Scintillation detectors

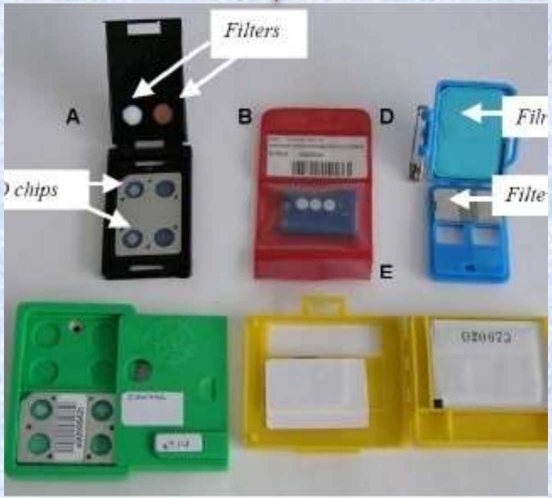
Radiation monitoring instruments are distinguished into:

Area survey meters (or area monitors)

Gas filled detectors:

➢ Ionization chambers
➢ Proportional counters
➢ GM counters

Personal dosimeters (or individual dosimeters)



Solid state detectors:

- Scintillator
- Semiconductor detectors

★ Luminescence: Emission of photons (visible light, UV, X ray) after absorption of energy. Energy deposition in the material by

★ Light ➔ Photoluminescence

★ Heat ➔ Thermoluminescence

★ Sound ➔ Sonoluminescence

★ Electric energy ➔ Electrolumineszence

★ Mechanical deformation ➔ Triboluminescence

★ Chemical reactions ➔ Chemoluminescence

★ Living organism ➔ Bioluminescence

★ Scintillation: Emission of photons following the excitation of atoms and molecules by radiation (γ, or particle radiation).

★ Fluorescence: emission of light by a substance that has absorbed light or another electromagnetic radiation of a different wave length. In most cases the emitted light has a longer wavelength. The emission follows shortly after (appr. 10 ns).

★ Phosphorescence: Similar to fluorescence, however the re-emission is not immediate. The transition between energy levels and the photon emission is delayed (ms up to hours).

Scintillation:

- Voltage is not applied to these types of detectors
- **Incident radiation interacts with the scintillator material** they produce flashes of light
- This is known as scintillation or fluorescence
  - These materials can be used as radiation detectors
    - ✓ **Excites electrons in material**
- The amount of light given off is measured

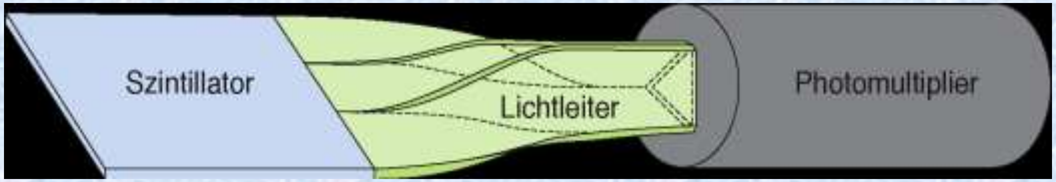
Applications in nuclear and particle physics:

- Trigger detectors for slow detectors (e.g. drift chambers),
- Time of flight counters (TOF-Counter),
- Calorimeters,
- Position detectors (scintillating fibres),
- Detection and spectroscopy of thermal and fast neutrons,
- Neutrino detectors (liquid scintillators)

Scintillation Detectors:

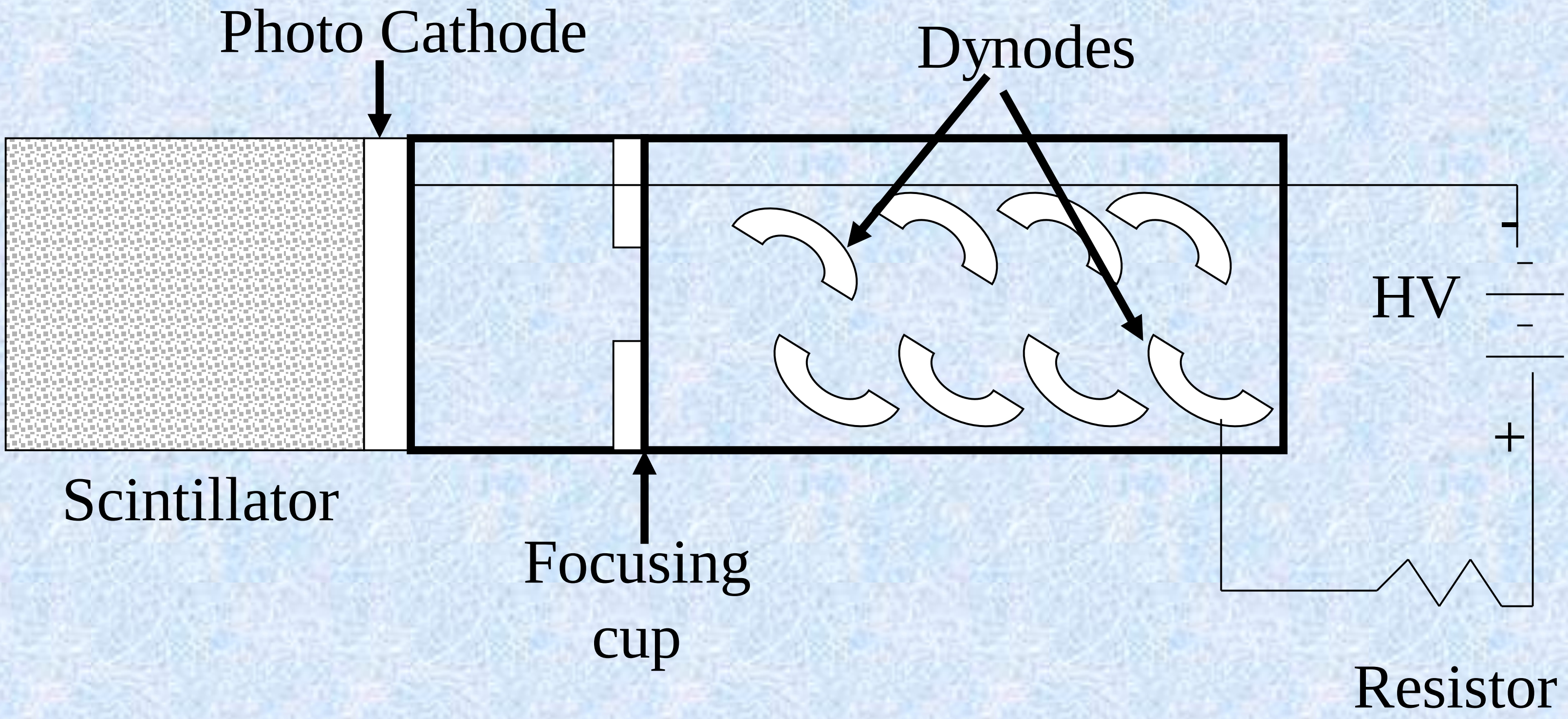
Definition: A scintillation counter is an instrument for detecting and measuring ionizing radiation by using the excitation effect of incident radiation on a scintillator material, and detecting the resultant light pulses

- ➢ Scintillators are materials: solids, liquids, gases
- ➢ That produce sparks or scintillations of light when ionizing radiation passes through them.
- ➢ The amount of light produced in the scintillator is very small.
- ➢ It must be amplified before it can be recorded as a pulse or in any other way.
- ➢ The amplification or multiplication of the scintillator's light is achieved with a device known as photo multiplier tube.
- ➢ The operation of a scintillation counter may be divided into two broad steps.
- ✓ Absorption of incident radiation energy by the scintillator and production of photons in the visible part of electromagnetic spectrum.
- ✓ Amplification of the light by the photo multiplier tube and production of the output pulse.



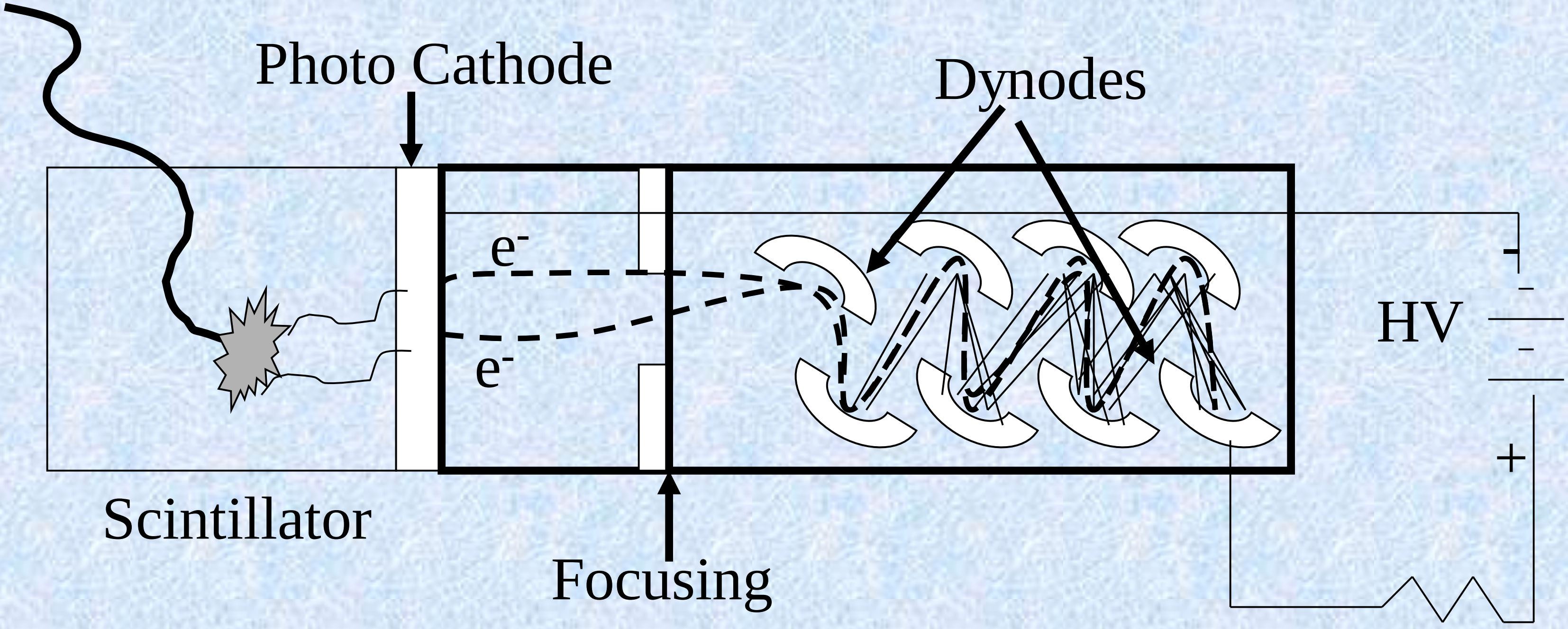
Scintillation Detector

(Light Production)



Scintillation Detector

(Light Production)



6 Steps of Scintillation Detection

Inside scintillator:

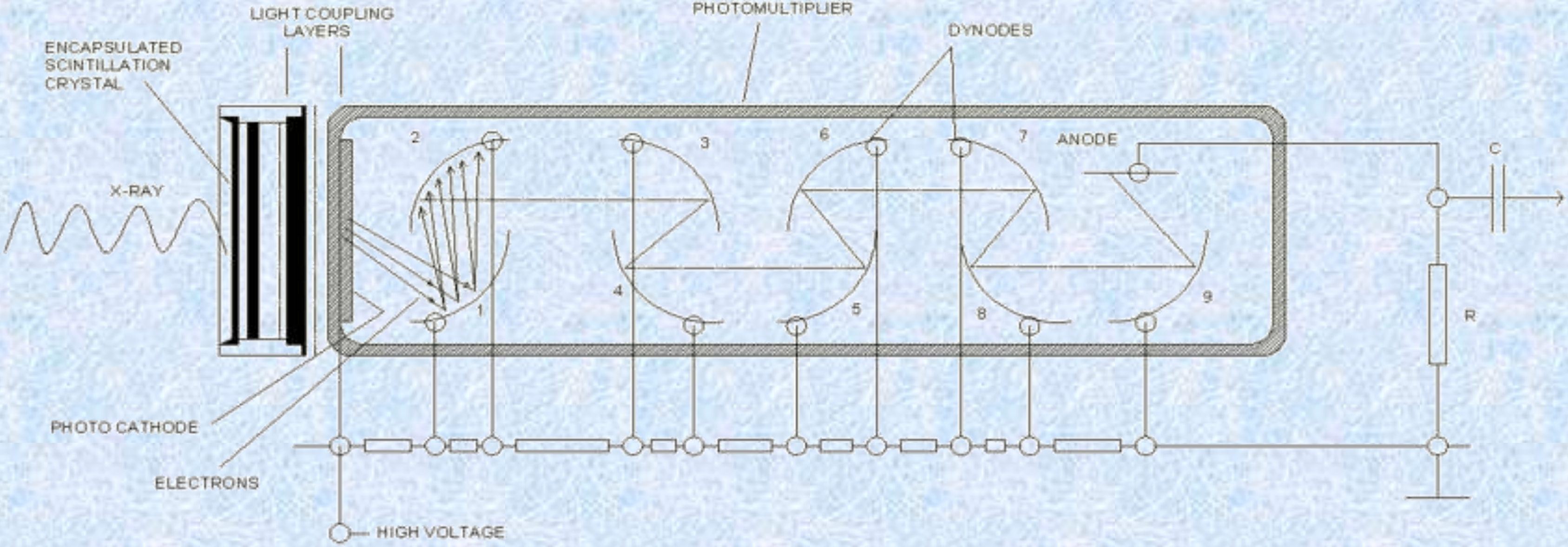
1. Excitation due to absorption of radiation
2. Emission of light photons from de-excitation
3. Transit of light to photocathode inside photomultiplier tube

Inside photomultiplier tube:

4. Production of photoelectrons in photocathode
5. Multiplication of photoelectrons

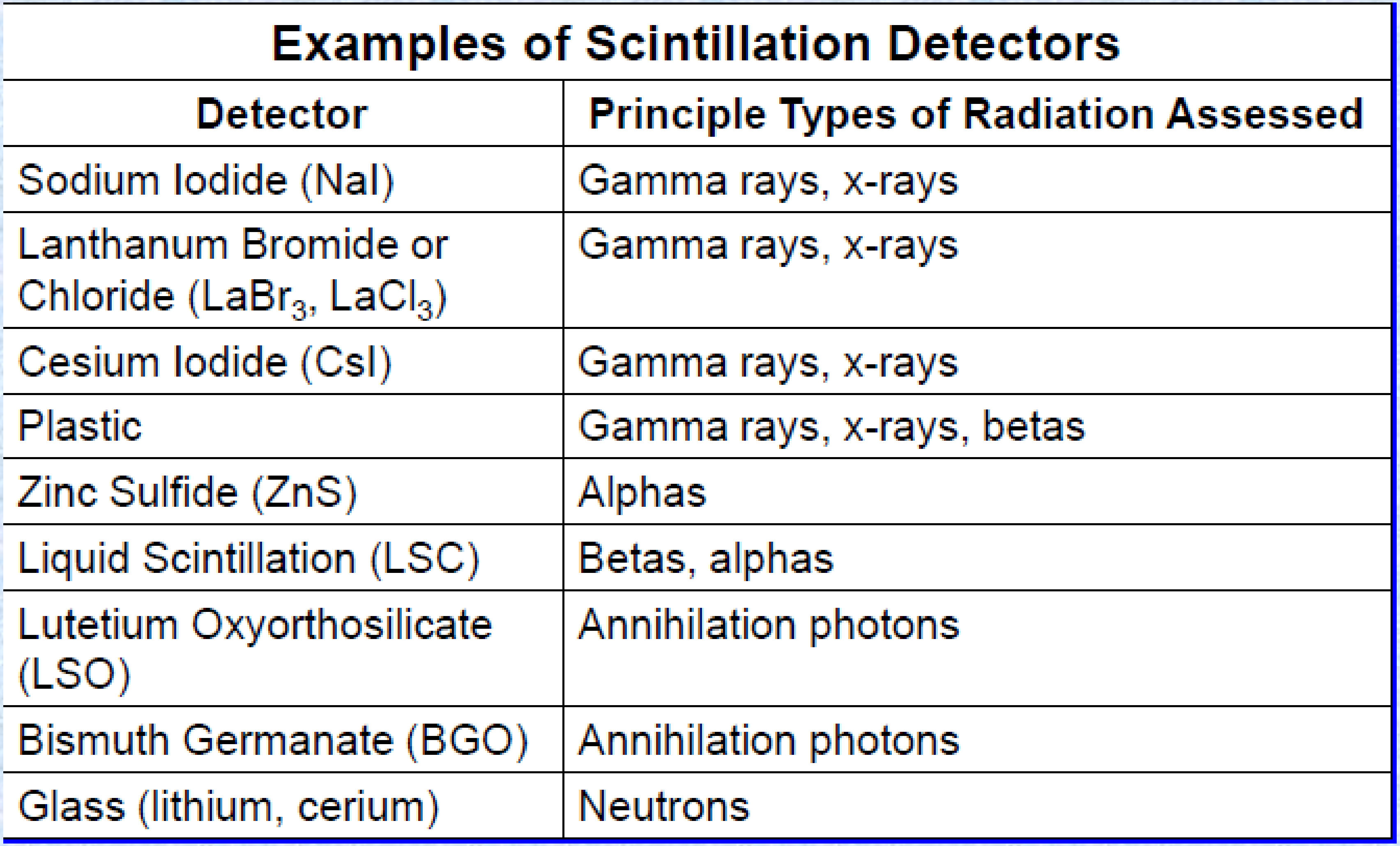
Outside scintillator and photomultiplier tube:

6. Conversion of electronic detector output to useful information



- Two general types:
  - Inorganic
    - Inorganic crystals (Zinc sulfide (ZnS), **Sodium iodide** (NaI), **Cesium iodide** (CsI)**, Lithium iodide**(LiI): as pure crystal or doped with thallium (TI)
    - **Barium fluoride (**BaF2), Cer,, CeF3, PbWO4
    - High atomic numbers, high density and very good signal
    - Advantages for stopping radiation

  - Organic
    - Organic single crystal (anthracene, naphthalene, stilbene)
    - Lower density, high atomic number, nearly tissue equivalent



Examples of Scintillation Detectors

Detector	Principle Types of Radiation Assessed
Sodium Iodide (NaI)	Gamma rays, x-rays
Lanthanum Bromide or Chloride ($LaBr_3$, $LaCl_3$)	Gamma rays, x-rays
Cesium Iodide (CsI)	Gamma rays, x-rays
Plastic	Gamma rays, x-rays, betas
Zinc Sulfide (ZnS)	Alphas
Liquid Scintillation (LSC)	Betas, alphas
Lutetium Oxyorthosilicate (LSO)	Annihilation photons
Bismuth Germanate (BGO)	Annihilation photons
Glass (lithium, cerium)	Neutrons

Inorganic Scintillators:

★ Different types of inorganic scintillators:

- – Inorganic crystals, Glasses and Noble gases (gaseous or liquid)

★ The consequence are very different response times.

- ✓ Inorganic crystals and glasses: rather slow (compared to organic crystals)
- ✓ Noble gases: fast

★ Inorganic scintillators are relative radiation resistant.

★ High atomic numbers, high density and very good signal.

★ Emitted light usually at **400–500** nm.

★ Advantages:

✓ High density, short radiation length

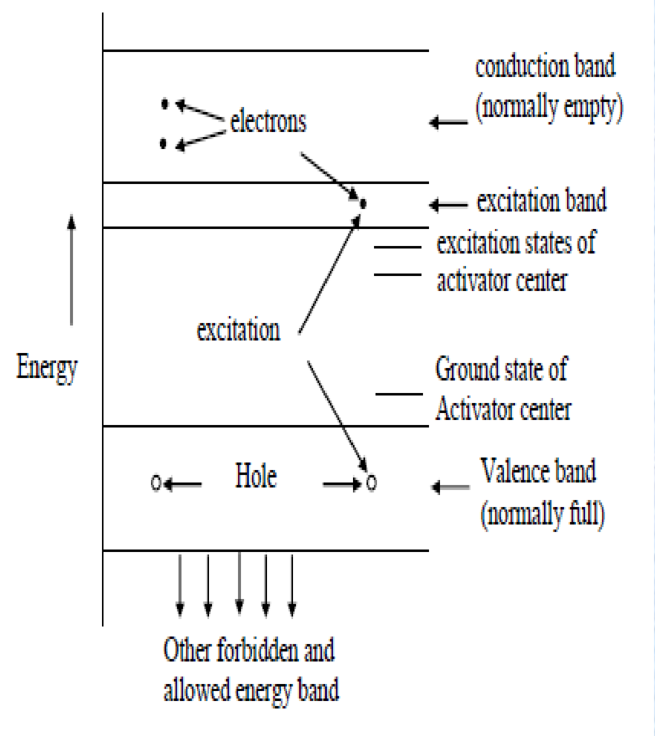
✓ High light output

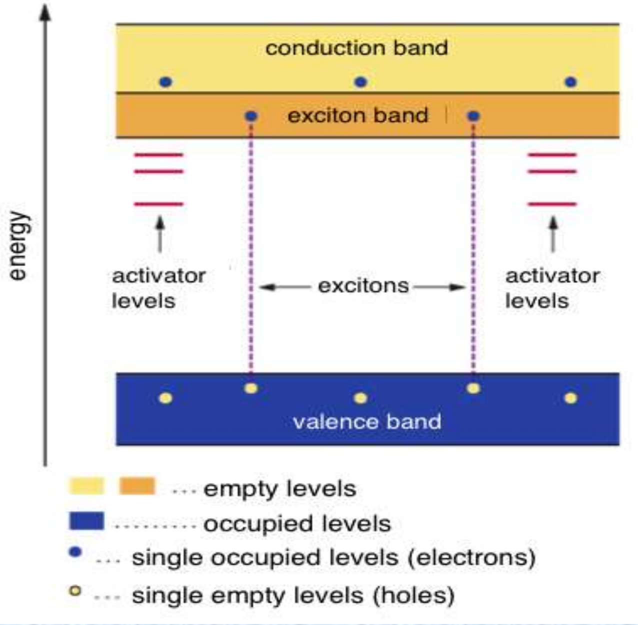
★ Disadvantages:

✓ Usually slower than organic scintillator: Decay times a few hundred ns/μs.

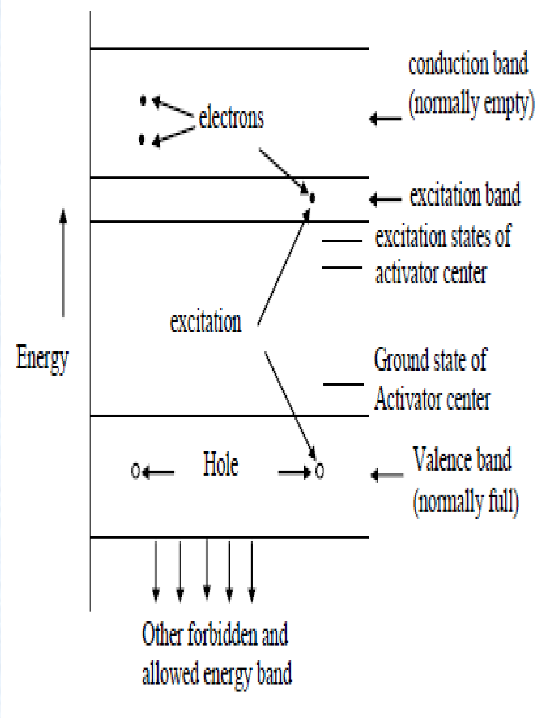
The mechanism of the scintillation process:

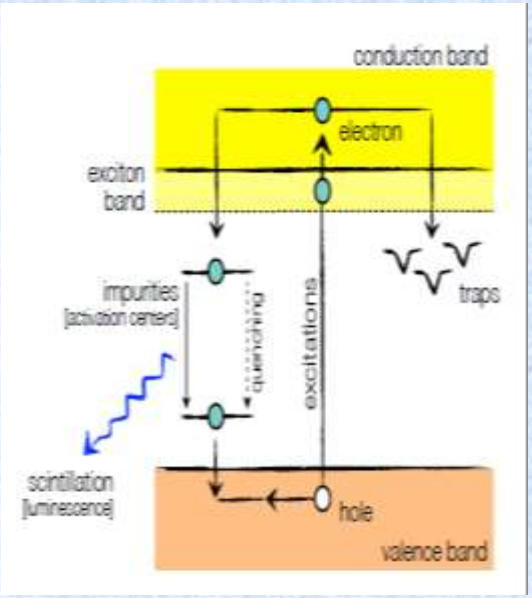
- ➢ The luminescence of scintillator can be understood in terms of the allowed and forbidden energy bands of a crystal.
- ➢ In a crystal, the allowed energy states widen into bands.
- ➢ In the ground state of the crystal, the uppermost allowed band that contains electrons is completely filled. This is called the valence band.
- ➢ The next allowed band is empty (in the ground state) and is called the conduction band.
- ➢ An electron may obtain enough energy from the incident radiation to move from the valence to the conduction band.
- ➢ Once there, the electron is free to move anywhere in the lattice. The removed electron leaves behind a hole in the valence band,





- Sometimes, the energy given to the electron is not sufficient to raise it to the conduction band. Instead, the electron remains electrostatically bound to the hole in the valence band.
- The electron-hole pair thus formed is called an excitation.
- In terms of energy states, the excitation corresponds to elevation of the electron to a state higher than the valence but lower than the conduction band.
- The width of the excitation band is of the order of 1 eV, while the gap between valence and conduction bands is of the order of 8 eV.
- The transition of the impurity atom from the excited to the ground state, if allowed, results in the emission of a photon in times of the order of 10^{-8} s.





- If this photon has a wavelength in the visible part of the electromagnetic spectrum, it contributes to a scintillation.
- Thus, production of scintillation is the result of the occurrence of these events.

1. Ionizing radiation passes through the crystal,
2. Electrons are raised to the conduction band.
3. Holes are created in the valence band
4. Excitations are formed.
5. Activation centers are raised to the excited states by absorbing electrons, holes and excitations.
6. De-excitation is followed by the emission of a photon.

Time constants:

Fast: recombination from activation centers (ns to µs)

Slow: recombination due to trapping (ms to sec)

Application!:

- The light output of inorganic crystals is in good approximation linear to the energy deposited by high energy particles.
- Inorganic crystals are perfect devices for homogeneous calorimeters.
- Lead tungstate (PbWO4) crystals, also short radiation length, fast and very radiation hard.

Scintillating Glasses:

★ A typical scintillating glass is cerium doped with lithium or boronsilicate.

★ High melting point and high resistance against organic and inorganic substances (except hydrofluoric acid).

★ Application of scintillating glasses predominantly as neutron detector (detectors also sensitive to β and γ radiation).

Scintillating Noble Gases:

★ Scintillating gases: Helium, Xenon, Krypton and Argon (partially also Nitrogen)

★ The fluorescence mechanism in noble gases is a purely atomic process and the life time of the excited states is therefore short.

★ Scintillating gas detectors are very fast response time ≤ 1 ns.

★ The emitted light is in the UV range. In this range classic photomultipliers are not sensitive. The use of wave length shifters is mandatory (e.g. as coatings on the walls).

★ Due to the relative low density the light yield of gaseous scintillators is low.

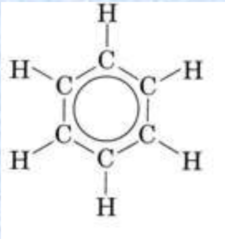
★ Can be compensated by high pressure operation (up to **200** atm).

Organic Scintillators

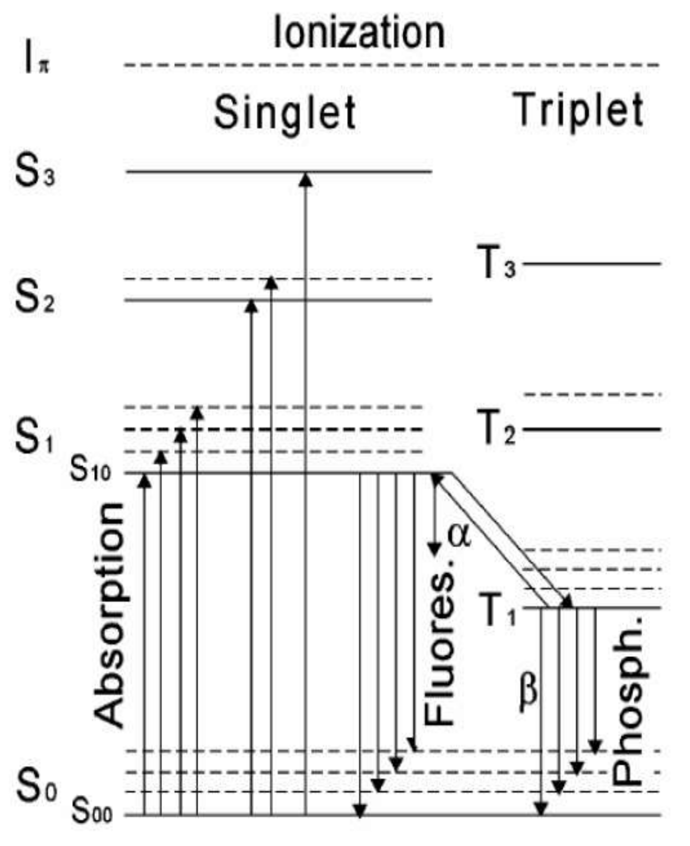
- Scintillation mechanism in organic materials is quite different from the mechanism in inorganic crystals.
- Organic scintillators: **Effective for measuring beta particles.**
- Types: Organic crystals, Organic liquids and Plastic scintillators
- Organic scintillators are aromatic hydrocarbon compounds (containing benzene ring compounds)
- Low atomic numbers, low density and very poor signal
- Mechanism: transition of electrons between molecular orbitals ➔ organic scintillators are fast (ns).
- Organic single crystal (anthracene, naphthalene, stilbene)
- Organic crystals consist of only one component/molecular, florescence can be observed independently of the physical state
- Liquid and Plastic scintillators are usually composed of **2–3** components:

Light output:

- The dependence of light output from energy deposition is usually not linear in organic scintillators.
- A high density of excited molecules along the particle track causes deexcitation without photon emission (quenching effect).
- Light output becomes saturated



- Energy from a charged particle is absorbed and excites the electron into a variety of excited states - the singlet states (spin = 0) are labeled S1, S2, S3.
- For organic scintillators the spacing between S0 and S1 is 3 to 4 eV, the spacing between the upper states is much smaller.
- Each of the S levels is subdivided into a series of levels with much finer structure (corresponding to the vibrational states of the molecule).
- The typical spacing is 0.15 eV.
- The 2nd subscript denotes the fine structure level.
- Spacing between S states is 3-4 eV, spacing in vibrational structure is 0.15 eV



Organic Scintillator Mechanism:

❖ At room temperature, average energy is approximately 0.025 eV so all molecules are in the S00 state.

❖ When the charged particle passes through, kinetic energy is absorbed by the molecules, and electrons are excited to the upper levels.

❖ The higher states S2, S3, de-excite quickly (picoseconds) to S1 state through radiationless transitions (internal conversion).

❖ States such as S11, S12 that have extra vibrational energy and are not in thermal equilibrium with neighboring molecules, quickly lose energy.

❖ After negligibly short time a population of excited molecules in S10 state is produced as the net effect of the excitation process.

❖ Scintillation light, prompt fluorescence, is emitted in transitions between S10 and the ground state.

❖ The prompt fluorescence intensity at time t following excitation is described by

$$I = I_0 e^{-t/\tau}$$

where τ is the fluorescence decay time for the S10 level.

❖ In most organic scintillators, τ is the order of a few nanoseconds therefore organic scintillators are fast.

❖ The lifetime for the T1 state is much longer than the S1 state. T1 is populated by a transition called an intersystem crossing. The lifetime of the T1 state can be ms.

- T1 → S0 transitions give rise to phosphorescence (delayed light emission).
- T1 lies below S0, therefore the wavelength of the emitted phosphorescence is longer than the wavelength of the fluorescent light.
- The phosphorescent light can be discriminated from the scintillation light on the basis of timing and wavelength.
- The energy level scheme explains why organic scintillators can be transparent to their own fluorescence emission.
- All fluorescence emissions (except S10 → S00) have a lower energy than the minimum required for absorption.
- There is little overlap between emission and absorption spectra, therefore the emitted light mostly passes straight on through the scintillation medium.

Organic Crystals:

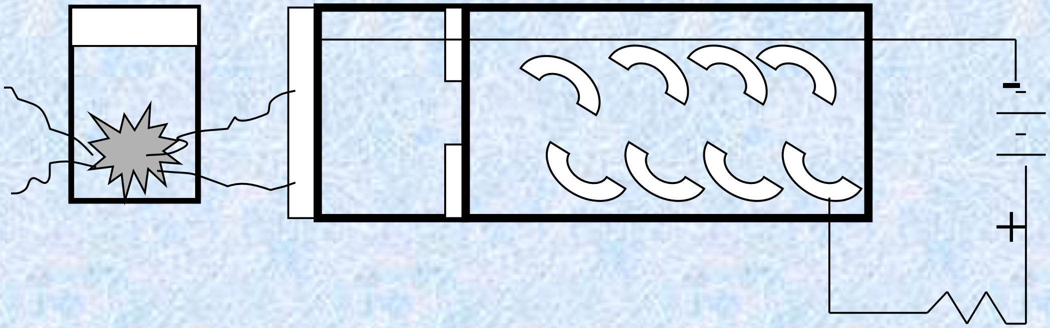
- ★ Crystals component:
  - ✓ Naphtalene (C10H8)
  - ✓ Anthracene (C14H10)
  - ✓ trans-Stilbene (C14H12)
- ★ Advantages:
  - ✓ Fast fluorescence: few ns
  - ✓ Mechanically strong
- ★ Disadvantages:
  - ✓ Anisotropic light output: “channeling” effect in crystals
  - ✓ Mechanically difficult to process.

Organic Liquid Scintillators:

- ★ Mixture of one or several organic scintillators in a solvent
- ★ Important solvents:
  - ✓ Benzol (C6H6)
  - ✓ Xylol (C8H10)
  - ✓ Triethylbenzol
  - Toluol (C7H8)
  - Phenylcyclohexan (C12H16)
  - Decalin (C10H18)
- ★ Advantages:
  - ✓ Fast fluorescence
  - ✓ Any possible detector shape
  - ✓ Easy use of additives (wave length shifter)
  - ✓ Very sensitive to impurities

Liquid Scintillation

- Dissolving an organic scintillator in a solvent
- Very low background
- Laboratory instrument



Plastic Scintillators:

★ Plastic scintillators used in numerous applications in particle and nuclear physics.

★ Dissolving & polymerizing

★ Crystals component:

- ✓ The support structure is a polymere matrix containing a primary scintillator
- ✓Matrix materials: Polyvinyltoluol, Polyphenylbenzol, Polystyrol, PMMA

★ Advantages:

- ✓ Fast fluorescence: ≤ 3 ns
- ✓ Any kind of shape possible
- ✓ Easy to machine, cheap

★ Disadvantage:

- ✓ Not very radiation resistant

Wave Length Shifter:

- Wave length shifter absorb photons of a certain wave length and re-emit photons at a different wave length (usually longer) to better match the scintillator light to the read out device.
- Important wave length shifter materials:
  - ✓ POPOP (1,4-bis-[2-(5-Phenyloxazolyl)]-Benzen; C24H16N2O2)
  - ✓ bis-MSB (1,4-bis(2-Methylstyryl)-Benzen; C24H22)
  - ✓ BBQ (Benzimidazo-Benzisochinolin-7-on)
- Wave length shifter can be mixed into the scintillator or integrated into the light guide.

Photo Detectors:

Different photo detectors used to read light from scintillators and transform it into electric signals:

- ✓ Photomultipliers
- ✓ New silicon devices: APD, SiPM
- ✓ Hybrid Photon Detectors
- ✓ Gaseous Detectors
- ✓ Photo diode

Photomultiplier tube (PMT):

Definition: This is an electron tube which holds two parts: photocathode (it is sensitive for light) + amplifier part

Photocathode: It transforms the light pulses to electron current.

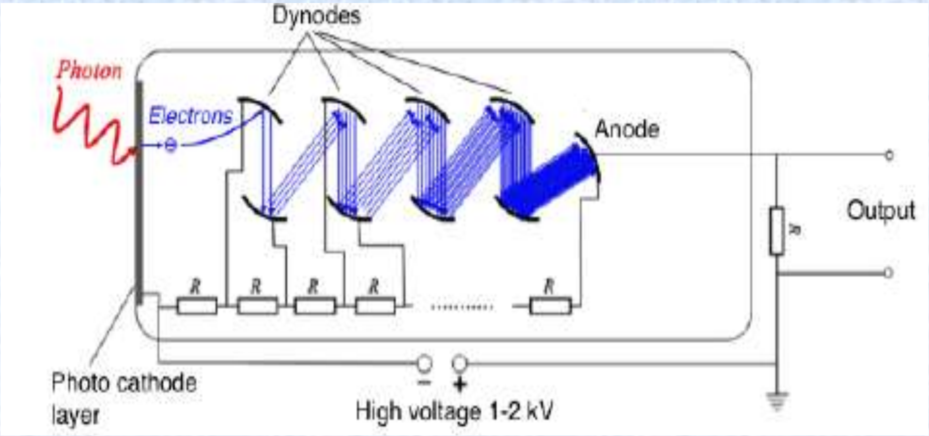
- **Light-sensitive material that absorbs photons and emits photoelectrons**
- Photoelectrons strike successive dynodes and are multiplied (secondary electron production)

Amplifier: It amplifies the electron current to stronger values.

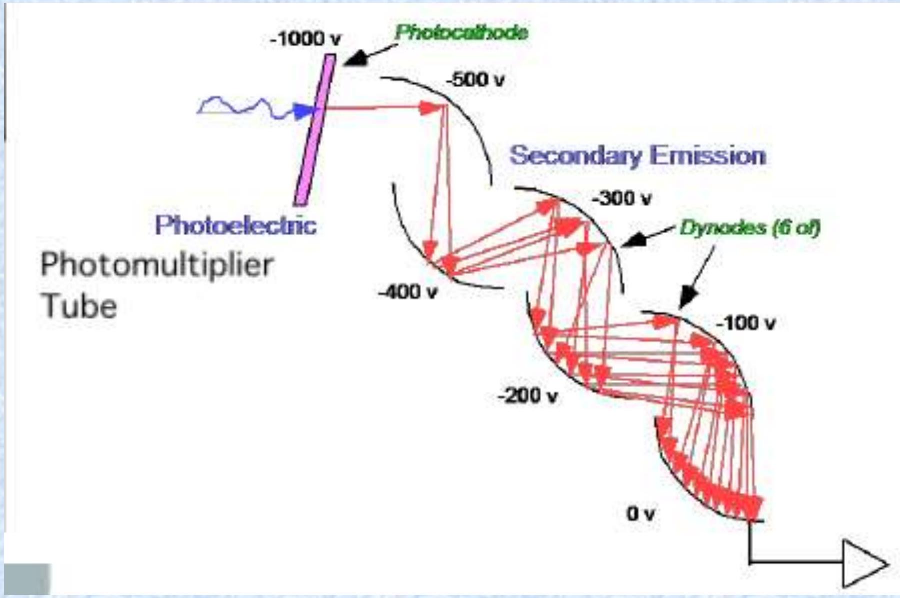
- The electrons are accelerated towards the **1**st dynode and produce secondary emission.
- This process is repeated at each dynode and finally the largely amplified electrons reach the anode.

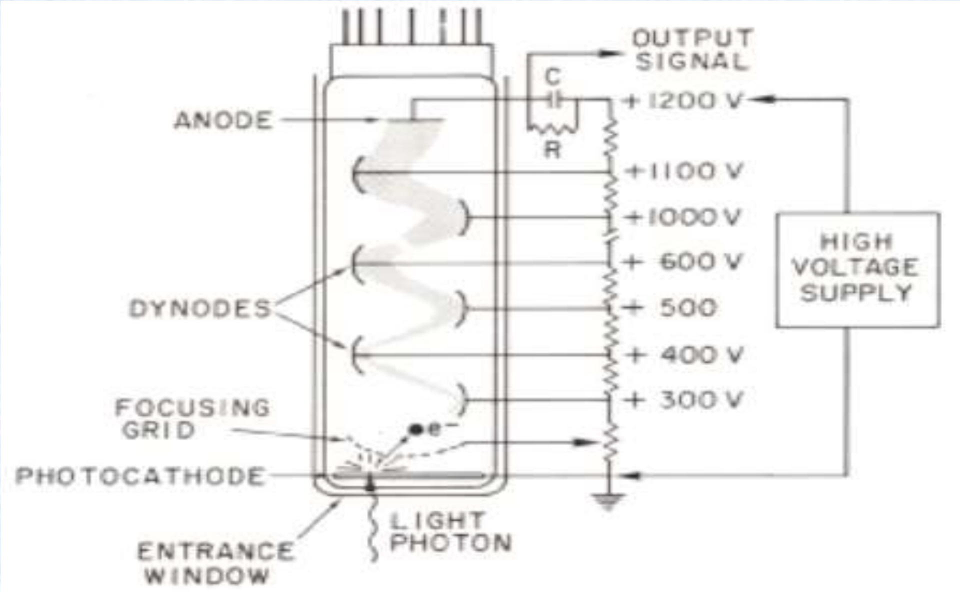
An important application: detection of gamma radiation

- Photo effect, Compton-scattering and pair-generation –some of them is needed to generate the effect. (Light pulses in the crystal)



- In a counting system using a scintillator, the light produced by the crystal is amplified by a photo multiplier tube and is transformed into an electric current. This current is fed into a RC circuit and a voltage pulse is produced.
- The photo multiplier tube or the photo tube is an integral part of a scintillation counter.
- A photo multiplier consists of an evacuated glass tube with a photo cathode at its entrance and several dynodes in the interior.
- The photons produced in the scintillator enter the photo tube and hit the photo cathode, which is made of a material that emits electrons when light strikes it.
- The electrons emitted by the photo cathode, are guided, with the help of an electric field, towards the first dynode, which is coated with a substance that emits secondary electrons, if electrons impinge upon it.
- The secondary electrons from the first dynode move towards the second, from these towards the third, and so on.
- Typical commercial photo tubes may have up to 15 dynodes.
- The voltage difference between two successive dynodes is of the order of 80-120 V.
- The photo cathode material (coated the dynodes) used in most commercial photo tubes is a compound of cesium and antimony (Cs-Sb).





❖ The sensitivity of a photocathode is usually quoted in terms of the quantum efficiency.

❖ The quantum efficiency of the photocathode is defined as the probability for the conversion of light to an electrical signal and is defined as:

$$\text{Quantum efficiency} = \frac{\text{number of photoelectrons emitted}}{\text{number of incident photons}}$$

Electron Multiplication:

- A PMT takes the electrical signal from the photocathode and amplifies through a dynode chain by the process of electron multiplication.
- Electrons are ejected from the photocathode into the vacuum with an energy of ≈ 1 eV and are accelerated by a voltage of a few hundred volts toward an electrode.
- The accelerated electron has an energy of a few hundred electron volts upon arrival at the electrode; this deposition of kinetic energy can result in the re-emission of secondary electrons.
- It typically takes 2-3 eV to excite an electron in the dynode, so 100V can theoretically create ≈ 30 electrons.
- However, there is the same problem as in the photocathode; electrons must be near the surface to be emitted, otherwise they lose too much energy through collisions and are unable to overcome the potential barrier at the surface.
- Only a small proportion of the electrons excited up to the conduction band reaches the surface and creates secondary electrons.
- The overall multiplication factor for a single dynode is given by:

$$\delta = \frac{\text{number of secondary electrons emitted}}{\text{primary incident electron}}$$

δ is typically 4 ~ 6 for voltages of a few hundred volts.

Multiple Stage Multiplication:

❑ Photomultiplier tubes employ dynode chains of several stages of multiplication to create electron gains of the order of 10^6.

❑ Electrons are created in the photocathode, and accelerated toward the first dyode, where secondary electrons are emitted.

❑ The secondary electrons are accelerated by the electric field toward a second dynode, where they create secondary electrons, and so on. This can be repeated many times.

❑ The overall gain for the PM tube = $\alpha\delta^N$

Where N is the number of multiplication stages,

α is the fraction of electrons collected by the multiplier structure,

δ is the multiplication factor for a single electrode.

❑ For typical tubes δ is around 5 and α approaches unity. 10 stages of multiplication result in an overall tube gain of 5^{10} or 10^7

Statistics of Electron Multiplication:

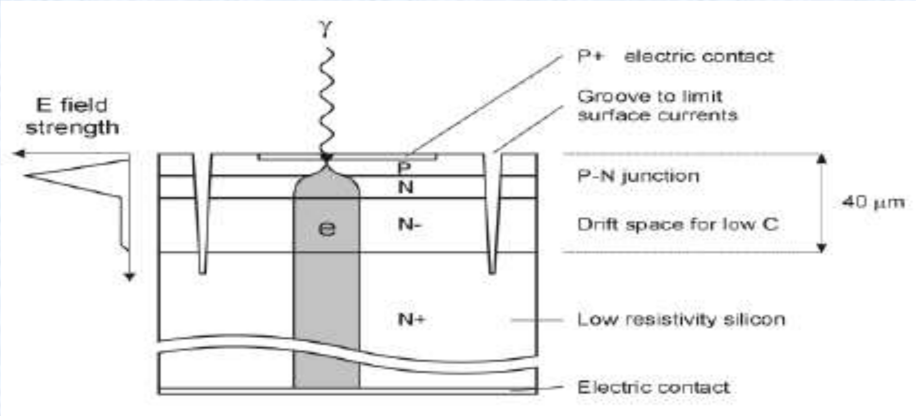
- The emission of secondary electrons from the dynodes is a statistical process, so the multiplication factor δ is not a fixed constant but varies from event to event around a mean value.
- Therefore pulses are amplified overall down the dynode chain by a mean value which has some statistical variation.
- We measure a final mean voltage that has statistical spread, i.e. we measure not just a single energy, but a mean energy with a spread.
- The dynode chain therefore affects the energy resolution of the system.
- We can assume a simple model where the production of secondary electrons follows a Poisson distribution about an average yield.
- A single photoelectron incident on the first dynode results in a mean number of secondary electrons of $\delta \pm \sqrt{\delta}$. The relative variance is thus $1/\delta$.
- The process is compounded over N identical stages of the PM tube, and the mean number of electrons collected at the anode is given by δ^N.
- The relative variance in this number is $1/\delta + 1/\delta^2 + 1/\delta^3 + \ldots + 1/\delta^N \cong 1/(\delta - 1)$
- The variance in the dynode chain adds to the poor observed energy resolution of scintillation detectors.

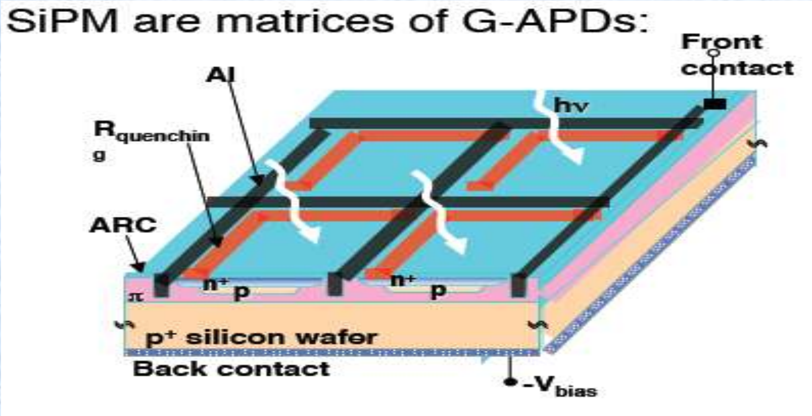
Photodiodes:

- An alternative way to detect the scintillation light 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.
- Advantages: higher quantum efficiency and compact size.
- Disadvantages: electronic noise is a major problem due to the small signal amplitude.

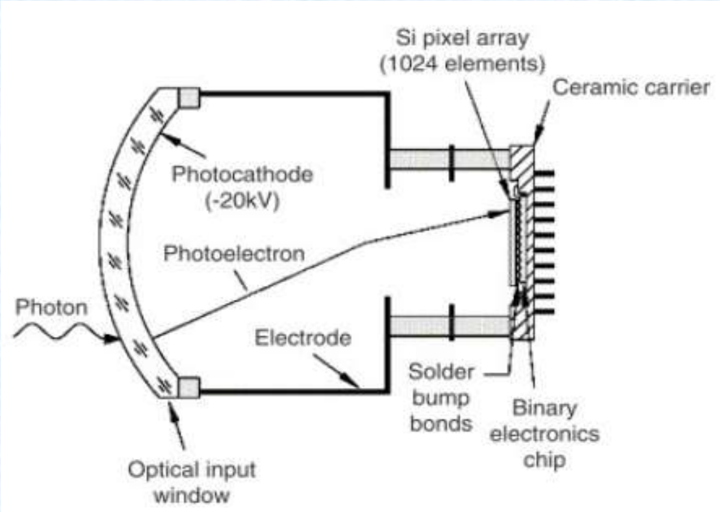
New silicon devices: APD, SiPM

- ❑ Avalanche Photo Diodes (APDs) are silicon devices operated in reverse bias mode in the breakdown region.
- ❑ Geiger mode APDs (G-APD) operate in full breakdown, current limited by quenching resistor.




SiPM are matrices of G-APDs:

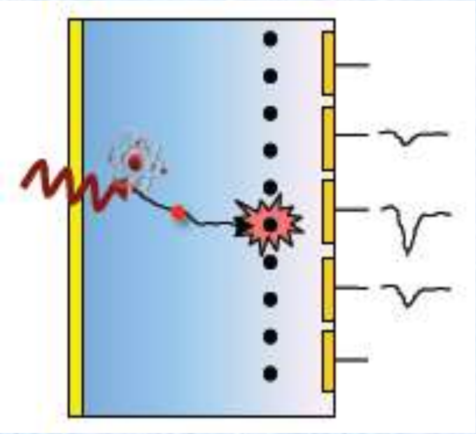
Hybrid Photon Detectors: Photoelectrons are accelerated in vacuum and detected with a silicon hybrid pixel detector.



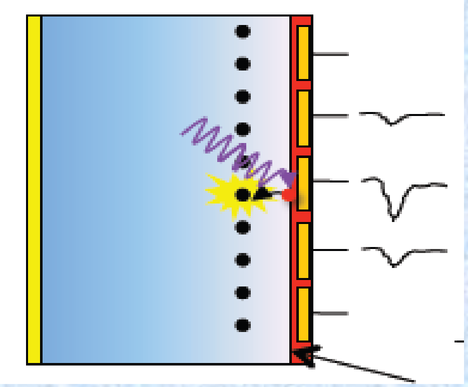
Gaseous Detectors:

Two techniques:

- ☐ Photo sensitive additive (TMAE, TEA) mixed to counter gas:



- ☐ Solid photo cathode deposited:
- ✓ Thin caesium iodide (CsI) coating on cathode pads



Plastic scintillator dosimetry system

❖ Plastic scintillators are a relatively new development in radiotherapy dosimetry.

❖ The light generated (fast fluorescence: ≤ 3 ns) in the scintillator during its irradiation is carried away by an optical fibre to a PMT located outside the irradiation room.

❖ A typical setup requires two sets of optical fibres which are coupled to two different PMTs, allowing subtraction of the background radiation from the measured signal.

❖ Response of the scintillation dosimeter is linear in the dose range of therapeutic interest.

❖ Plastic scintillators are almost water-equivalent in terms of electron density and atomic composition. Typically, they match the water mass stopping power and mass energy absorption coefficient to within ±2% for the range of beam energies in clinical use including the kV region.

❖ Plastic scintillators is characterized with good reproducibility and long term stability so it is used in particle and nuclear physics.

❖ Plastic scintillators are independent of dose rate and can be used from 10 μGy/min (ophthalmic plaque dosimetry) to about 10 Gy/min (external beam dosimetry). They have no significant directional dependence and need no ambient temperature or pressure corrections.

Dead time of scintillation counter*:*

- The dead time or resolving time is the minimum time that can elapse after the arrival of two successive particles and still result in two separate pulses.
- For a scintillation counter, this time is equal to the sum of three time intervals.
  - ✓ Time it takes to produce the scintillation, essentially equal to the decay time of the scintillator (0.23 msec).
  - ✓ Time it takes for electron multiplication in the photo tube, of the order of 20-40 ns.
  - ✓ Time it takes to amplify the signal and record it by a scalar. The recovery time of commercial scales is of the order of 1 μs.
  - ✓ The time taken for amplification and discrimination is negligible.
- By adding the three above components, the resulting dead time of a scintillation counter is of the order of **1-5** μs.
- This is much shorter than the dead time of gas-filled counter, which is of the order of tens of hundreds of micro seconds.

★ Advantages:

– Fast response time (especially organic scintillators, ~ ns)

– Sensitive to deposited energy

– Construction and operation simple ➔ cheap and reliable

★ Disadvantages:

– Aging (especially plastic scintillators)

– Radiation damage (especially plastic scintillators)

– Hygroscopic (especially inorganic crystals)

– Low light output (especially gaseous scintillators)

– In combination with the optical readout sensitive to magnetic fields (e.g. when using photo multipliers)

The two main classes of scintillator are compared below:

- Organic scintillators: Nearly all organic scintillators are plastic since it is cheap and easily moulded.
- Inorganic scintillators: Higher density makes these useful for total absorption EM calorimeters

Semiconductor detectors

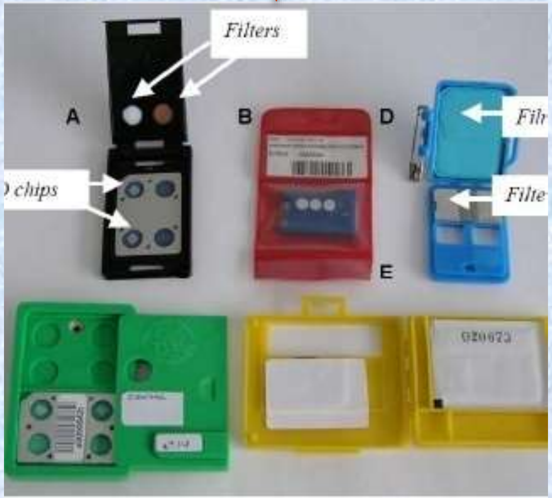
Radiation monitoring instruments are distinguished into:

Area survey meters (or area monitors)

Gas filled detectors:

➢ Ionization chambers
➢ Proportional counters
➢ GM counters

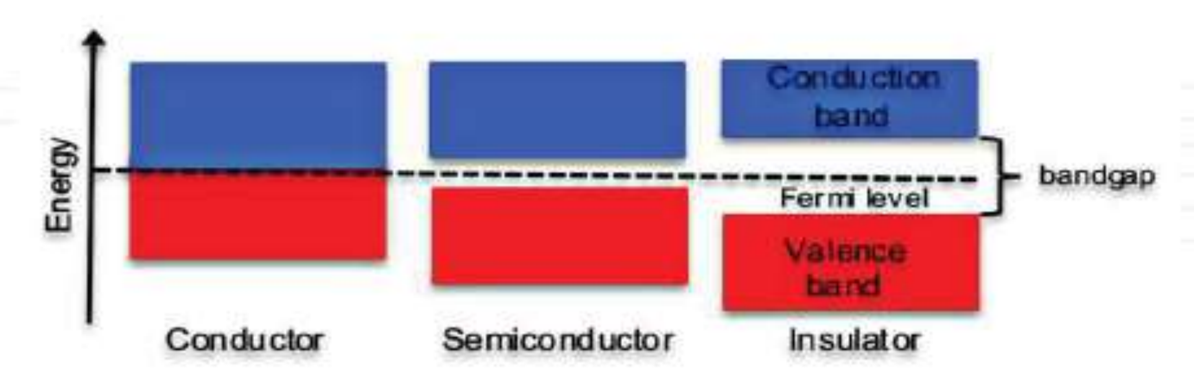
Personal dosimeters (or individual dosimeters)



Solid state detectors:

□ Scintillator
□ Semiconductor detectors

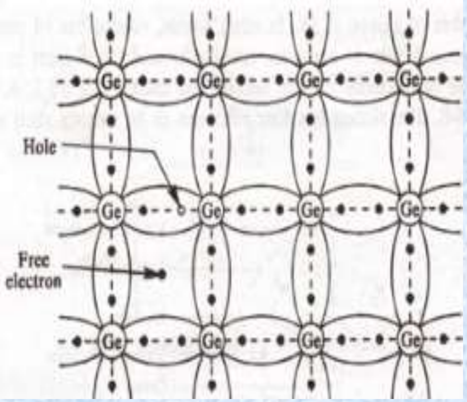
- Semiconductors are materials (inorganic or organic), which have the ability to control their electronic conduction depending on chemical structure, temperature, illumination, and presence of dopants.
- The name semiconductor (energy gap less than 4eV) comes from the fact that these materials usually present an intermediate conductivity between conductors and insulators.
- In solid-state physics, energy gap or band gap is an energy range between valence band and conduction band where electron states are forbidden.
- The valence band is the region where electrons are connected to the lattice atoms.
- The conduction band is the region that contains the energy levels where free electrons can move through the crystal structure.
- The width of the forbidden energy band is what categorizes the material as conductor, semiconductor, or insulator.

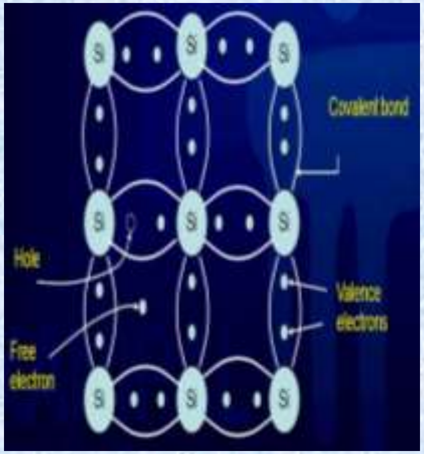


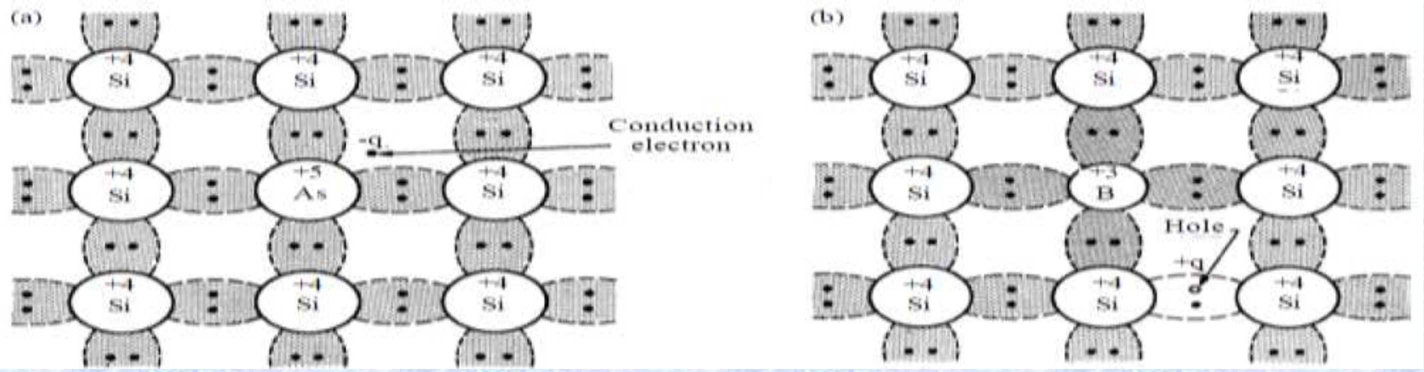
- There are many semiconductor materials, the best known are silicon (Si) and germanium (Ge).
- Germanium is more used than silicon for radiation detection because the average energy necessary to create an electron-hole pair is 3, 6eV for silicon and 2, 6eV for germanium, which provides the latter a better resolution in energy.
- In addition, in gamma spectroscopy, germanium is preferred due to its atomic number being much higher than silicon and which increases the probability of γ-ray interaction.
- Some of the compounds (or mixtures) of semiconductor materials include: Cadmium Telluride (CdTe), Cadmium Zinc Telluride (CdZnTe), Gallium Arsenide (GaAs), Mercurous Iodide (HgI2), and other materials.

INTRINSIC SEMICONDUCTOR

- A semiconductor in which there is a balance between the number of electrons in the conduction band and the number of holes in the valence band is called an **intrinsic semiconductor**.
- **The valence band is completely full and the conduction band completely empty.**
- **Both silicon and germanium are tetravalent, Each atom shares its four valence electrons with its four immediate neighbours, so that each atom is involved in four covalent bonds, but each bond is not so strong.**
- **When such energy is supplied, one of the covalent bond is broken and the electron (-ve carriers) moves away to the conduction band, a vacancy is created in the valence band. This vacancy is called hole (+ve charge carriers).**
- **The hole does remain stable and is quickly filled by the electron from the adjacent covalent bond.**
- **This way electron and hole moves in opposite direction. (electrons move in a direction opposite** to the applied electric field and **the holes move in the direction of the electric field).**
- **This electron-hole pairs is referred to as intrinsic conduction.**







Bond representation for (a) n type and (b) p type semiconductor

EXTRINSIC SEMICONDUCTORS

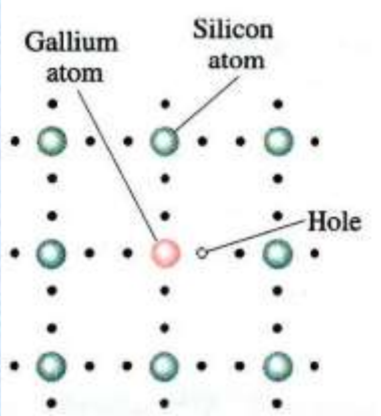
✓ Impurities from III or V groups are added, they are called doping semiconductor is called extrinsic semiconductor. This addition of small amounts of impurities drastically affects its properties.

✓ N type (N, P, As, Sb, Bi): These atoms have 5 outer electrons in their outermost orbital to share with negibouring atoms and are commonly called “pentavalent” impurities.

✓ Substituting a arsenic atom with 5 valence electron for a Si atom in a Si crystal leaves as extra unbonded electron that is relatively free to move around the crystal. As each impurity atom “donates” one electrons, pentavalent atoms are generally known as “donor” **(positively charged)**

✓ Therefore, each arsenic atom added, one free electrons will be available in Si crystal. A small amount of arsenic impurity provides enough atoms to supply millions of free electrons.

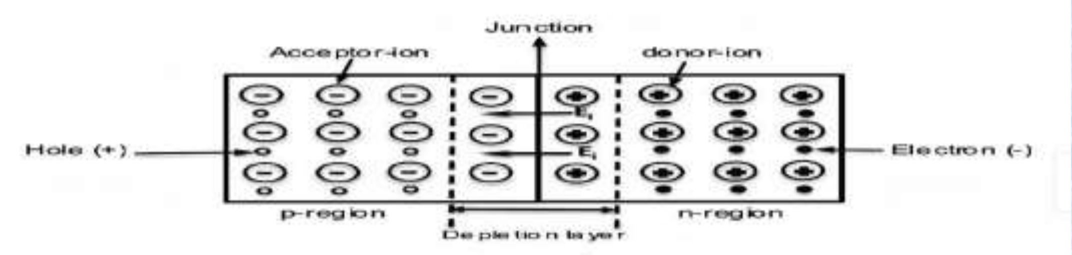
- ✓ P type (B, Al, Ga, In, Tl): These atoms have 3 outer electrons (Trivalent) in their outermost orbital to share with negibouring atoms.
- ✓ Substituting gallium atom with 3 valence electrons for a Si atom in a Si crystal leaves a hole (a bond missing an electron) that is relatively free to move around the crystal.
- ✓ A neighbouring electron is attracted to it and will try to move into the hole to fill it.
- ✓ However, the electron filling the hole leaves another hole behind it as it moves.
- ✓ As each impurity atom generates a hole known as "**acceptors**" as they are continually "accepting" extra or free electrons. Acceptors are negatively charged.
- ➢ Both *n*-type and *p*-type materials have much greater conductivity than pure semiconductors.



Semiconductor detector

- ❖ Semiconductors detectors belong to the class of solid state detectors.
- ❖ They act like solid-state ionization chambers on exposure to radiation.
- ❖ The sensitivity of solid state detectors is higher than that of gas-filled detectors because:
  - ✓ Average energy required to produce an ion pair is one order less
  - ✓ Material density is compared to gases
- ❖ The high sensitivity of semiconductor detectors helps in miniaturizing radiation-monitoring instruments.
- ❖ Example:
  - ✓ Commercial electronic pocket dosimeter based on a semiconductor detector and
  - ✓ Survey instruments in gamma spectroscopy systems.

- **Operation similar to gas-filled detectors, but chamber filled with solid semiconductor material**
- Normally, a semi conducting substance will have an equal number of electrons and holes.
- Semiconductor materials can be modified or doped with electrons (**excess of electrons)** is referred to as "n-type" and that with excess holes as "p-type".
- If an electric field is applied across the p-n junction to have a forward bias with the positive terminal connected to the p-type a current can flow across the junction.
- If a reverse bias, no current is observed; the excess electrons and holes are swept away from the junction, forming a thin charge "depletion layer" at the interface.
- When the charged particles cross the depletion layer, electron-hole pairs are produced.
- These cause a current across the junction and produce a signal.
- Thus, the p-n junction functions like an ion chamber with a sensitive volume corresponding to the depletion layer.
- **Benefits compared to other types: Very little fluctuation in output for a given energy of radiation and fast response time**



- ❑ Silicon diode dosimeter is a p-n junction diode. The diodes are produced by taking n-type or p-type silicon and counter-doping the surface to produce the opposite type material. These diodes are referred to as n-Si or p-Si dosimeters, depending upon the base material.
- ❑ Both types of diodes are commercially available, but only the p-Si type is suitable for radiotherapy dosimetry, since it is less affected by radiation damage and has a much smaller dark current.
- ❑ Radiation produces electron-hole (e-h) pairs in the body of the dosimeter including the depletion layer. The charges (minority carriers) produced in the body of the dosimeter, within the diffusion length, diffuse into the depleted region. They are swept across the depletion region under the action of the electric field due to the intrinsic potential. In this way a current is generated in the reverse direction in the diode.
- ❑ Diodes are more sensitive and smaller in size compared to typical ionisation chambers. They are relative dosimeters and should not be used for beam calibration, since their sensitivity changes with repeated use due to radiation damage.

MOSFET dosimeter

❖ The Metal-Oxide Semiconductor Field Effect Transistor (MOSFET), a miniature silicon transistor, seems to be a promising candidate for medical dosimetry.

❖ MOSFETs are small in size even compared to diodes, offering very little attenuation of the beam when used for in in-vivo dosimetry. They require a special read-out facility.

❖ A single dosimeter can cover the full energy range of photons and electrons, although the energy response should be examined, since it varies with radiation quality.

❖ Similarly to diodes, MOSFETs exhibit a temperature dependence. As they show non-linearity of response with total absorbed dose, regular sensitivity checks are required.

❖ MOSFETs are also sensitive to changes in the bias voltage during irradiation (it must be stable) and their response drifts slightly after the irradiation (the reading must be taken in a specified time after exposure). They have a limited life-span.

❖ MOSFETs have been in use for the past few years in radiotherapy applications, such as surface dose measurements, radio surgery, in vivo dosimetry, and brachytherapy measurements.

MOSFET dosimetry systems

Physical principle:

- Ionizing radiation generates charge carriers in the Si oxide.
- The charge carries moves towards the silicon substrate where they are trapped.
- This leads to a charge buildup causing a change in threshold voltage between the gate and the silicon substrate.

Measuring Principle:

✓ MOSFET dosimeters are based on the measurement of the threshold voltage, which is a linear function of absorbed dose.

✓ The integrated dose may be measured during or after irradiation.

Advantages

❑ MOSFETs are small

❑ Although they have a response dependent on radiation quality, they do not require an energy correction for mega-voltage beams.

❑ During their specified lifespan they retain adequate linearity.

❑ MOSFETs exhibit only small axial anisotropy (±2% for 360º).

Disadvantages

❑ MOSFETs are sensitive to changes in the bias voltage during irradiation (it must be stable).

❑ Similarly to diodes, they exhibit a temperature dependence.

Chemical dosimetry systems

- In chemical dosimetry, the ionizing radiation produces chemical changes in the medium that can be measured by using a suitable measuring system.
- Oxidation, reduction, and chemical dissociation are the principal mechanisms of chemical detectors.
- The intensity of these changes is characterized by radiation chemical yield (G), which is defined as a number of molecules, ions, atoms, or free radicals of product or dissolved reaction components for 100 eV of absorbed energy, or even defined as the mean number of moles produced/destroyed by mean energy transmitted to the matter

$$G = \frac{\overline{n}}{\overline{E}}$$

where n¯ is the mean moles [illegible] and E¯ is the mean transmitted energy.

- GSI unit is moles per joule

- The most widely used chemical dosimetry standard is the Fricke dosimeter.
- The fricke dosimetry system provides a reliable means for measurement of absorbed dose to water by ferrous ions oxidation.
- The dosimeter consists of a solution with 1 mmol/l ferrous sulfate (or ferrous ammonium sulfate), 1 mol/l NaCl, and 0.4 mol/l sulfuric acid.
- When the frick solution is irradiated, the ferrous ions (Fe^{2+}), are oxidized by radiation to ferric ions (Fe^{3+}).
- Radiation induced ferric ion concentration can be determined using spectrophotometry, which measures the absorbance (224 and 304 nm) of the solution.
- In this case, G-value is defined as the number of moles of ferric ions produced per joule of the energy absorbed in the solution.
- The usual range of the fricke dosimeter is from 30Gy to 400 Gy.
- Fricke dosimeter response is expressed in terms of its sensitivity, known as the radiation chemical yield, G-value, and defined as the number of moles of ferric ions produced per joule of the energy absorbed in the solution.
- Chemical dosimetry standard is realized by the calibration of a transfer dosimeter, in a total absorption experiment and the subsequent application of the transfer dosimeter in a water phantom, in reference conditions.

- The response of the Fricke solution is determined first using the total absorption of an electron beam. An accurate determination of the energy response of the transfer instrument is necessary, i.e., knowing the electron energy, the beam current and the absorbing mass accurately, the total absorbed energy can be determined and related to the change in absorbance of the Fricke solution. Next, the absorbed dose to water at the reference point in a water phantom is obtained using the Fricke dosimeter as the transfer dosimeter.

Gel dosimetry systems

- ☐ Gel dosimetry systems are the unique true 3D dosimeters suitable for relative dose measurements.
- ☐ Gel dosimetry can be divided in two types:
  - ✓ Fricke gels based on the well established Fricke dosimetry and
  - ✓ Polymer gels.
- ☐ A major limitation of the fricke gel systems is the continual post-irradiation diffusion of ions resulting in a blurred dose distribution.

- In polymer gel monomers such as acrylamid are dispersed in a gelatine or agarose matrix. Upon radiation exposure, monomers undergo a polymerization reaction resulting in a 3D polymer gel matrix which is a function of absorbed dose that can be evaluated using NMR, x-ray computer tomography, optical tomography, vibrational spectroscopy or ultrasound.
- A number of various polymer gel formulations are available including polyacryl-amide gels generally referred as PAG gels (e.g., BANG^{TM} gel) and the new normoxic gels (e.g., MAGIC gel); the latter are not sensitive to the presence of atmospheric oxygen.
- There is a semi-linear relationship between the NMR relaxation rate and the absorbed dose at a point in the gel dosimeter. Hence, by mapping the relaxation rates using an NMR scanner, the dose map can be derived by computation and by proper calibration.
- No significant dose rate effects in polymer gels have been observed using NMR evaluation, although dose response depends on temperature at which the dosimeter is evaluated. The strength of the magnetic field during evaluation may also influence the dose response. Care should be taken of post-irradiation effects such as continual polymerization, gelation and strengthening of the gel matrix that may lead to the image distortion.
- Gel dosimetry is a highly promising relative dosimetry technique that may prove particularly useful for dose verification in complex clinical situations (e.g., intensity modulated radiotherapy), in anatomically shaped phantoms, and for evaluation of doses in brachytherapy, including cardiovascular brachytherapy.