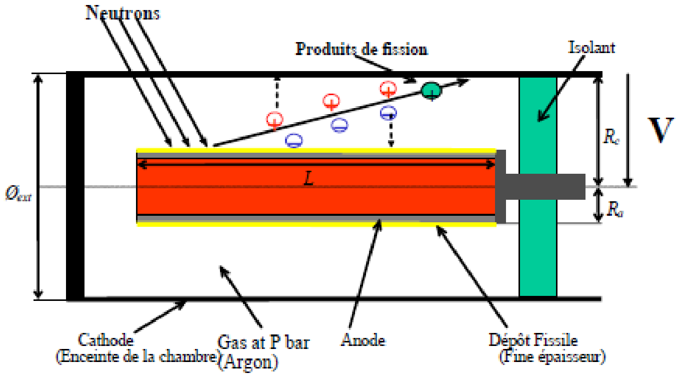
Fissile deposit is coated in the inside of the cylindrical chamber.
Ionization of gas molecules are induced by FP
Sensitivity depends on the type and mass of Fissile deposit.
Varied volumes and forms (from fraction of cm^3 to litre volume !)

⇒ **Often used for neutron flux measurements in power and experimental reactors**

⇒ **Also used for experimental reactor instrumentation**



Fission Chamber



$$S = f(\tau_{fiss}, V, P, \ldots)$$

$$\tau_{fiss} = N\sigma\phi$$


4 mm FC

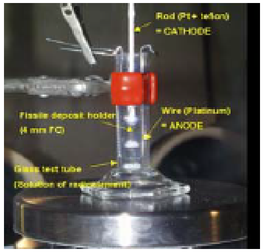

exotic geometries

Output Signal depends on :

H.V., gas pressure, geometry, converter material, its mass, its thickness, its density, neutron flux…harsh environment.

The main manufacturing steps :

- Process of converter material deposition :
- Chamber assembly
- Filling the chamber with gas (Argon)
- Primary tests of fission chamber



Ionization chambers

Advantages & disadvantages of ionization chambers

Advantages

Insensitivity to applied voltage

Proportionality of saturation current conditions to energy deposit

Less Vulnerability to Gas Deterioration

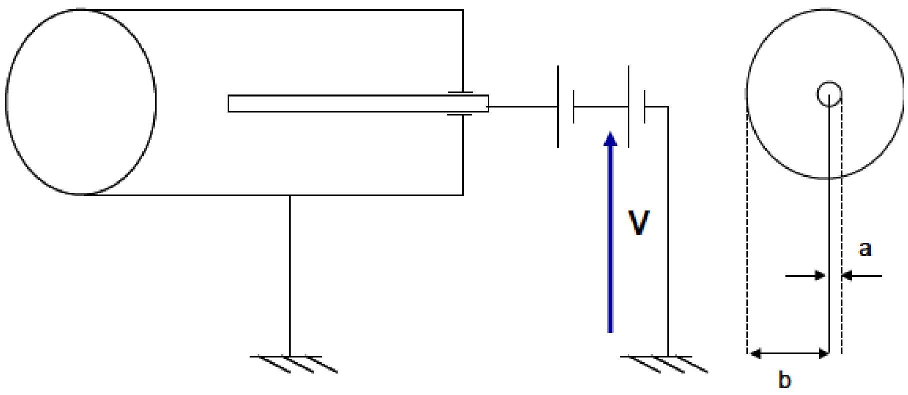
Disadvantages

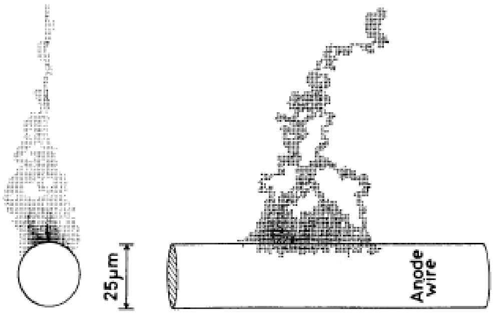
Low Current

Vulnerability to atmospheric (T°, P)

Proportional counters

Proportional counters

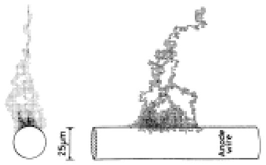




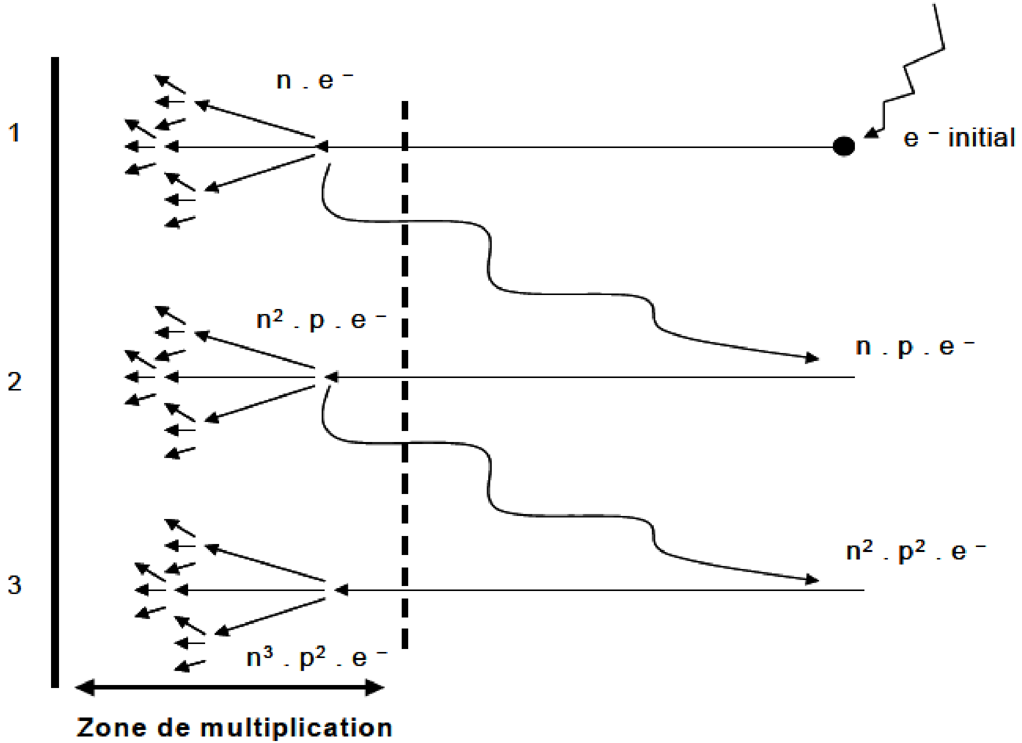
$$E_r = \frac{V}{r \times \ln\left(\frac{b}{a}\right)}$$

- For ionization chamber, when the incident particle energy is not very large or the flux is small, the pulse amplitude may not be large enough to achieve acceptable signal to noise ratio. The easiest way to achieve large number of charge pairs is to allow the primary charges produced by the incident radiation to create additional charges. The basic requirement for the avalanche to occur is therefore application for very high electric potential between the two electrodes. Cylindrical geometry is suitable for this purpose.
- The anode in such chamber is in the form of a thin wire stretched across the center of the chamber while the wall of the cylinder acts as the cathode. This geometry ensures a higher electric field intensity near the anode wire as compared to the cathode. This non uniformity in the electric field ensures, among other things, better electron collection efficiency as compared to parallel plate geometry. Moreover, the high field enables the electrons to initiate the process of avalanche multiplication. For every counter geometry there is a unique range of applied voltage in which the number of charges produced in the avalanche is proportional to the number of primary charges produced by the incident radiation: $N = MxN_0$

Proportional counters



MULTIPLICATION FACTOR



In 1 :

acceleration of primary electrons

⇒ production of n secondary ionizations

(Avalanche of TOWNSEND)

In 2 :

Positive ions creation :

⇒ emission of photons

⇒ p (p<<1) photoelectrons emitted by photoelectric effect

In 3 :

n.p electrons ⇒ production of $n^2.p$ ionizations within multiplication zone

etc…

Finally for 1 initial electron we obtain ⇒ $F = n + n^2p + n^3p^2 + n^4p^3 + \dots + n^{k+1}p^k$

Proportional counters

Multiplication Factor

$F = n + n^2p + n^3p^2 + n^4p^3 + \dots + n^{k+1}p^k$

1 - if $n.p < 1$ ⇒ Progression has a finite limit

⇒ it is the proportional counter regime

$$\lim F_{k \to \infty} = \frac{n}{1 - np}$$

for $n.p \ll 1$ then $F \approx n$

If N initial number of ion pairs created within the counter

Total collected charge will be $Q = N \,.\, F \,.\, Q_e$ ⇒ **Pulse amplitude** ⇒ $V = \dfrac{N.F.q_e}{C}$

2 - if $n.p > 1$ ⇒ Progression limit tends $F \to \infty$

⇒ This is GEIGER MÜLLER regime.

Proportional counters

Applications of proportional counters

3 – Detection of neutrons

Mainly three types of counters

⇒ - BF_3 counters

⇒ - Boron line counters

⇒ - Helium 3 counters

Reactions used are :

$^{10}B\ (n\ ,\ \alpha\ )\ ^{7}Li$

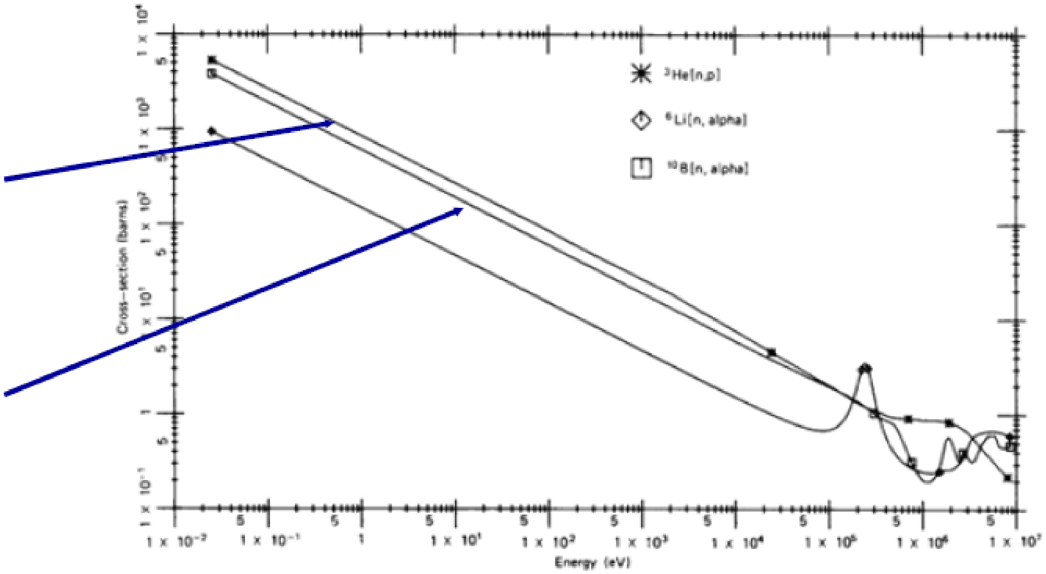
Cross section for thermal n

3900 barns

$3He\ (n\ ,\ p\ )\ ^{3}H$

Cross section for thermal n

5500 barns



Proporti

Applications of p

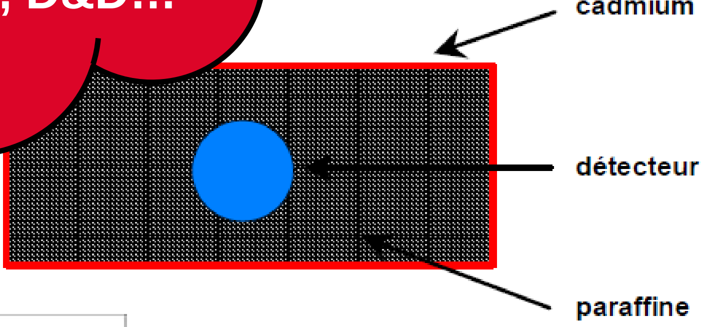
Nuclear non-destructive Assays (DDT, Photofission, coincidence countings…) for Radwaste, HS, D&D…

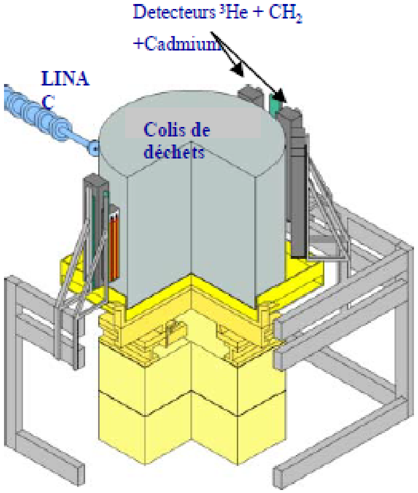
Detection of fast neutrons

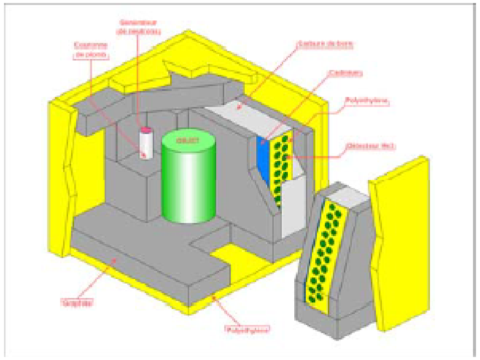
For fast neutron dete

- Cadmium envelop to stop/absorb therm

- A polyethylene bloc to slow down fast neutrons
Before reaching 3He thermal neutron rter gas

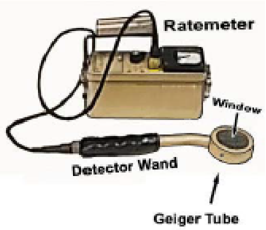




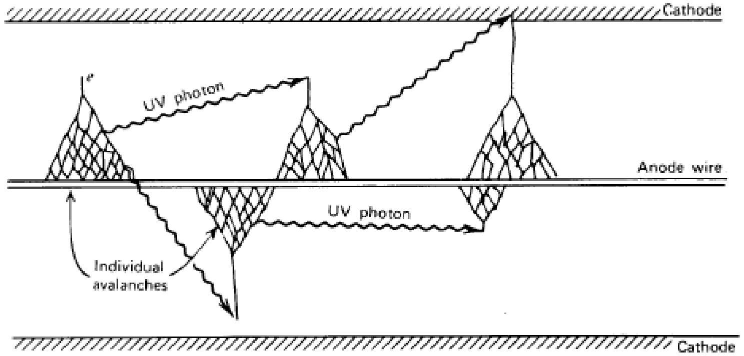


Geiger-Mueller counters

Geiger-Mueller counters



- The process of avalanche multiplication can spread throughout the detector to produce the so called breakdown in the gas. The spread is mainly caused by UV photons emitted during the localized avalanches. These photons have high enough energy to produce secondary electrons in the gas as well as in the electrodes and windows of the detector. The electrons thus produced drift towards the anode under the influence of the effective field inside the chamber. Since this field is very high, the electrons attain high enough energy between the collisions to produce secondary avalanches. The secondary avalanche may produce more ultraviolet photons, which may produce more avalanches and so on. This spread of avalanches throughout the detector volume is generally known as Geiger breakdown and the detector that behaves in this way is called a *Geiger-Mueller* or simply *GM* counter.
- In such counter, whenever a single ionization takes place, it initiates an avalanche process which spread so quickly that it causes the breakdown. The current flowing though the detector in this situation is extremely high and is limited only by the external circuitry. The voltage pulse is also quite high, generally of the order of several volts. This is the big advantage since it eliminates the need for amplification, something that is required in almost all the other types of detectors



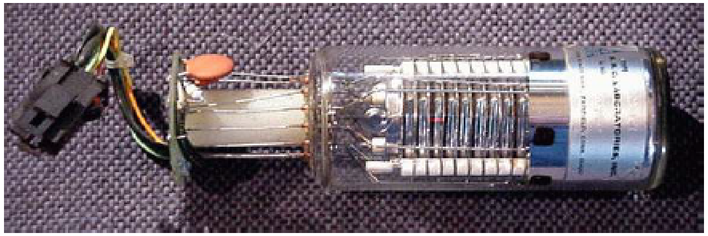
- It is evident that the GM tubes can not provide any information about the particle energy since every particle causing an ionization in the gas produces the same pulse amplitude irrespective of its energy. Hence GM is absolutely useless for spectroscopic purposes or for measurement to reveal properties of the incident radiation. GM can be used for particle counting purpose only.

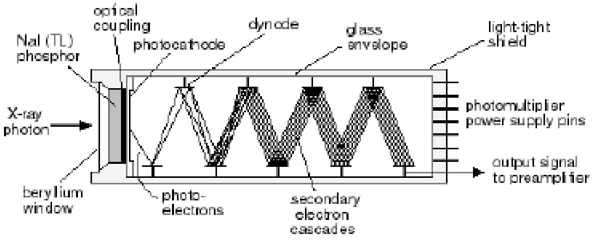
GM counters (cont.)

- GM counters also must contain gases with specific properties
- Gas amplification produces billions of ion pairs after an interaction – signal from detector requires little amplification
- Often used for inexpensive survey meters
- In general, GM survey meters are inefficient detectors of x-rays and gamma rays
- Over-response to low energy x-rays – partially corrected by placing a thin layer of higher atomic number material around the detector

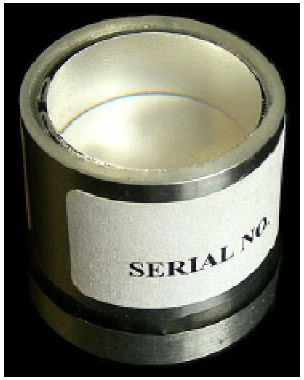
GM counters (cont.)

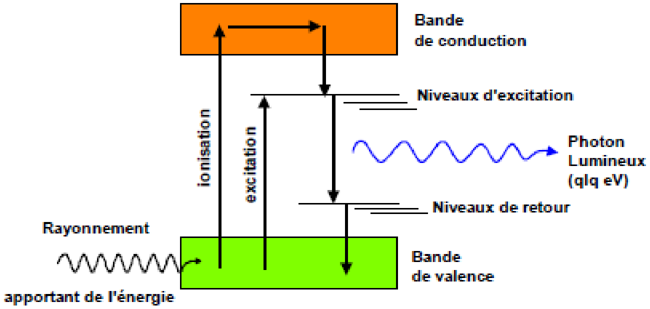
- GM detectors suffer from extremely long dead times – seldom used when accurate measurements are required of count rates greater than a few hundred counts per second
- Portable GM survey meter may become paralyzed in a very high radiation field
- should always use ionization chamber instruments for measuring such fields





Scintillation detectors





Scintillation detectors

Basics steps involved in scintillation detection of radiation

Interaction of radiation with scintillation material

⇓

Transfer of energy to the bound states of the material

⇓

Relaxation of the exited states resulting in the emission of light photons

⇓

Collection of photons by the photo-detector

⇓

Photoelectrons production of photocathode (photoelectric effect)

⇓

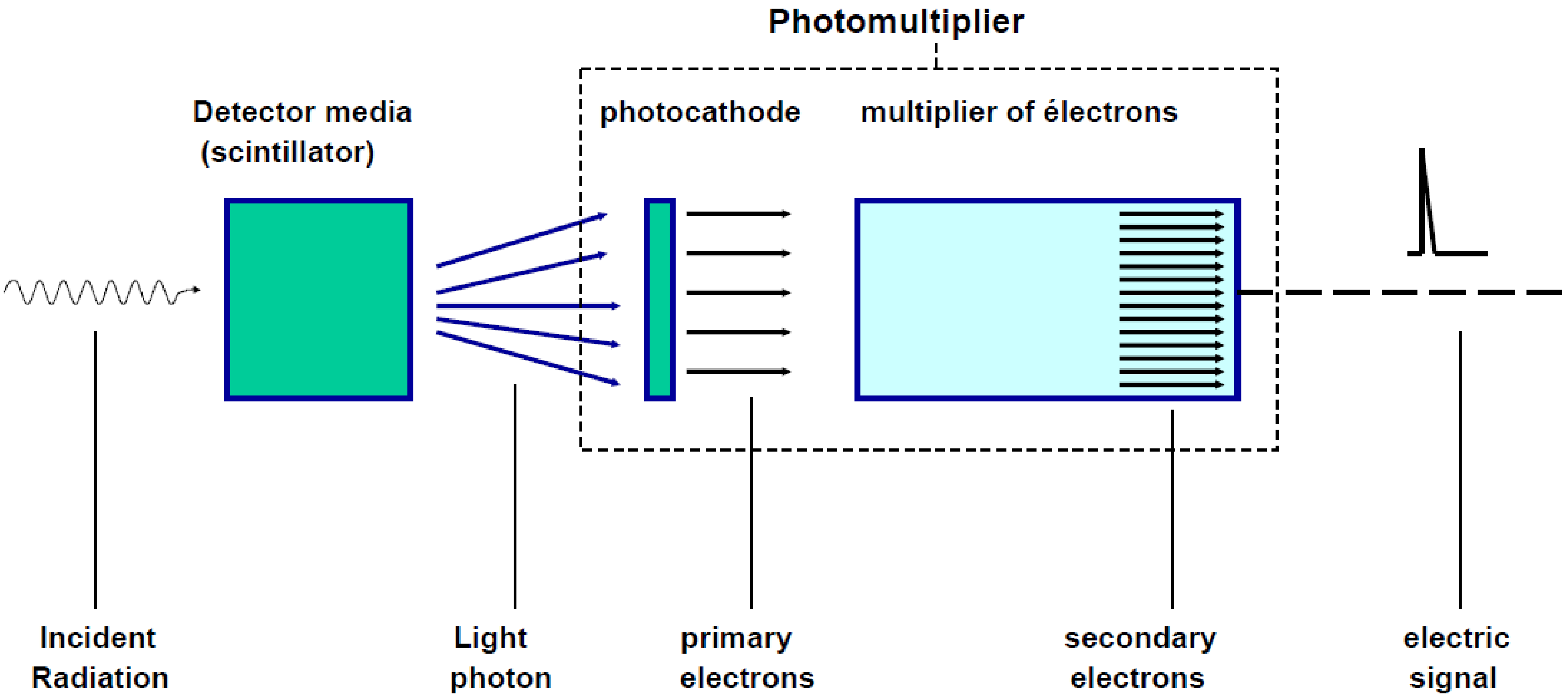
Multiplication of electrons through photomultiplier unit

⇓

Detection of the photo-detector signal by associated electronics

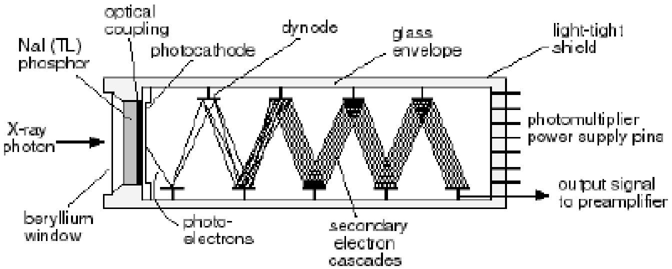
Scintillation detectors

General principle

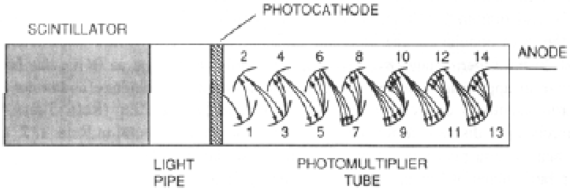


Scintillation detectors

- Scintillators are used in conventional film-screen radiography, many digital radiographic receptors, fluoroscopy, scintillation cameras, most CT scanners, and PET scanners, NDA like gross gamma spectrometry, beta and alpha spectrometry /counting.
- Scintillation detectors consist of a scintillator and a device, such as a PMT, that converts the light into an electrical signal



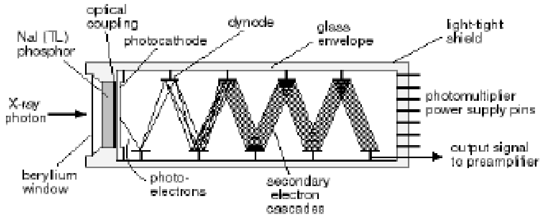
Scintillators



- Desirable properties:
  - High conversion efficiency
  - Decay times of excited states should be short
  - Material transparent to its own emissions
  - Color of emitted light should match spectral sensitivity of the light receptor (photocathode)
  - For x-ray and gamma-ray detectors, μ should be large
  - High detection efficiencies
  - Rugged, unaffected by moisture, and inexpensive to manufacture

Scintillators (cont.)

- Amount of light emitted after an interaction increases with energy deposited by the interaction
- May be operated in pulse mode as spectrometer
- High conversion efficiency produces superior energy resolution

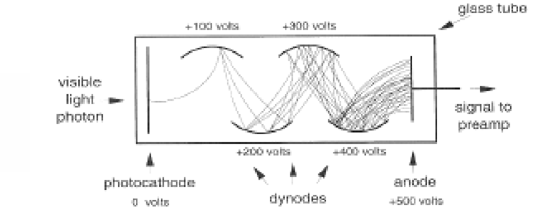


Materials

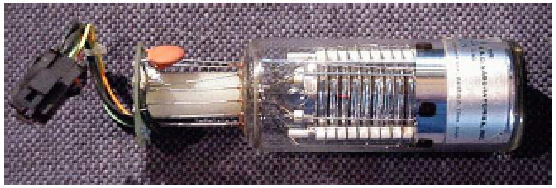
- Sodium iodide activated with thallium [NaI(Tl)], coupled to PMTs and operated in pulse mode, is used most nuclear application fields (NDA, medecine applications)
  - Fragile and hygroscopic
- Bismuth germanate (BGO) is coupled to PMTs and used in pulse mode as detectors in nuclear application (HS, NDA, most PET scanners)

Photomultiplier tubes

- PMTs perform two functions:
  - Conversion of ultraviolet and visible light photons into an electrical signal
  - Signal amplification, on the order of millions to billions
- Consists of an evacuated glass tube containing a photocathode, typically 10 to 12 electrodes called dynodes, and an anode



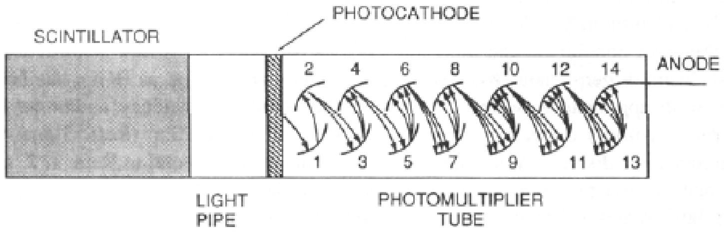
Dynodes



- Electrons emitted by the photocathode are attracted to the first dynode and are accelerated to kinetic energies equal to the potential difference between the photocathode and the first dynode
- When these electrons strike the first dynode, about 5 electrons are ejected from the dynode for each electron hitting it
- These electrons are attracted to the second dynode, and so on, finally reaching the anode

PMT amplification

- Total amplification of the PMT is the product of the individual amplifications at each dynode
- If a PMT has ten dynodes and the amplification at each stage is 5, the total amplification will be approximately 10,000,000
- Amplification can be adjusted by changing the voltage applied to the PMT



Choice of Scintillator

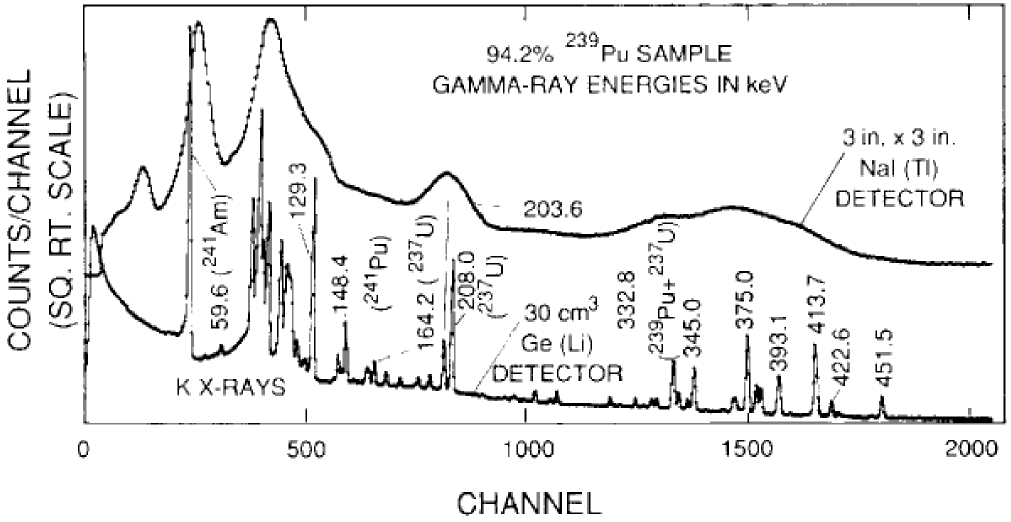
Which scintillator for which particle?

gammas	⇒	Na I (Tl) ou Cs I (Tl)
X	⇒	Na I (Tl) ou Cs I (Tl)
β	⇒	Organic / Plastic Scintillators
β (low E)	⇒	solutions liquides
α	⇒	gas ou ZnS
Thermal neutrons	⇒	Zn S + ^{10}B *(or doped plastic scintillators)*
Fast neutrons	⇒	Zn S + polymers *(or plastic)*
Fission product	⇒	Gas

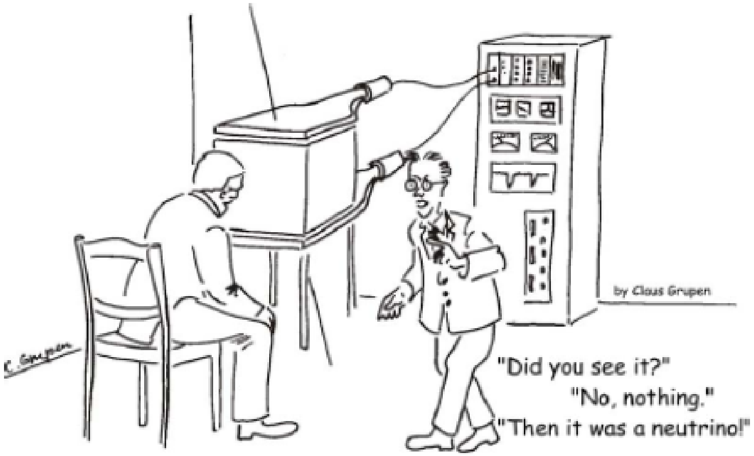
Scintillation detectors

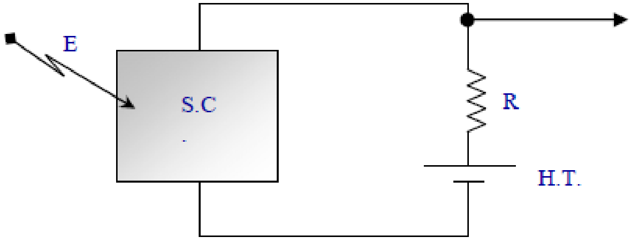
	Advantages	**Disadvantages**
Mineral	**High efficiency** **Linear response vs. Energy** **Portable apparatus**	**Response time >> (≈ 1 µs)** **⇒ Low Max Count Rate** **Bad Resolution**
Organic	**Very fast (≈10^{-8} s)** **Linear response (electrons)** **relatively cheap**	**Low efficiency** **not suitable for gammas and X**

Scintillation detectors

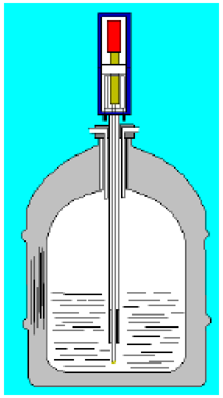


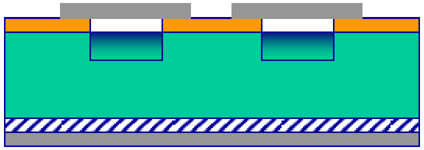
Gamma Spectrum of Plutonium Sample
With NaI(Tl) scintillator and HP-Ge detectors

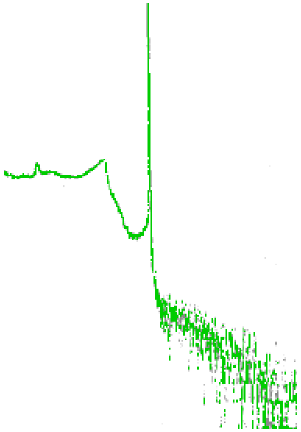




Semiconductor detectors

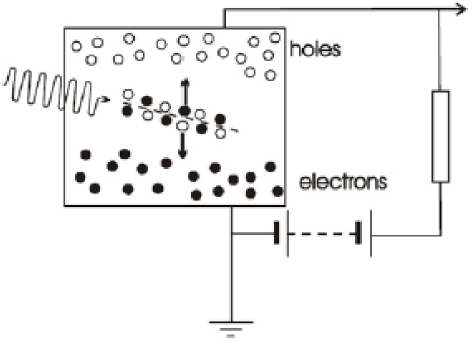


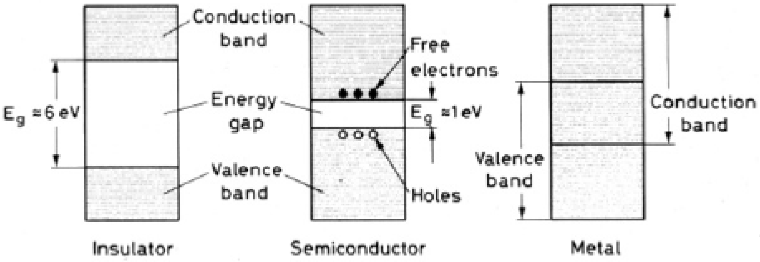




Semiconductor detectors

- . Semiconductor detectors are solid-state devices that operate essentially like ionization chambers. The charge carriers in semiconductors are not electrons and ions, as in gas counters, but electrons and holes. Radiation incident upon the semiconducting junction produces electron-hole pairs as it passes through it. Electrons and holes are swept away under the influence of the electric field, and the proper electronics can collect the charge in a pulse.
- A semiconductor is a solid material that has electrical conductivity between a conductor and an insulator. Insulators have larger band gaps (energies that electrons must acquire to be free to move from atom to atom). When a semiconductor is at room temperature, very few electrons gain enough thermal energy to leap the band gap, which is necessary for electrons to be available for electric current conduction. The smaller band-gaps of semiconductors, however, allow for other means besides temperature to control their electrical .





- Semiconductors are basically crystalline solids in which atoms are held together by covalent bonds. They are called semiconductors because their electrical conduction properties lie between those of insulators and conductors. Germanium (Ge) and Silicon (Si) are the two commonly used semiconductor materials.

Semiconductor detectors

Versus Gas Detectors

Gas filled detectors are commonly used because they are inexpensive and robust. They also proved to be extremely useful in many applications. However, solid state (or semiconductor) detectors are generally superior for most applications, so Si and Ge semiconductor detectors are considered the "Gold-Standard" in almost all spectroscopy applications.

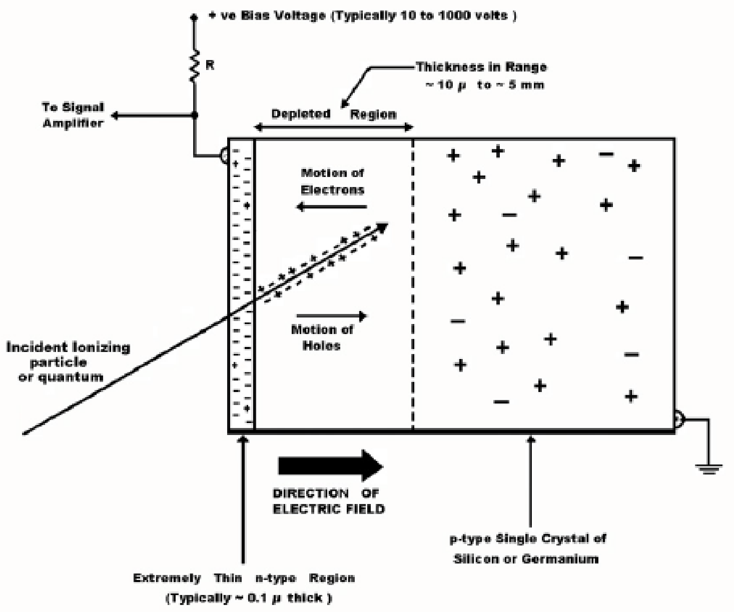
Basic operational concept for both types of detectors is very similar:

- Ionization of detector material atoms creates positive and negative charge carriers
- Drift/transport and collection of charge carriers due to external electrical field
- Induction of signal during charge collection due to motion of charge carriers

However, there are some differences:

- Solid state counter have higher density (**larger dE/dx**)
- Smaller energy to generate charge carriers in solid state detectors leads to **excellent energy resolution**
- Higher mobility of charge carriers in solid state detectors

Despite these differences, both types of charge carriers are fast and lead to very good timing characteristics



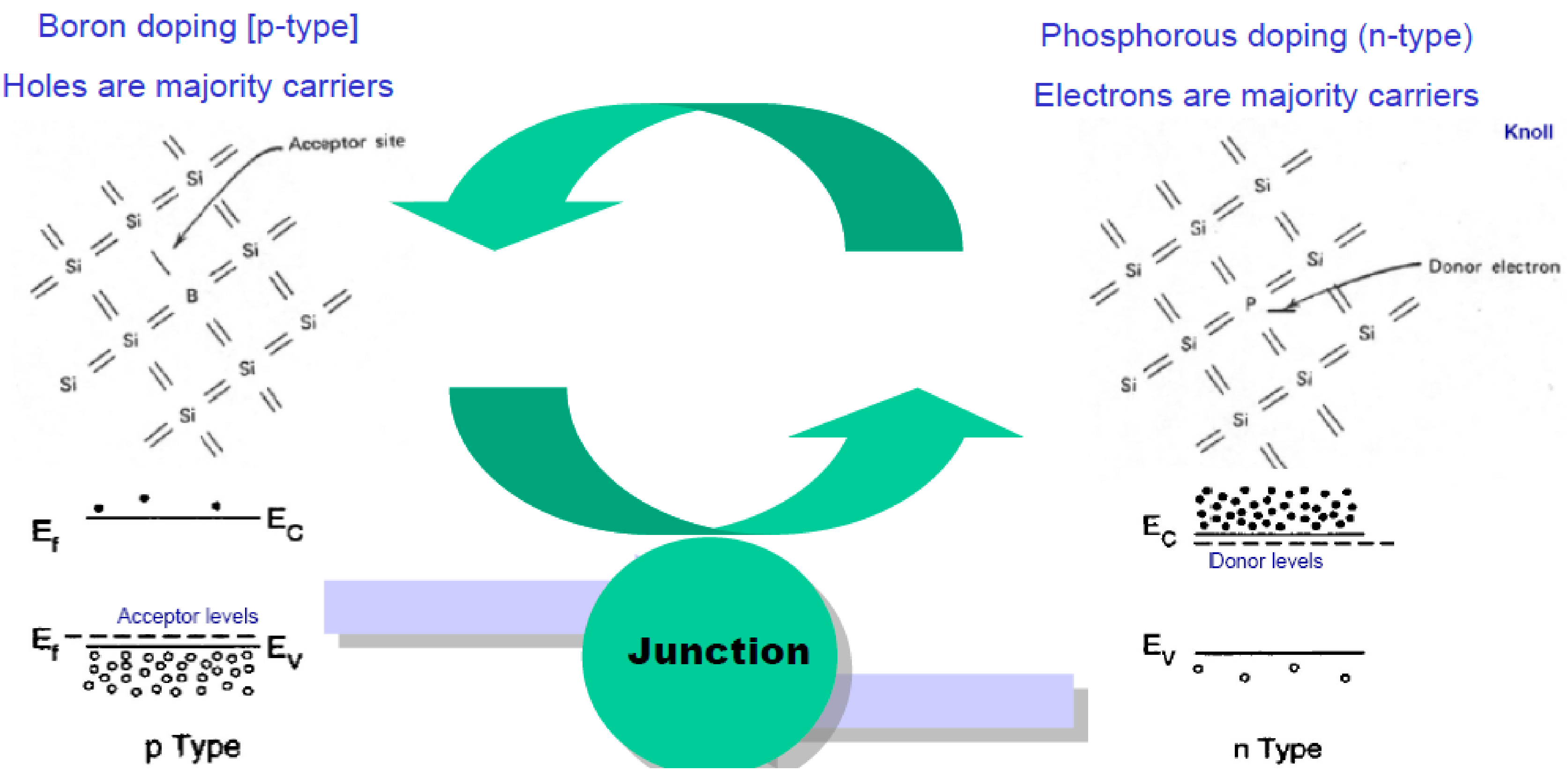
Why Semiconductor?

- **Low ionization energy**
  - Good Signal Level
- **Long mean free path**
  - Good charge collection efficiency
- **High mobility**
  - Fast charge collection
- **Si : Lower Z = 14**
  - Low multiple scattering
  - Little cooling
- **Ge : Higher Z = 32**
  - Higher stopping power
  - Cooling is required

Detector	Ionization Energy ω or I (ev)	Energy Resolution @ 5 MeV
Gas	30	0.6 %
Scintillation	100-500	1.1 - 2.4 %
Semiconductor	3	0.2 %

Basic principles

To dope the Silicon with impurities



Boron doping [p-type]

Holes are majority carriers

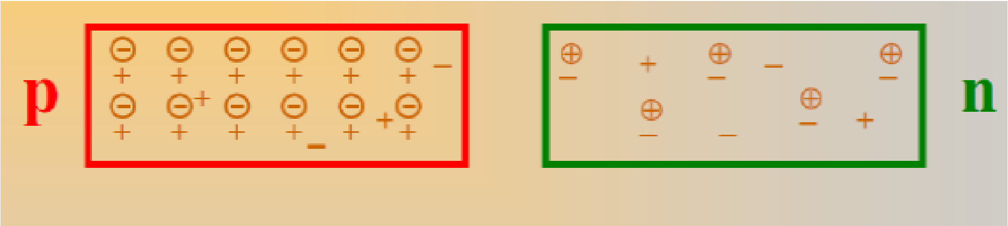
Phosphorous doping (n-type)

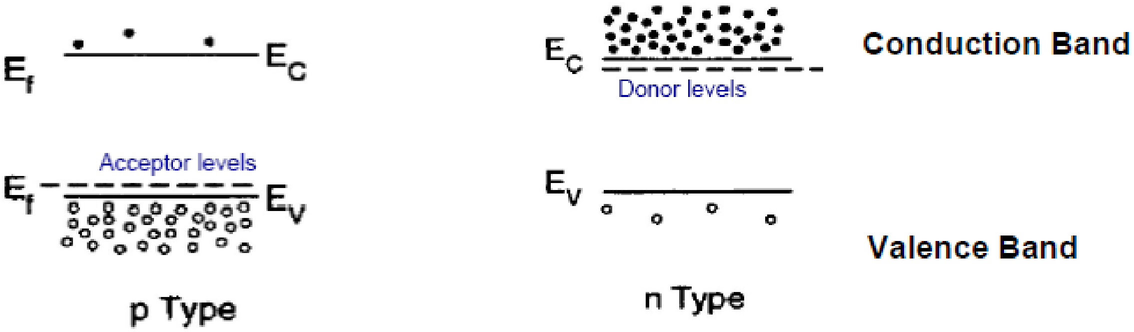
Electrons are majority carriers

Knoll

Basic principles

Construction of a p-n junction

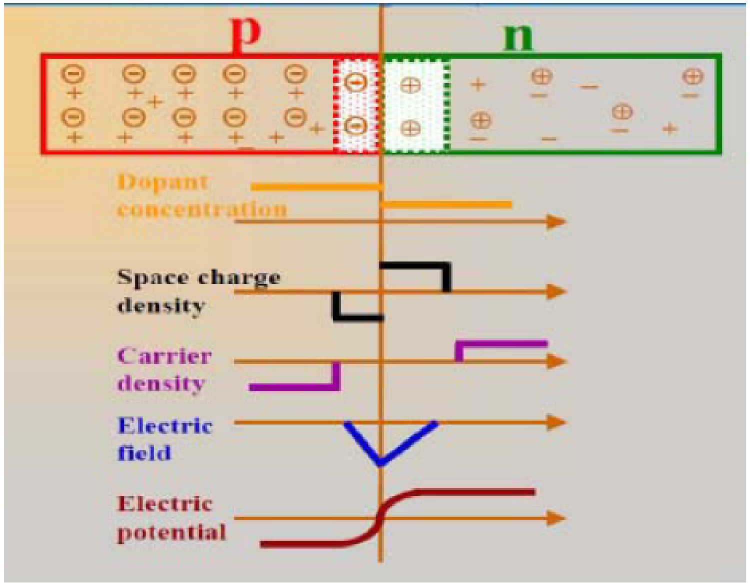


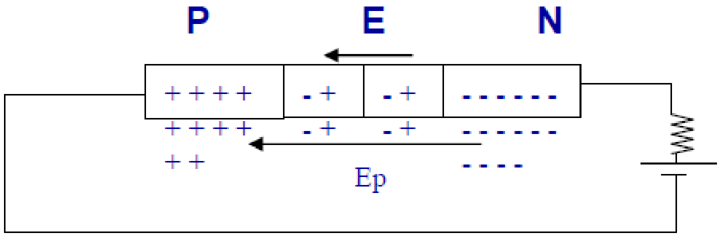


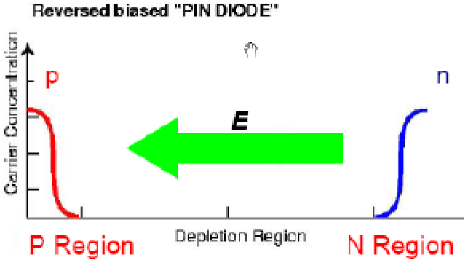
Basic principle of p-n junction

The magic recipe

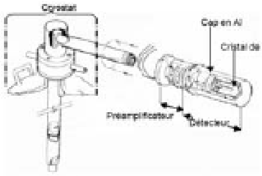
- . When brought together to form a junction, the majority carriers diffuse across the junction. Such migration leaves a region of net charge of opposite sign on each side, called **the space-charge region or depletion region**. The electric field set up in the region prevents further migration of carriers.







Examples of Semiconductor detectors

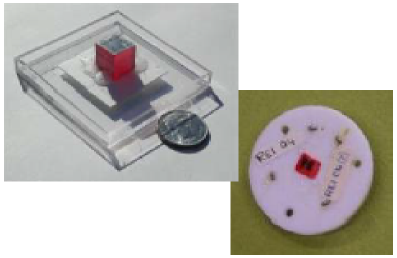


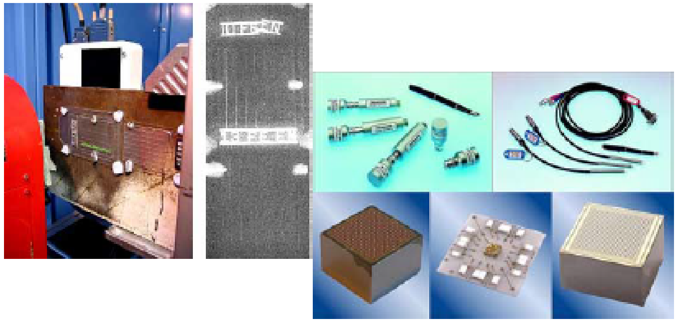
HP-Ge : Excellent Resolution, storable at 300K, for X and γ
HP-Si

Ge(Li) : Charged particles (α, β, p, FP).
Si(Li)

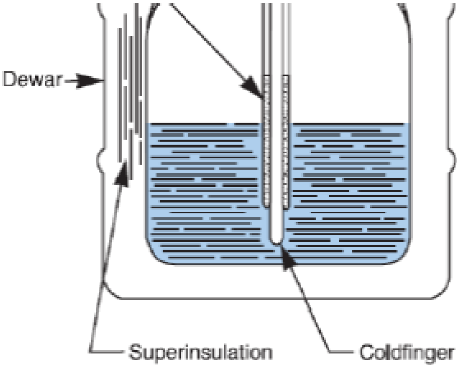
CdTe : Tomographie/Radiography measurements, X-γ Camera
CdZnTe

HgI2 : X-Ray detection
<< I_{lk} at room T°

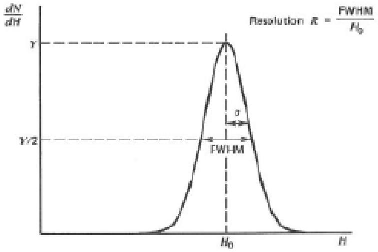


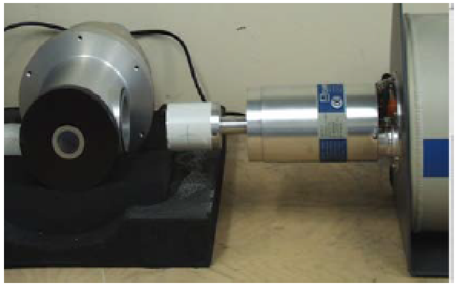


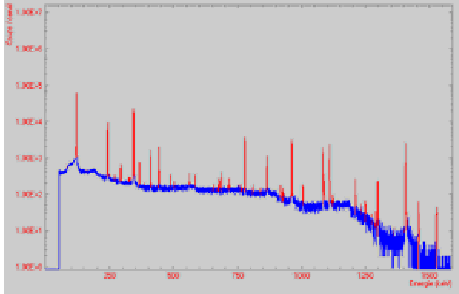
Liquid Nitrogen for Cooling



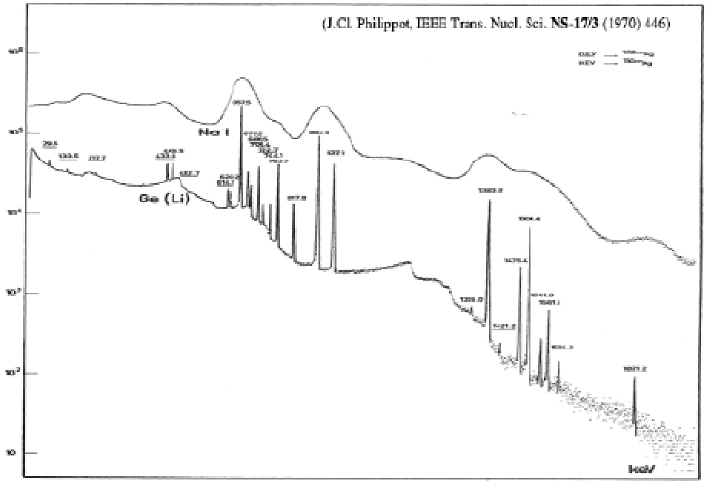
Energy Resolution







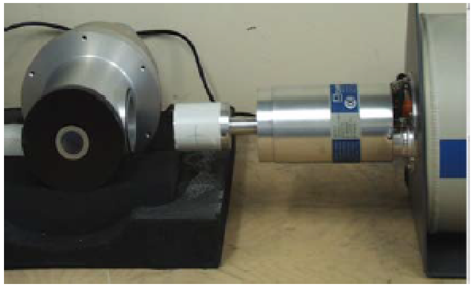
NaI (Tl) vs. Ge(Li)


(J.Cl. Philippot, IEEE Trans. Nucl. Sci. NS-17/3 (1970) 446)

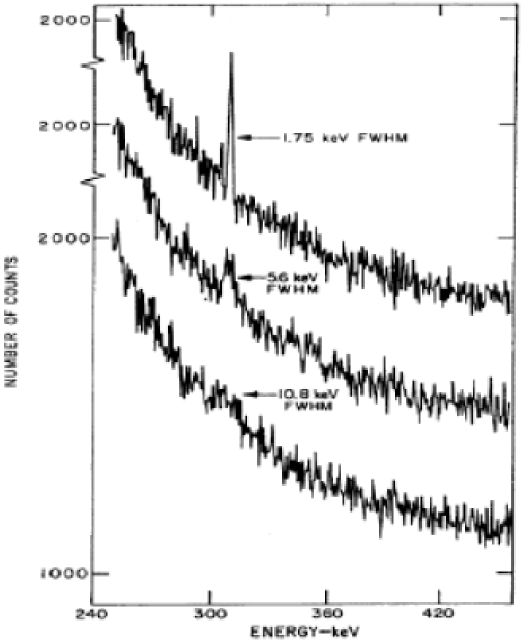
Comparative pulse height spectra recorded using iodide scintillator and a Ge(Li) detector for gamma source radiation from decay of 108w Ag and 110m Ag. Peak energies are labeled in keV (from Phillot, IEEE, TNS, 1970)

Semiconductor detector → **Excellent detector for energy measurement and material characterization !**

Energy Resolution

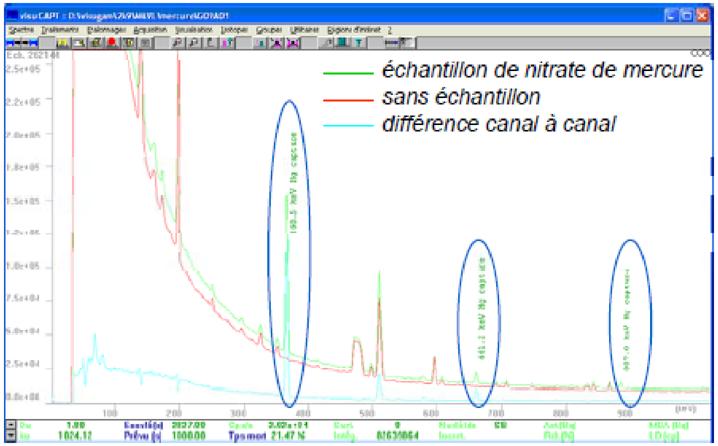


Signal to background ratio improves with better energy resolution (signal counts in fewer bins compete with fewer background counts)

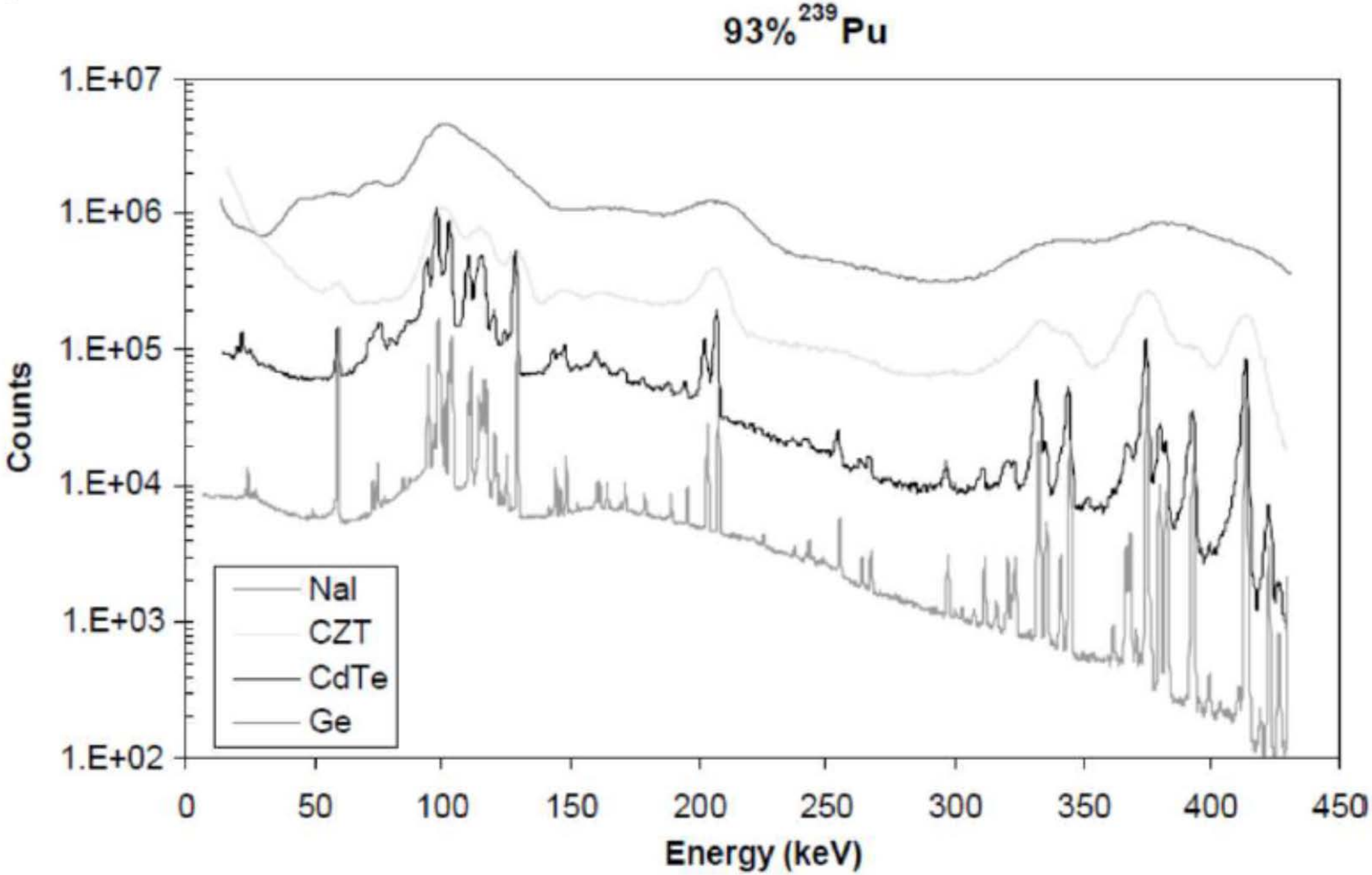


G.A. Armantrout, *et al.*, IEEE Trans. Nucl. Sci. **NS-19/1** (1972) 107

One can extract precise peak position and find New Peaks



A Gamma spectrum acquired with various SC detectors



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THANK YOU

"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are, if doesn't agree with experiment, it is wrong."
Richard Feynman (1918-1988)

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