Solid Scintillators

General

General

The Scintillation Process

1. Ionizing radiation deposits energy in the scintillator.

2 At least some of the absorbed energy causes electrons in the scintillator to go to a higher energy level.

3. At least some of these electrons immediately fall back down to a lower energy level. As they do, they each emit a photon of light. Collectively, the photons of light form a flash, or scintillation.

4. Each scintillation is converted into an electronic pulse by a photomultiplier tube (PMT).

General

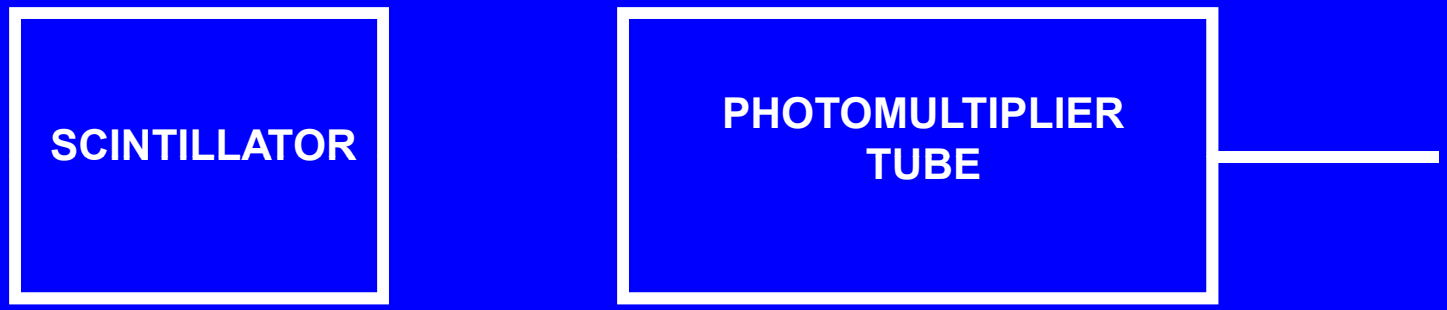
Two Points

One particle of radiation (e.g., a beta particle, gamma ray, or neutron) interacting in the scintillator results in one scintillation (flash) of light and, therefore, one pulse.

The greater the energy transferred to the scintillator, the greater the number of excited electrons, and the greater the number of photons of light emitted in the scintillation. In other words, the greater the deposition of energy, the brighter the flash of light and the larger the pulse.

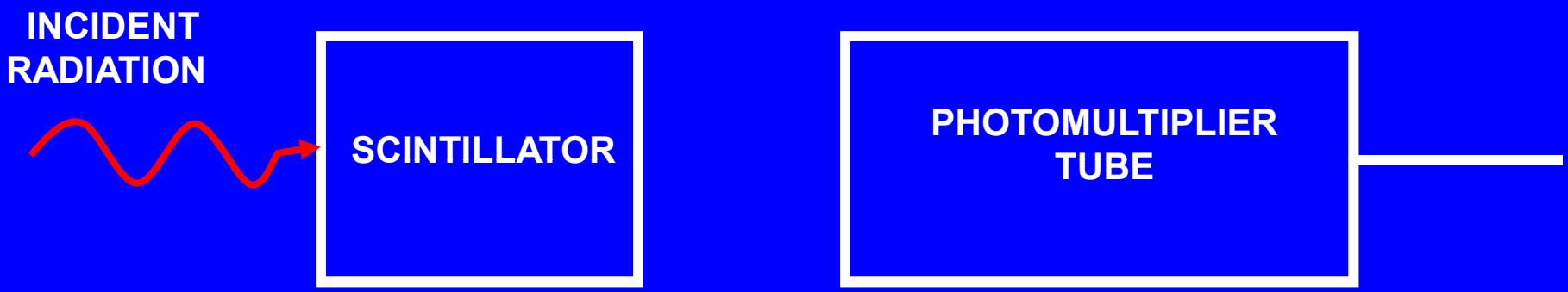
General

The Scintillation Process



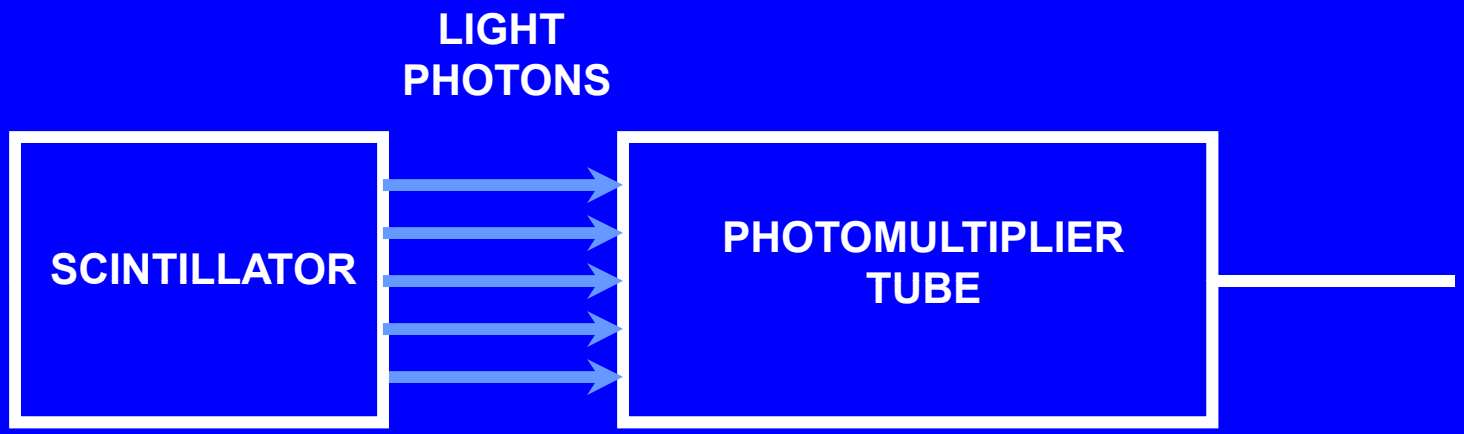
General

The Scintillation Process



General

The Scintillation Process

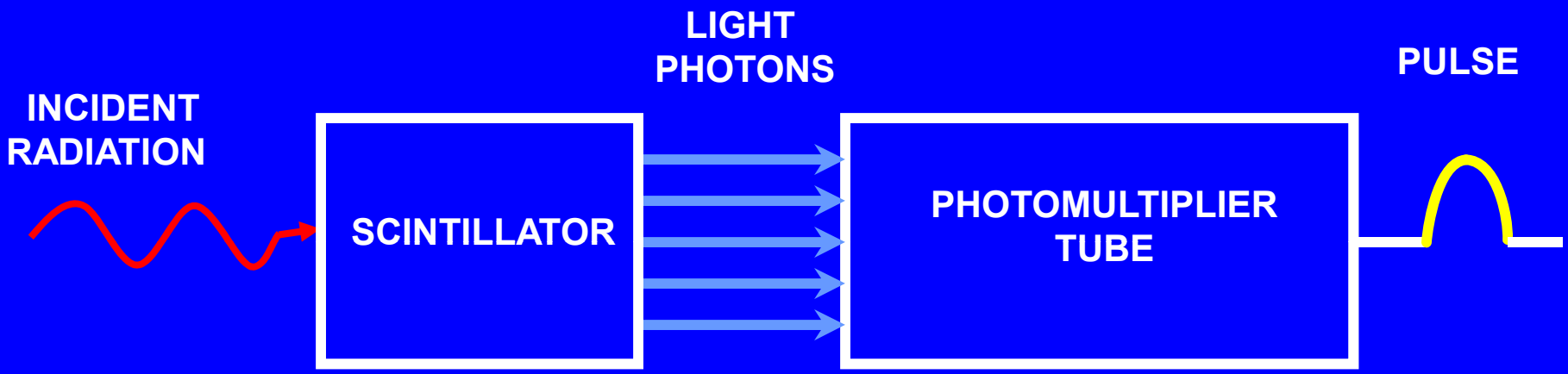


General

The Scintillation Process

General

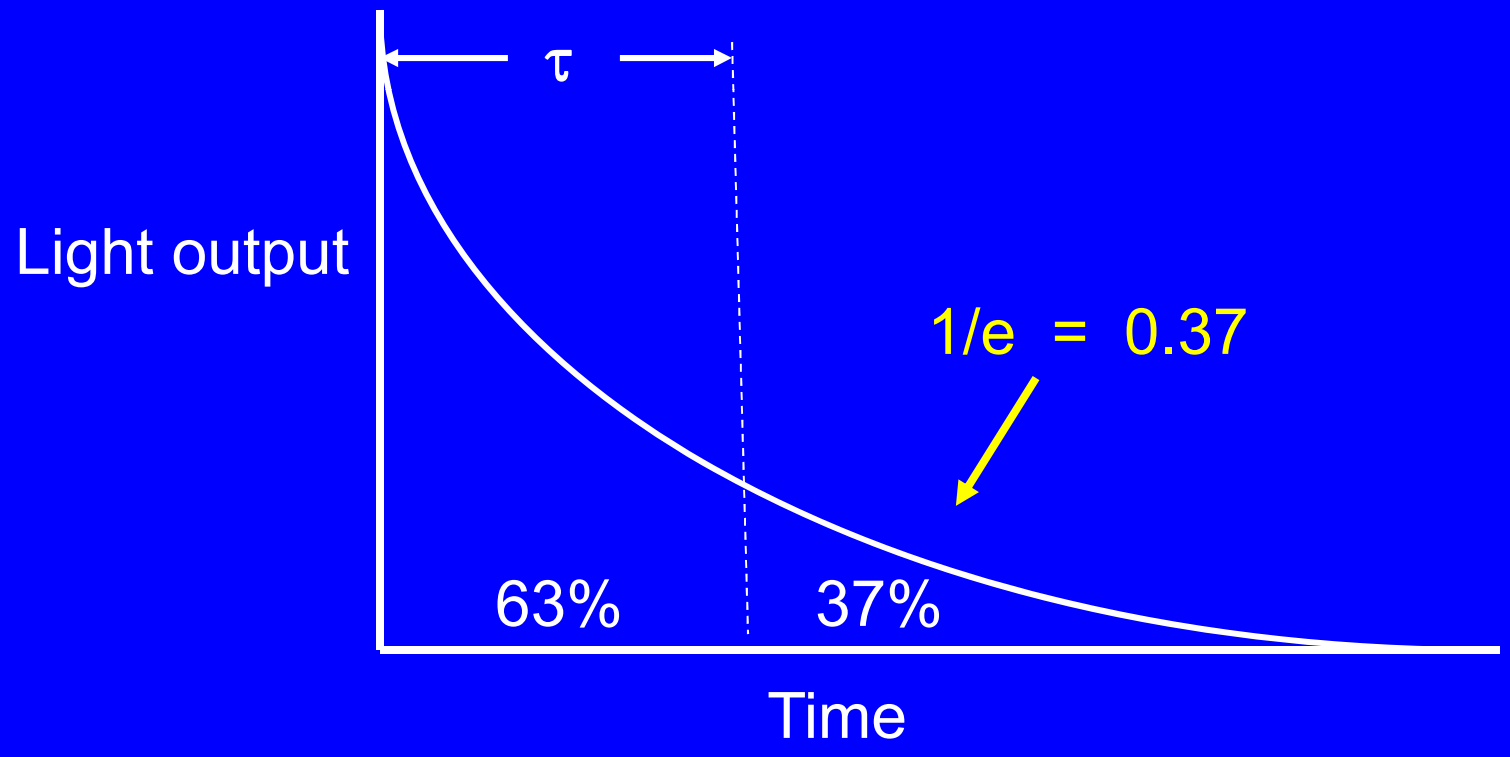
The Scintillation Process



General

Decay Time

The decay time (τ) is the time required for the emission of 63% of the light photons produced in a scintillation
In almost all cases, the shorter the decay time is, the better.



General

Properties of an Ideal Scintillator

1. The probability of the radiation interacting with the scintillator should be high.
2. A large portion of the absorbed radiation energy should be emitted as light.
3. A linear proportionality should exist between the energy deposited in the scintillator and the light produced.
4. The emission of light should occur as quickly as possible,
5. The scintillator emission spectrum should overlap the photomultiplier tube (or photodiode) absorption spectrum.

General

Types of Scintillating material

Chemically, the scintillating material might be:

Organic

Inorganic

Physically, the scintillating material might be a:

Gas

Liquid

Solid

General

The Scintillation Process

Inorganic scintillators might be a:

Gas (e.g., He, Xe)

Solid crystal (e.g., NaI, ZnS, CsI, LiI, LSO, $LaBr_3$)

Organic scintillators might be a:

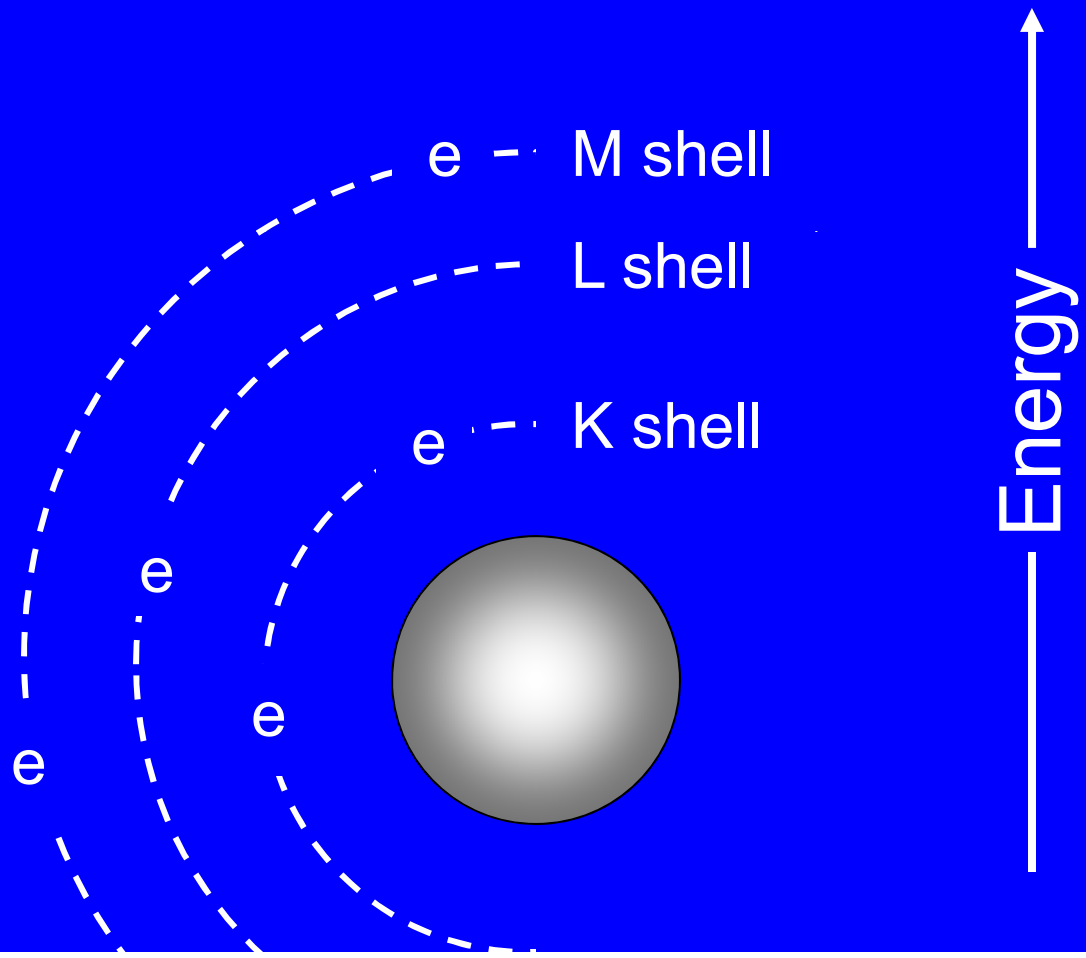
Solid crystal (e.g., anthracene, stilbene, naphthalene)

Distributed throughout the volume of a liquid or polymerized plastic (e.g., PPO in polystyrene)

Band Theory of Solids

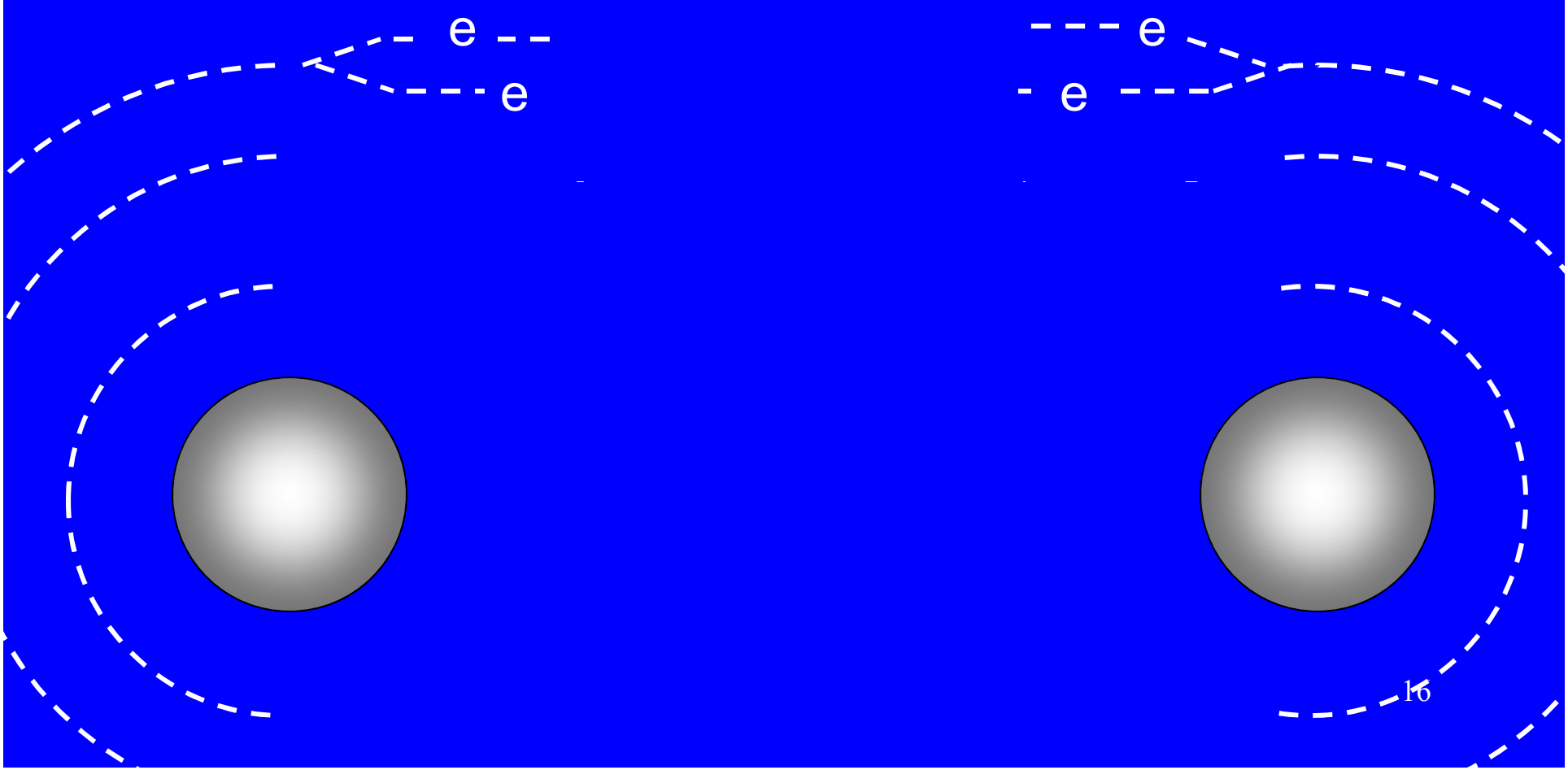
Band Theory of Solids

- The energy levels of electrons in an atom are referred to as shells.



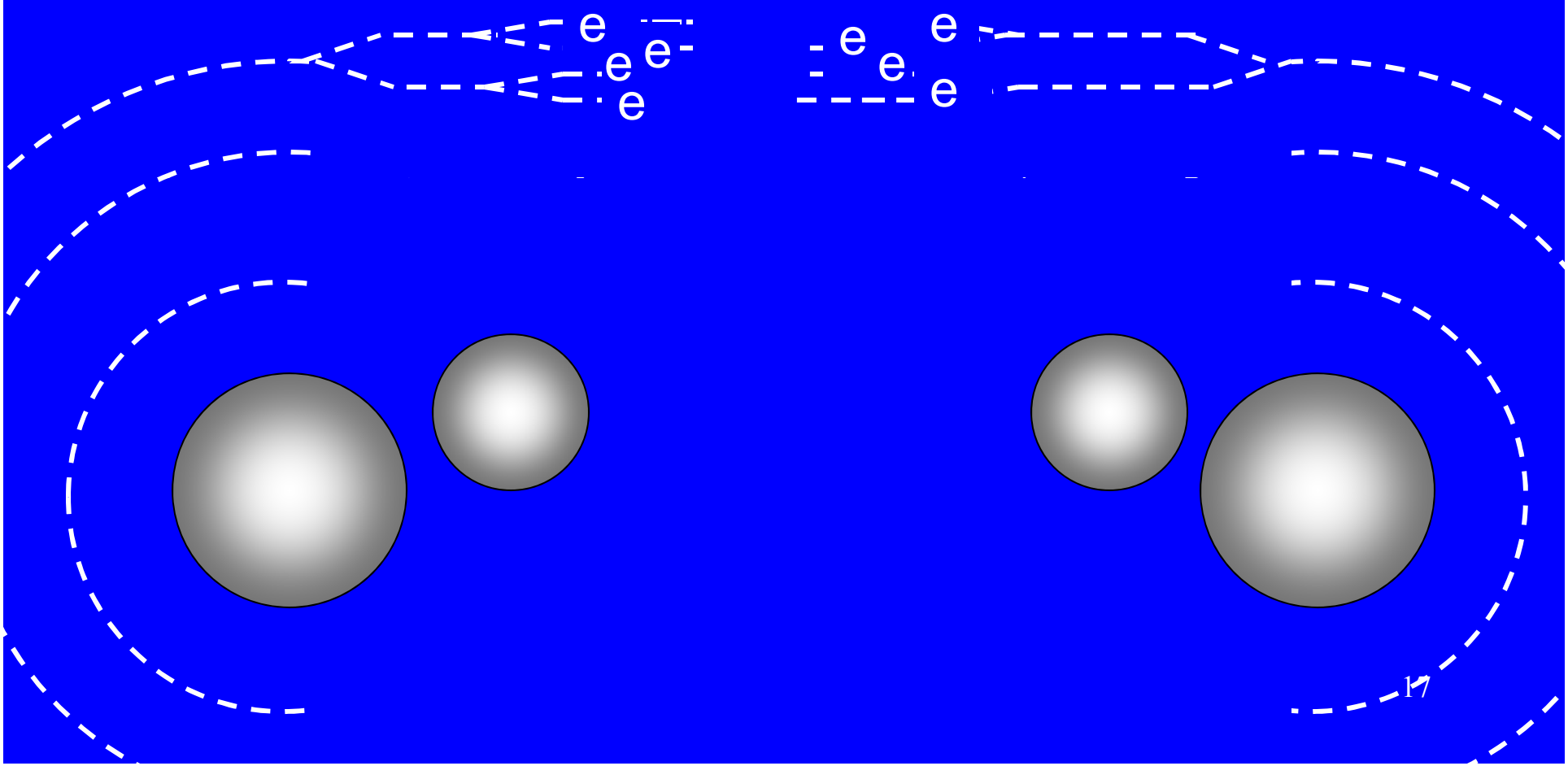
Band Theory of Solids

- When atoms are brought close to each other, the highest shell occupied by electrons, the valence shell, splits.



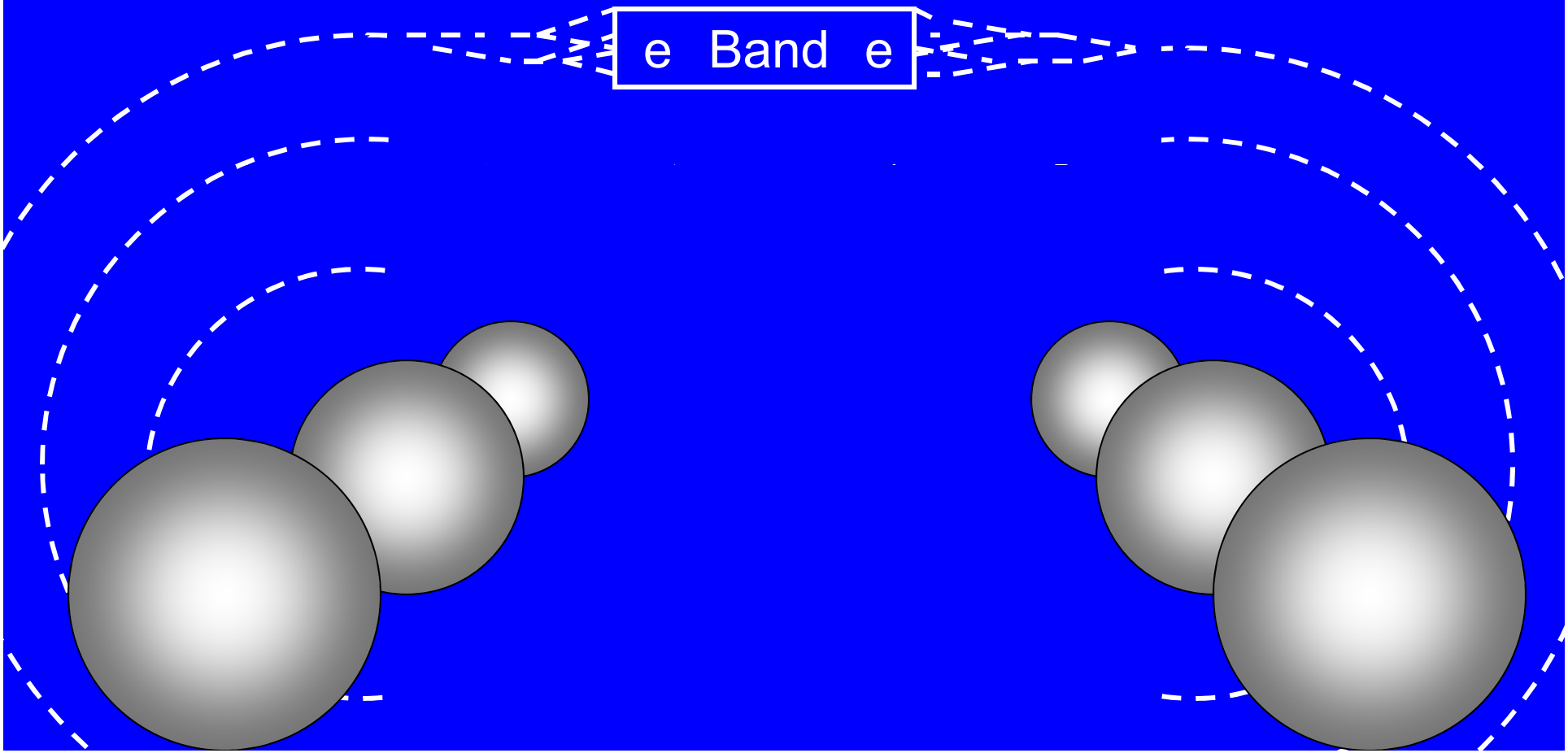
Band Theory of Solids

- The greater the number of atoms, the greater the splitting.



Band Theory of Solids

- When many atoms combine to form a solid, the valence shell has split so many times that it forms a continuum of energies, i.e., a band.



Band Theory of Solids

- The highest energy band occupied by electrons is the valence band.

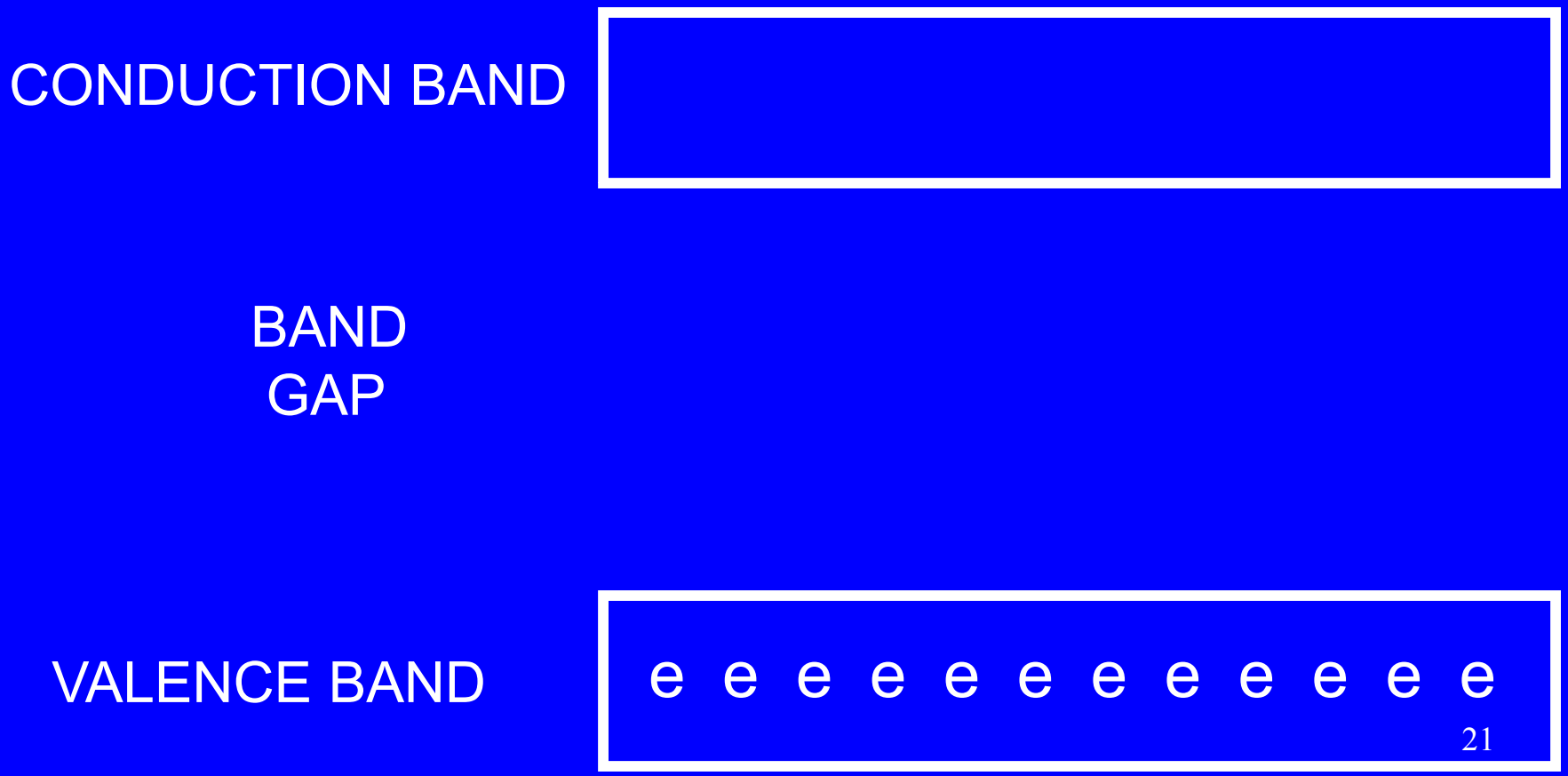
e Valence Band e

Band Theory of Solids

- The empty energy band above the valence band is the conduction band.

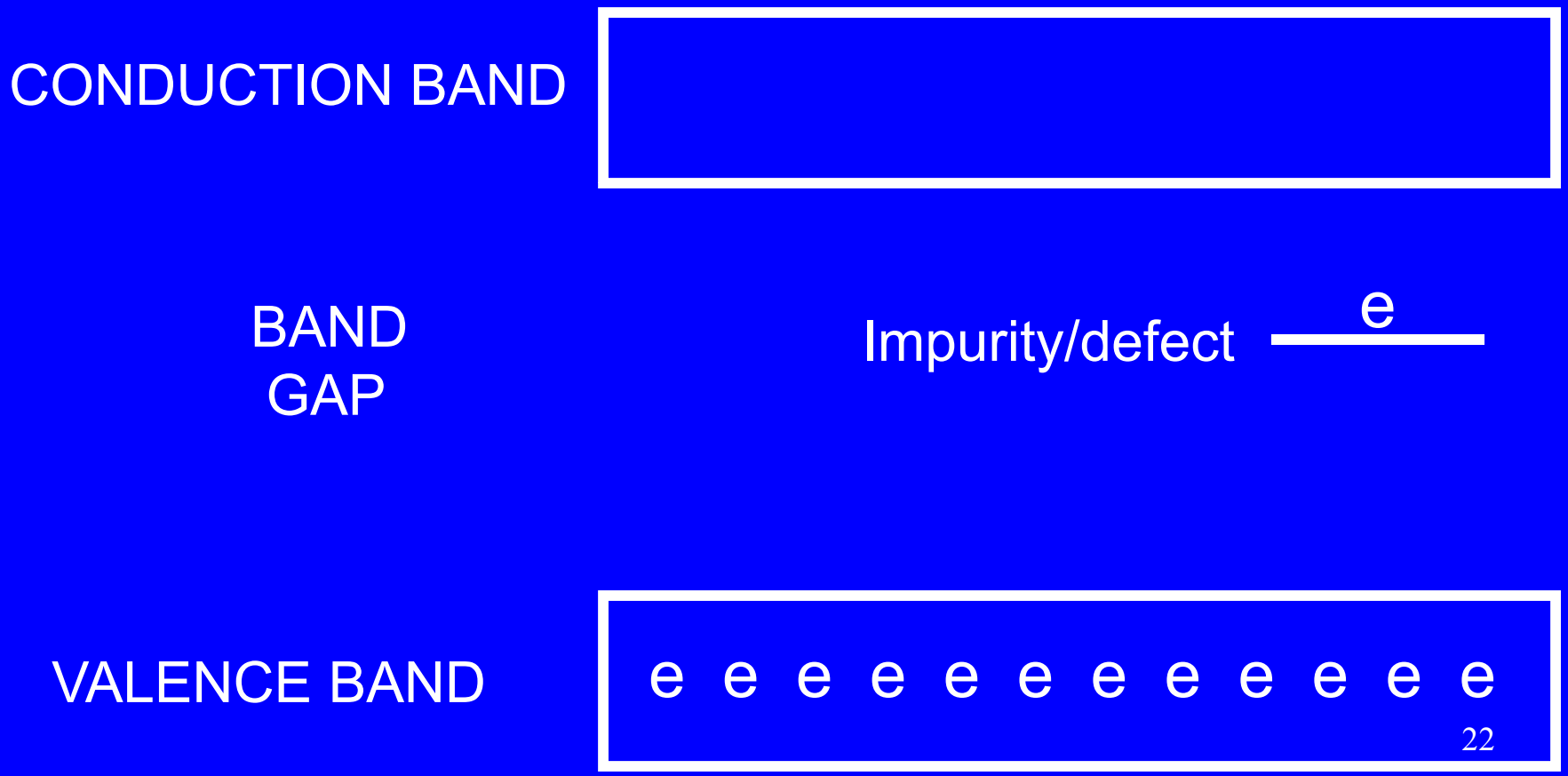
Band Theory of Solids

- The range of energies between the valence band and the conduction band is called the band gap or forbidden band.



Band Theory of Solids

- In a pure material, electrons cannot possess energies in the band gap. If there are impurities or defects, they can.



Band Theory of Solids

- **Insulator**. The valence band in an insulator is full. As such, the electrons are immobile and the material does not conduct electricity.
- **Conductor**. The valence band in a conductor is not full. As such, the electrons are mobile and the material conducts electricity.
- **Semiconductor**. The valence band in a semiconductor is full. As such, the electrons are immobile and the material does not conduct electricity.

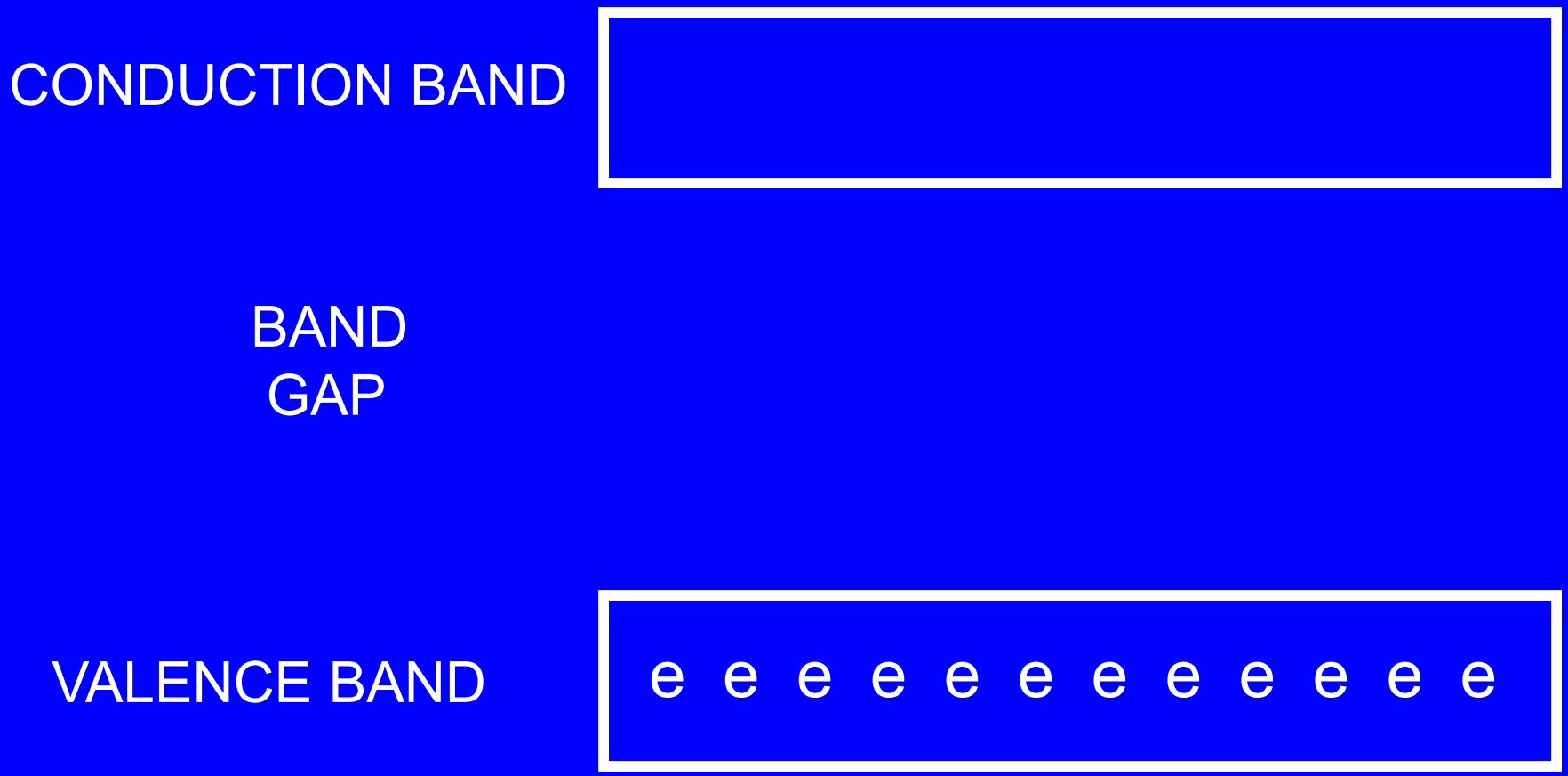
Band Theory of Solids

- The difference between a semiconductor and an insulator is the width of the band gap.
- In an insulator, the band gap is greater than 5 electron volts. In a semiconductor, the band gap is less than 5 electron volts (one electron volt is typical).

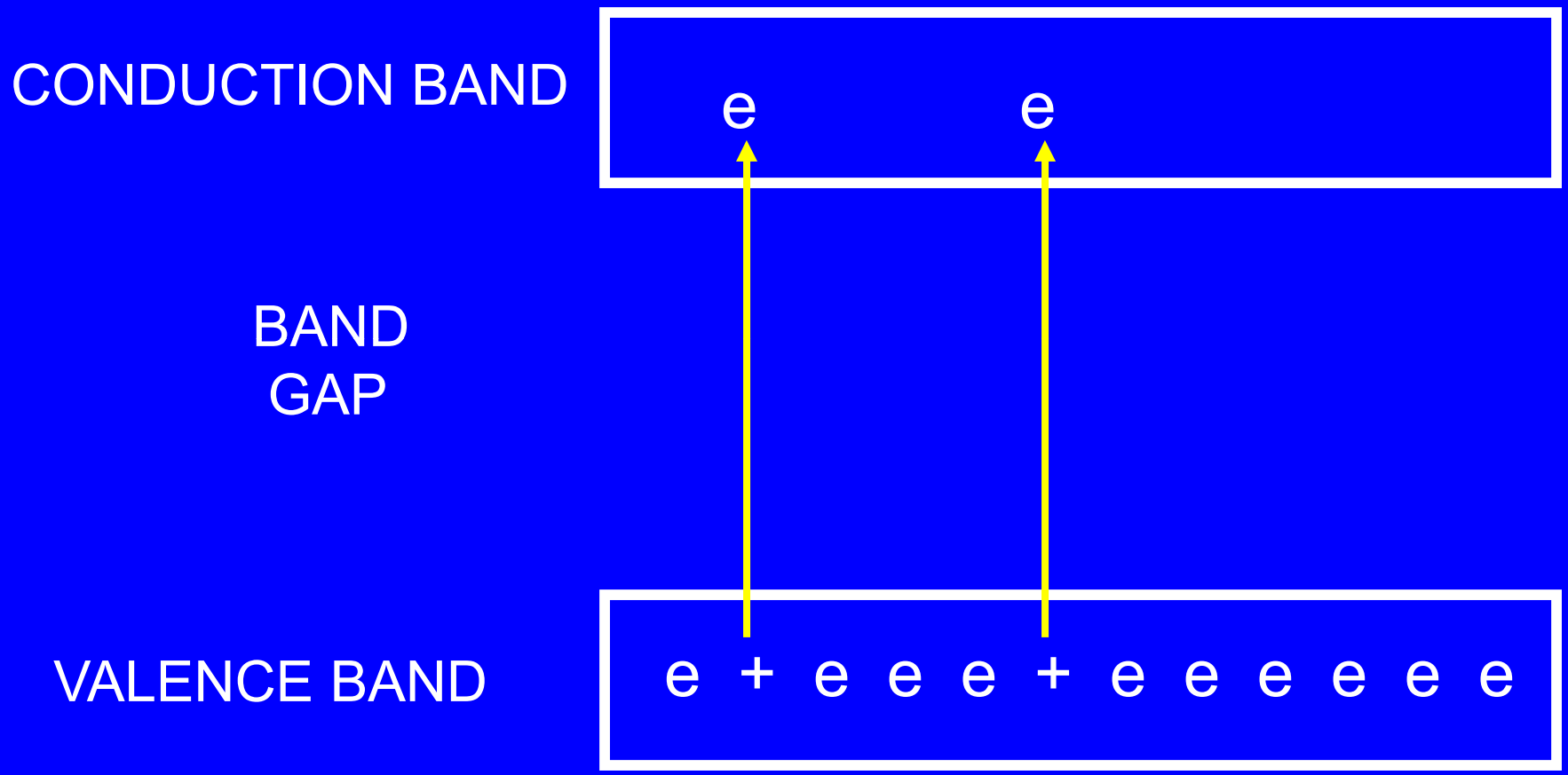
Inorganic Scintillators are insulators. This means that the band gap is greater than 5 eV.

The Scintillation Process and the Importance of Activators

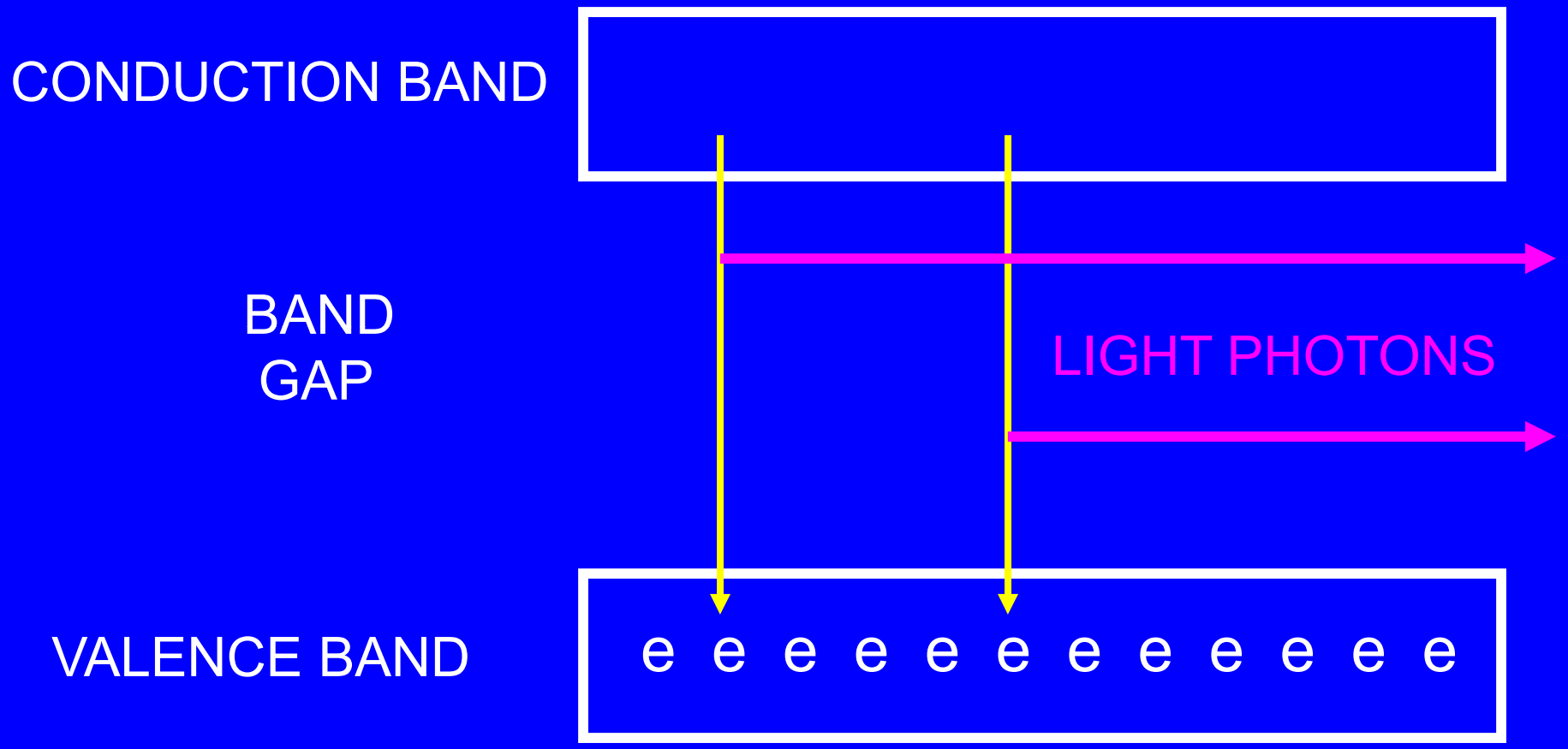
The Scintillation Process – no activator



The Scintillation Process – no activator



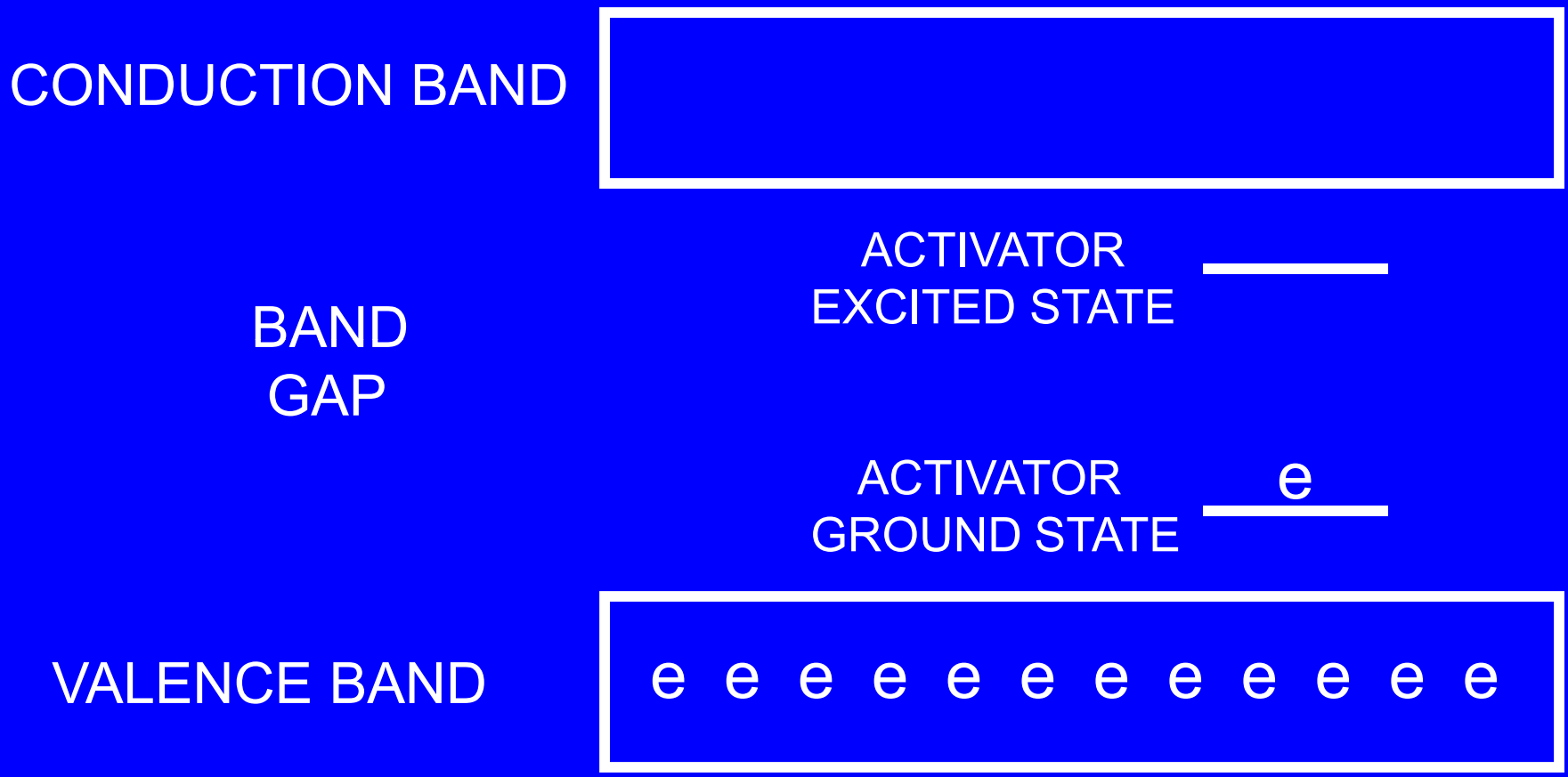
The Scintillation Process – no activator



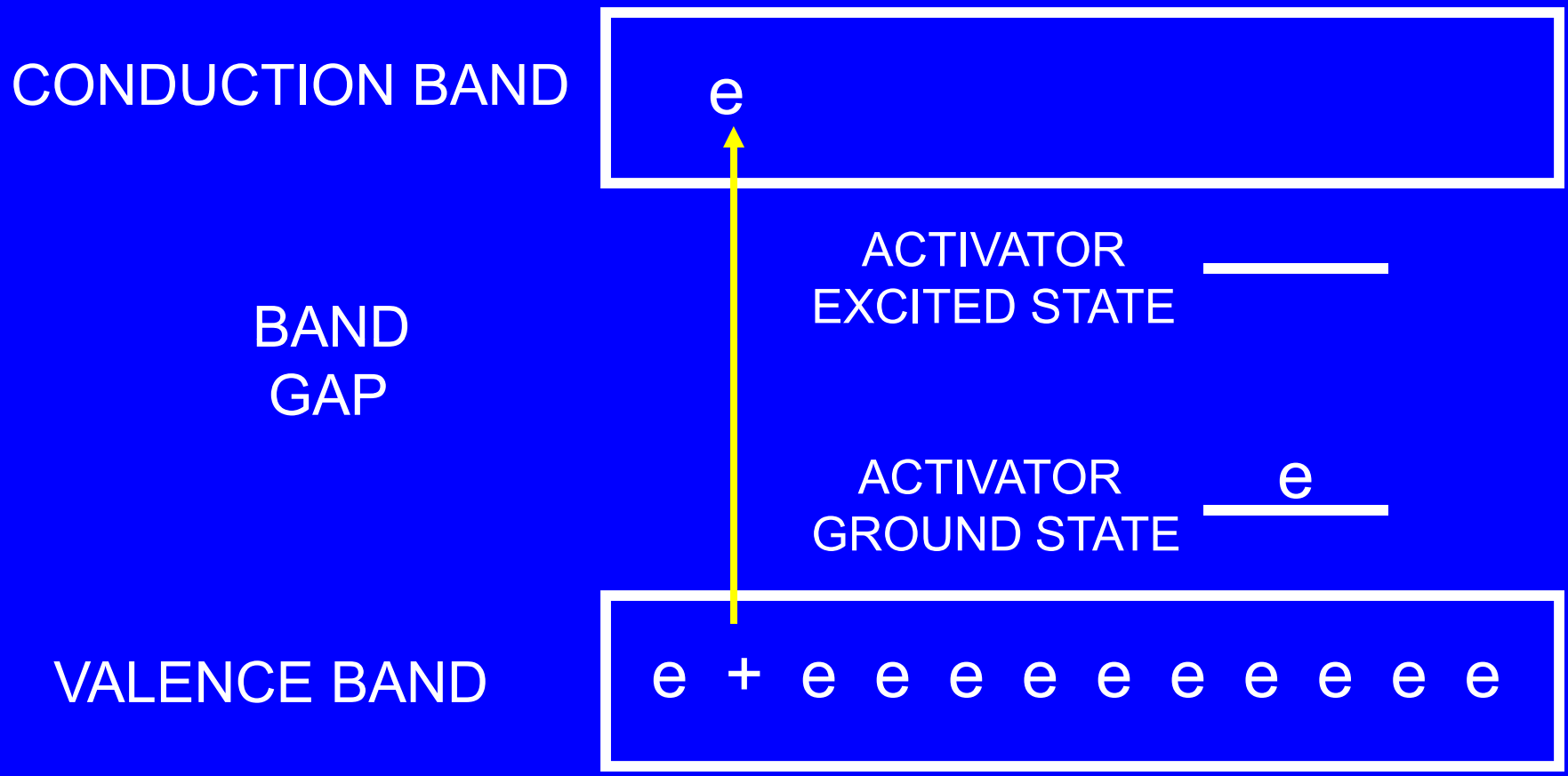
The Scintillation Process - with activator

- Unfortunately, the light that is emitted by a pure insulating material is of too high an energy.
- The short wavelength of the light is not readily detected by the photomultiplier tube.
- To reduce the energy (lengthen the wavelength) an activator impurity is added to the crystal.

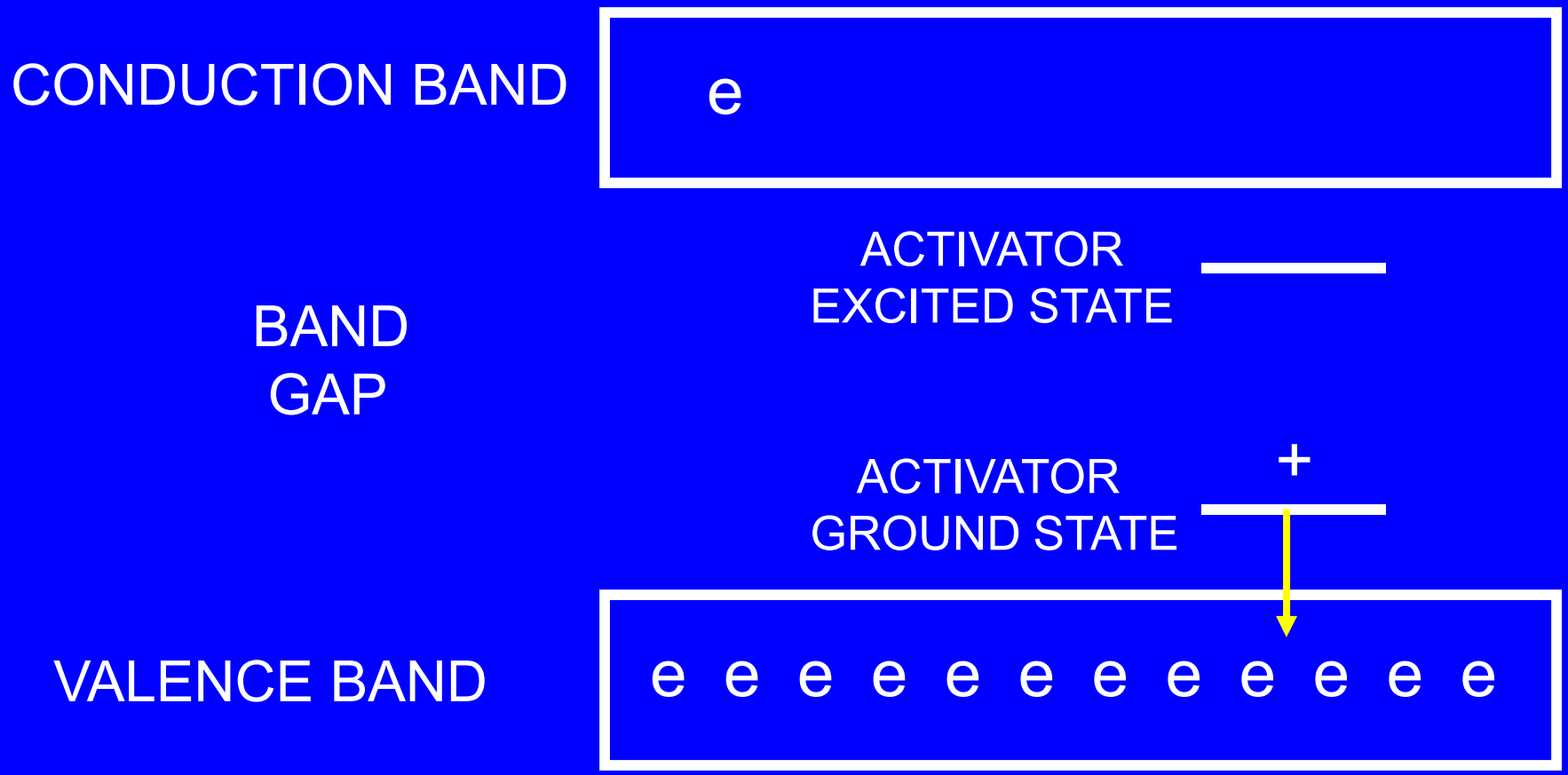
The Scintillation Process - with activator



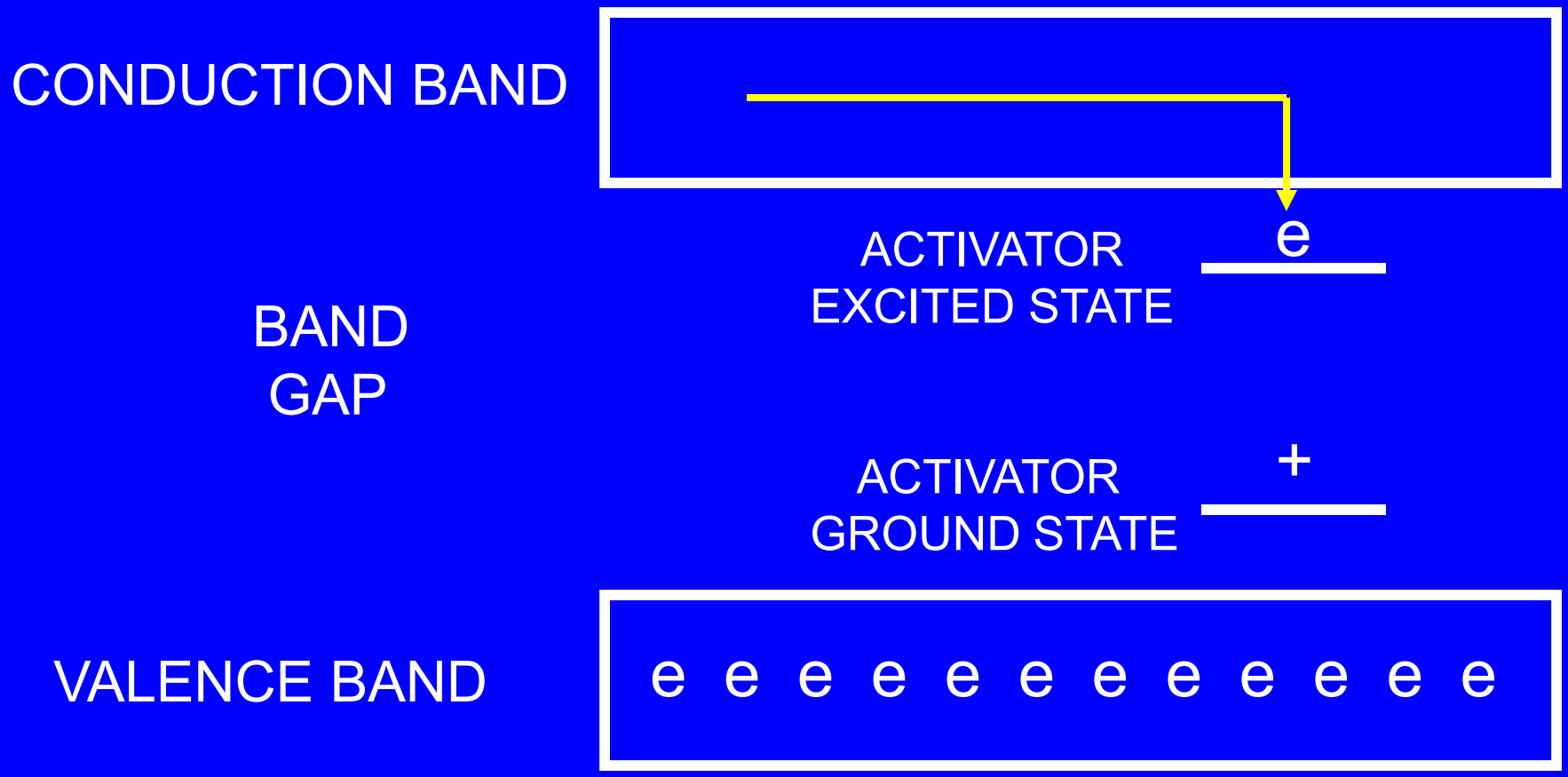
The Scintillation Process - with activator



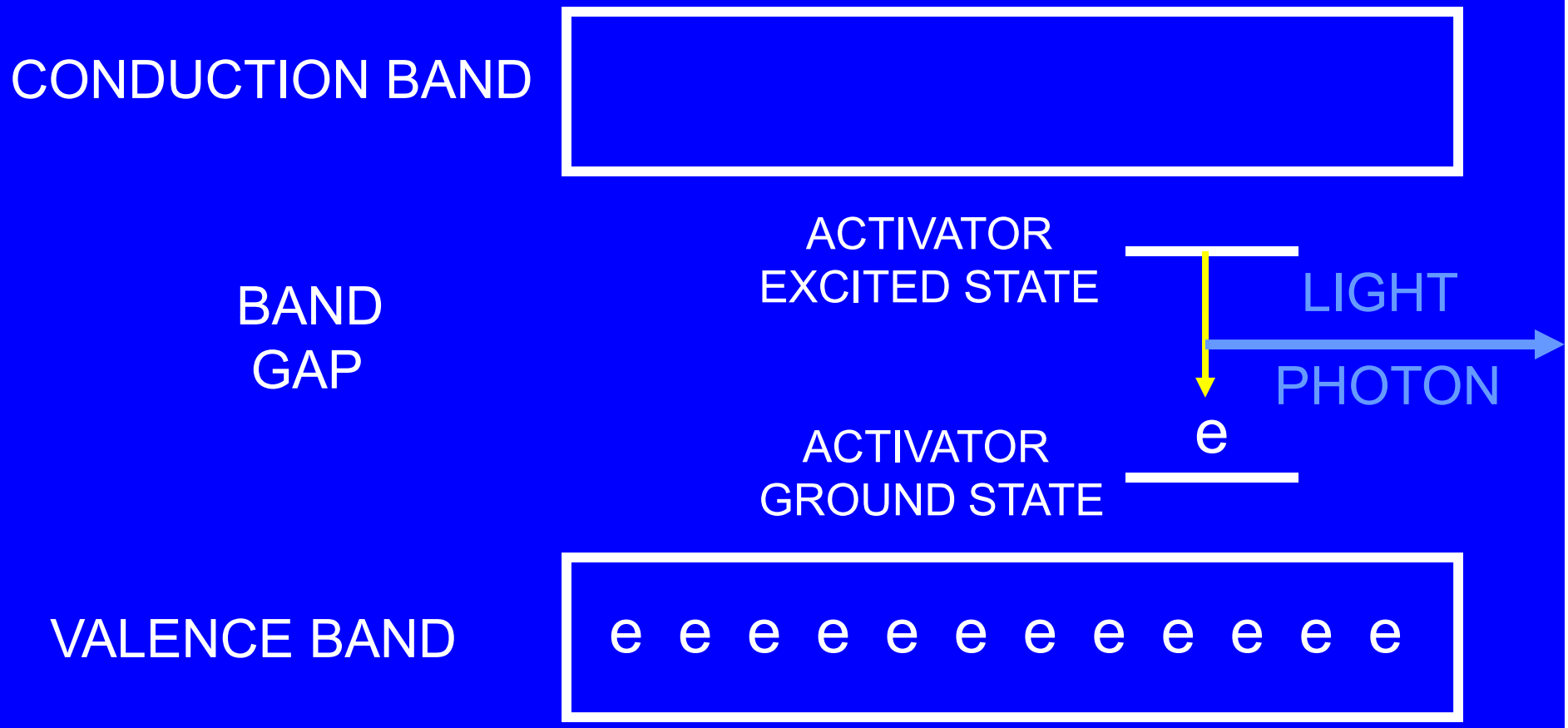
The Scintillation Process - with activator



The Scintillation Process - with activator



The Scintillation Process - with activator



Inorganic Scintillators

Inorganic Scintillators

Sodium Iodide (NaI)

Applications of NaI scintillation detectors include:

- Detection of gamma rays and x-rays
- Gamma spectroscopy
- Exposure rate measurements (e.g., uR meter)

Inorganic Scintillators

Sodium Iodide (NaI)

- NaI crystal activated with thallium
- Density 3.67 g/cm^3
- Clear colorless crystal
- Sodium's atomic number : 11
- Iodine's atomic number: 53
- Extremely high light yield – ca. 12% of energy deposited by gamma ray or x-ray is emitted as light
- 52 – 56 x 10^3 photons/MeV
- Large afterglow: 4% after 2 ms
  0.3-0.5% after 6 ms

Inorganic Scintillators

Sodium Iodide (NaI)

- Long decay time (230 ns) which limits their effectiveness at high count rates
- Maximum emission wavelength: 415 nm
- NaI crystals are fragile, susceptible to both thermal and mechanical shock
- Hygroscopic therefore hermetically sealed
- Can be grown very large (e.g., 4” x4” x 16”)

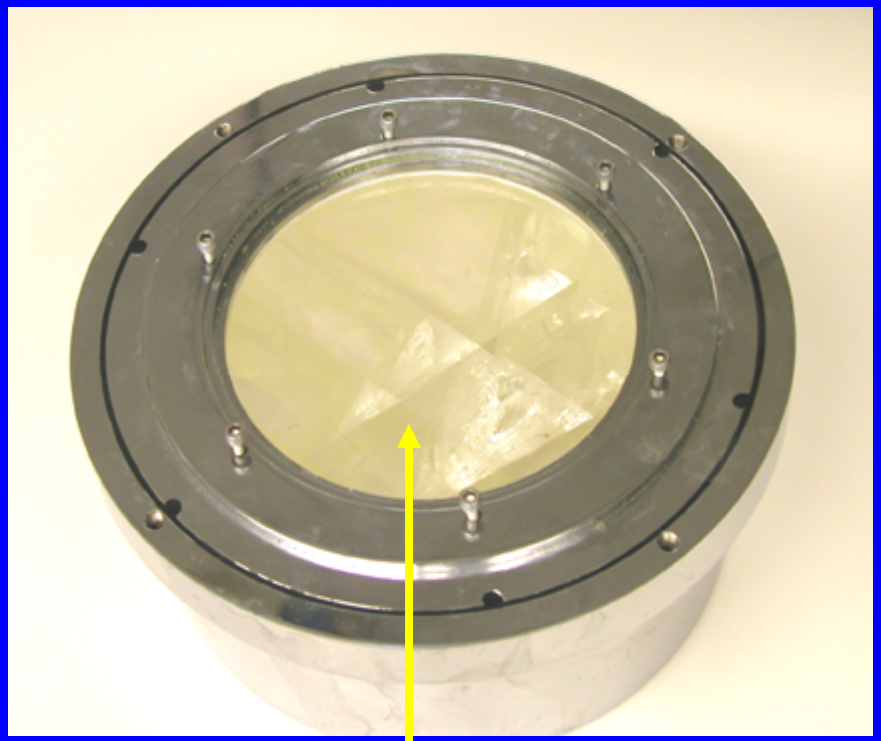
Inorganic Scintillators

Sodium Iodide (NaI)

- Typical crystal sizes for survey work (locating gamma emitters) are 1” to 2.” The background count rates increase with the crystal size and might range from 1000 to 10,000 cpm
- Typical crystal size for gamma spectroscopy in the lab: 3” x 3”
- Resolution: 7 to 8%

Inorganic Scintillators

Sodium Iodide (NaI)



Cracked NaI Crystal

Damaged NaI Crystals

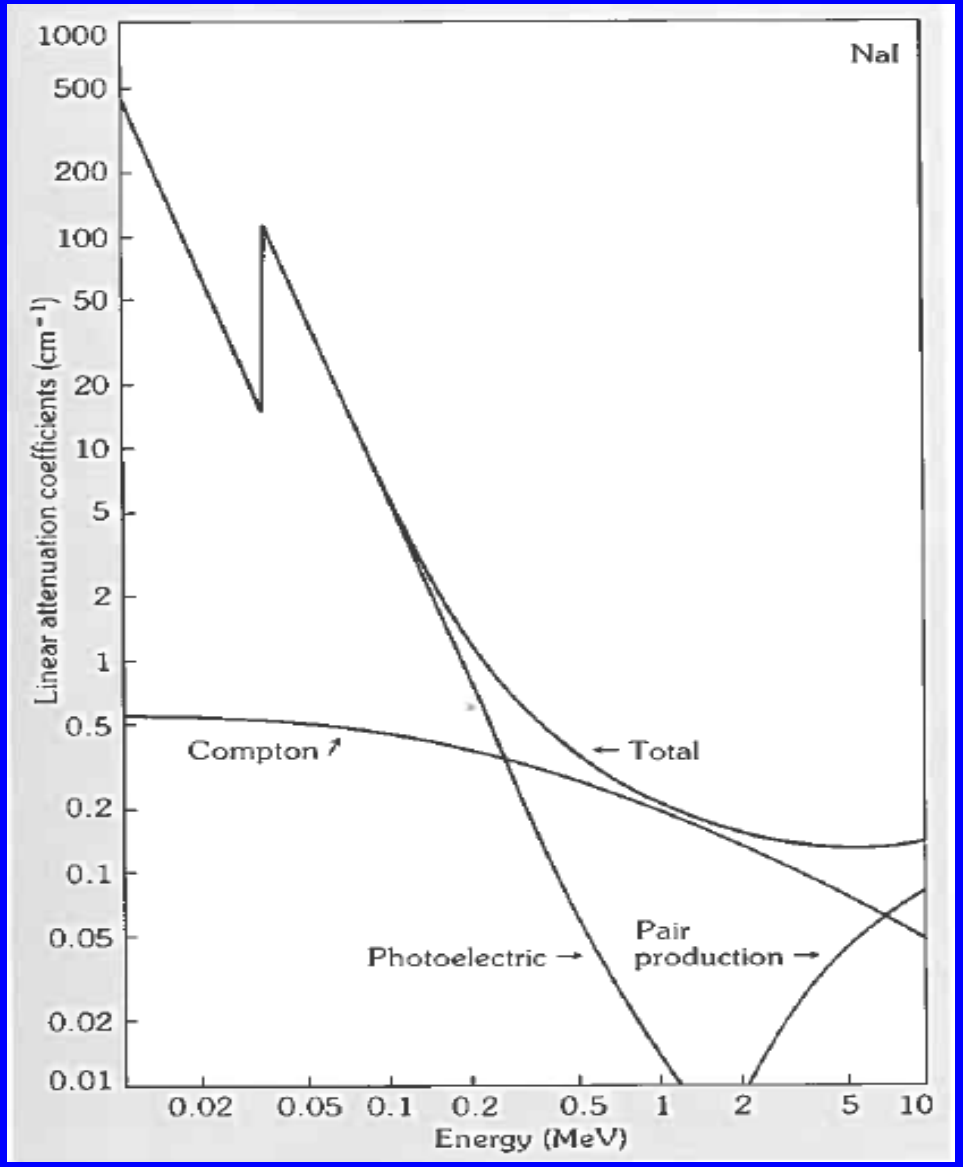
Inorganic Scintillators

Sodium Iodide (NaI)

Probability of interactions (linear attenuation coefficient) as a function of energy for NaI.

The NaI counting efficiency (e.g., survey meter) follows the Total probability curve.

The photopeak counting efficiency (gamma spectroscopy) follows the photoelectric effect probability.

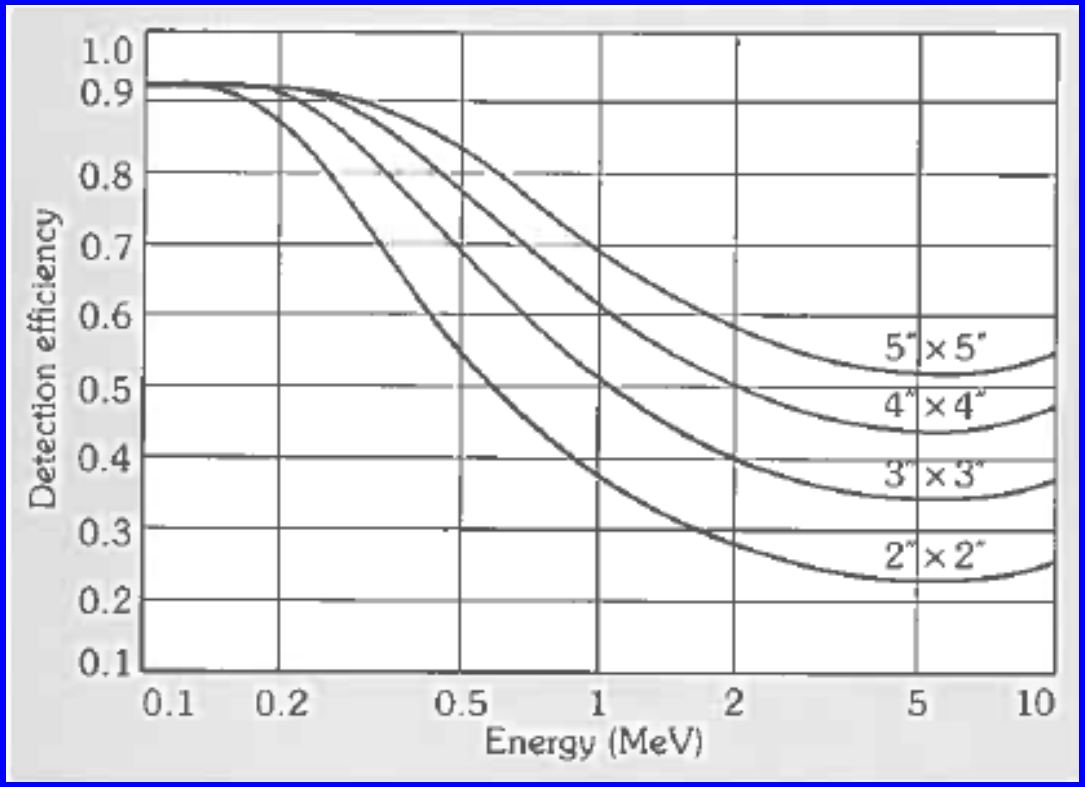


Inorganic Scintillators

Sodium Iodide (NaI)

Counting efficiency (total efficiency) for different sized NaI crystals.

The efficiency decreases below 100 keV (not shown) due to interactions in the detector housing.



The efficiency increases at the higher energies because of the increased probability of pair production.

Inorganic Scintillators

Lanthanum Halide ($LaBr_3$ and $LaCl_3$)

The primary application of lanthanum bromide is in gamma spectroscopy - especially the hand-held spectroscopy systems often used by field personnel. In a lab situation, germanium detectors are much preferred.

The cost of lanthanum halide detectors is too great for them to be just used to detect (i.e., locate) gamma emitters or measure exposure rates.

Inorganic Scintillators

Lanthanum Halide ($LaBr_3$ and $LaCl_3$)

- Relatively new category of scintillator materials – very expensive. Lanthanum bromide is more widely used than lanthanum chloride.
- Activated with cerium
- Density: 5.06 g/cm^3
- Lanthanum atomic number : 57
- Bromine atomic number: 35
- Higher light output than NaI
- Better resolution than NaI:

$LaBr_3$	2.8%
$LaCl_3$	3.8%
NaI	7-8%

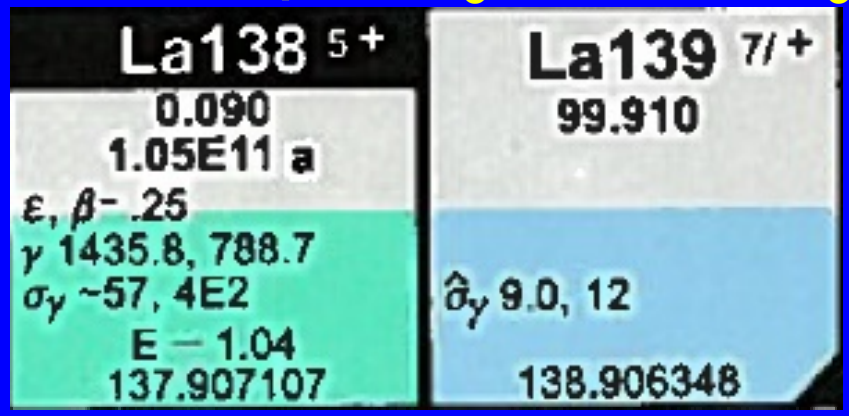
Inorganic Scintillators

Lanthanum Halide ($LaBr_3$ and $LaCl_3$)

- Much shorter decay time (26-28 ns) than NaI, hence it performs better at high count rates.
- Higher detection efficiency than NaI due to the greater density of the lanthanum halides.
- Hygrosopic
- The major disadvantage of lanthanum halide scintillators is the presence of the naturally occurring radionuclide La-138 (ca. 1 Bq/cm^3). This can compromise their performance for low level counting.

Inorganic Scintillators

Lanthanum Halide ($LaBr_3$ and $LaCl_3$)



- Approximately one third of the La-138 decays involve the emission of beta particles. In a low background spectrum, this results in what looks like bremsstrahlung below 255 keV.
- The 788.7 keV gamma is emitted in coincidence with the beta particles. The 1435.8 keV gamma is emitted in coincidence with barium x-rays.

Inorganic Scintillators

Cesium Iodide (CsI)

- Primarily application is for the detection of gamma rays and x-rays detection.
- It is not used for gamma spectroscopy due to its poor resolution.
- Used as the detection device in some Radiation Pagers.
- CsI (Tl) used in x-ray digital imaging systems

Inorganic Scintillators

Cesium Iodide (CsI)

- Density: 4.51 g/cm^3
- Cesium atomic number : 55
- Iodine atomic number: 53
- Can be grown into fairly large crystals
- Pure CsI crystals can be employed, but it is more common for CsI to be activated with thallium (Tl) or sodium (Na). CsI (Tl) has a peak light emission near 550 nm which makes it feasible to employ silicon photodiodes as the light collection device.
- CsI (Tl) typically used with photodiodes.
- Low afterglow possible (<0.1% after 5 ms)

Inorganic Scintillators

Cesium Iodide (CsI)

- Very efficient due to relatively high Z and density
- Resistant to thermal and mechanical shock
- CsI (Na) hygroscopic; CSI and CsI (TL) less so

	CsI	CsI(Na)	CsI(Tl)
Peak Emission Wavelength	ca. 300 nm	420 nm	550 nm
Decay Time	16 ns	630 ns	1000 ns
Photoelectron yield (% of NaI)	4 – 6 %	85%	45%

Inorganic Scintillators

Cadmium Tungstate ($CdWO_4$)

- Primary application is in x-ray detection (e.g., CT imaging systems)
- Density: 7.9 g/cm^3
- Atomic number of cadmium: 48
- Atomic number of tungsten: 74
- Peak light emission: 475 nm
- Light yield (photons/MeV): ca 12,000 – 15,000
- Photocathode yield (electrons/MeV): ca 30-50% that of NaI
- Decay time: ca. 5000 - 14000 ns
- Not hygroscopic
- Resolution: ca. 10%

Inorganic Scintillators

Bismuth Germanate (BGO)

- Primary application is in PET imaging systems
- $Bi_4Ge_3O_{12}$
- Density: 7.13 g/cm^3
- Atomic number of bismuth: 83
- Peak light emission: 480 nm
- Light yield (photons/MeV): ca 25% that of NaI
- Photocathode yield (electrons/MeV): ca 10-15% that of NaI
- Decay time: ca. 300 ns
- Almost no afterglow (0.005% after 3 ms)
- Not hygroscopic
- Resolution: ca. 10%

Inorganic Scintillators

Lutetium Oxyorthosilicate (LSO)

- Primary application is in PET imaging systems
- Cerium activated
- Density: 7.4 g/cm^3
- Atomic number of lutetium: 71
- Effective atomic number of LSO: 65
- Peak light emission at 420 nm
- Light yield: ca. 30,000 photons/MeV (75% of NaI)
- Photocathode yield (electrons/MeV)
- Decay time ca. 41- 46 ns
- Resolution: 10%
- Not hygroscopic

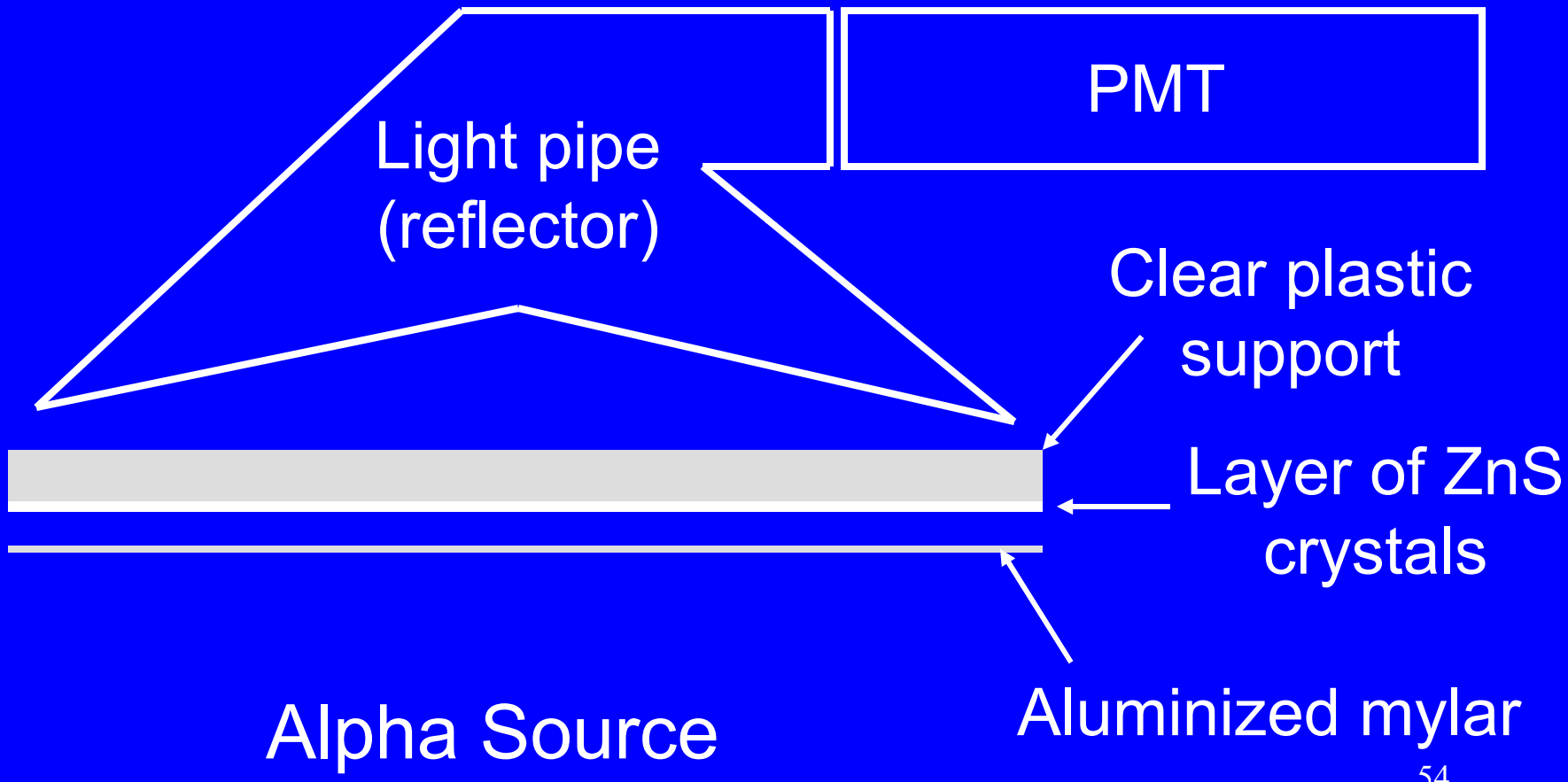
Inorganic Scintillators

Zinc Sulfide (ZnS)

- Primary application is for counting alpha particles. Has also been used in fast neutron detectors.
- Only available as very fine (powder) crystals
- Silver (Ag) used as activator
- For all practical purposes, ZnS only responds to alpha particles although it does have a weak response to neutrons.
- Typical background is 0 – 1 cpm
- Light leaks can be a problem.

Inorganic Scintillators

Zinc Sulfide (ZnS)



Inorganic Scintillators

Zinc Sulfide (ZnS)

Inorganic Scintillators

Glass

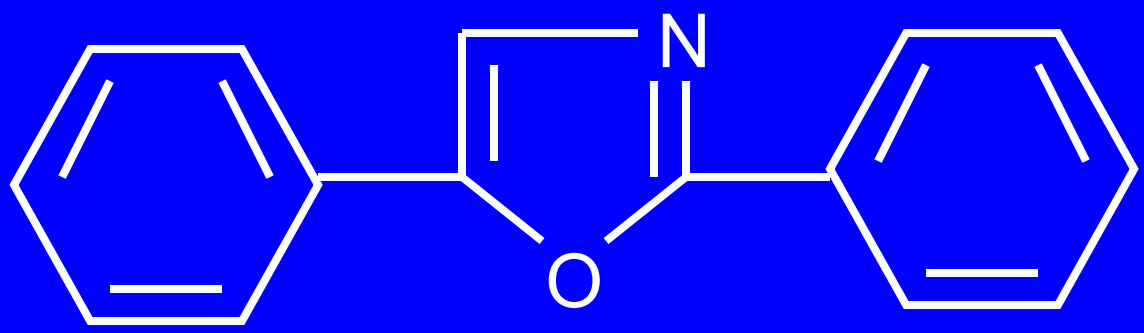
- Li-6 containing glass activated with cerium (Ce)
- Primarily for neutrons. Thermal neutron absorbed by Li-6 to produce alpha particle and recoil H-3 atom. Some of the kinetic energy of the alpha and tritium excites the cerium. The de-excitation of the cerium results in the emission of light (ca. 400 nm)
- Can be manufactured in many shapes and sizes
- Very rugged
- Shorter decay time than NaI

Organic Scintillators

Organic Scintillators

General

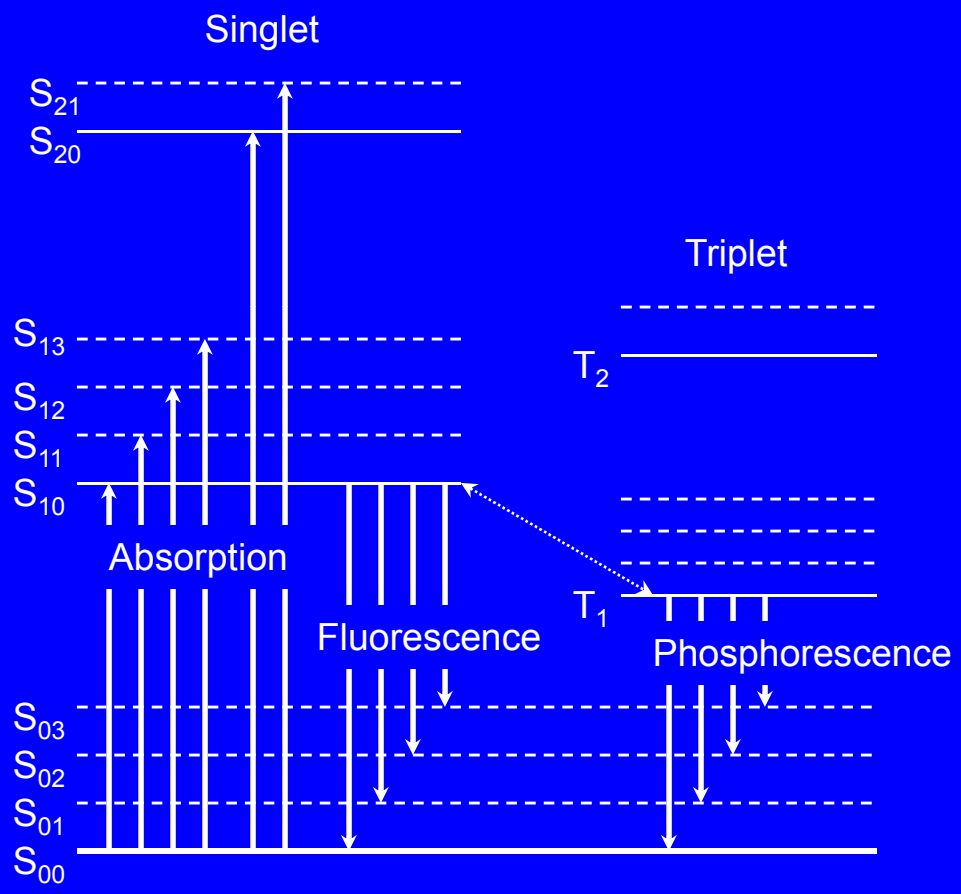
- Are aromatic hydrocarbons
- The individual molecules emit light – as such, organic scintillators can be solids, liquids or gases



PPO 2,5-diphenyloxazole

Organic Scintillators

Excitation levels of typical organic molecule



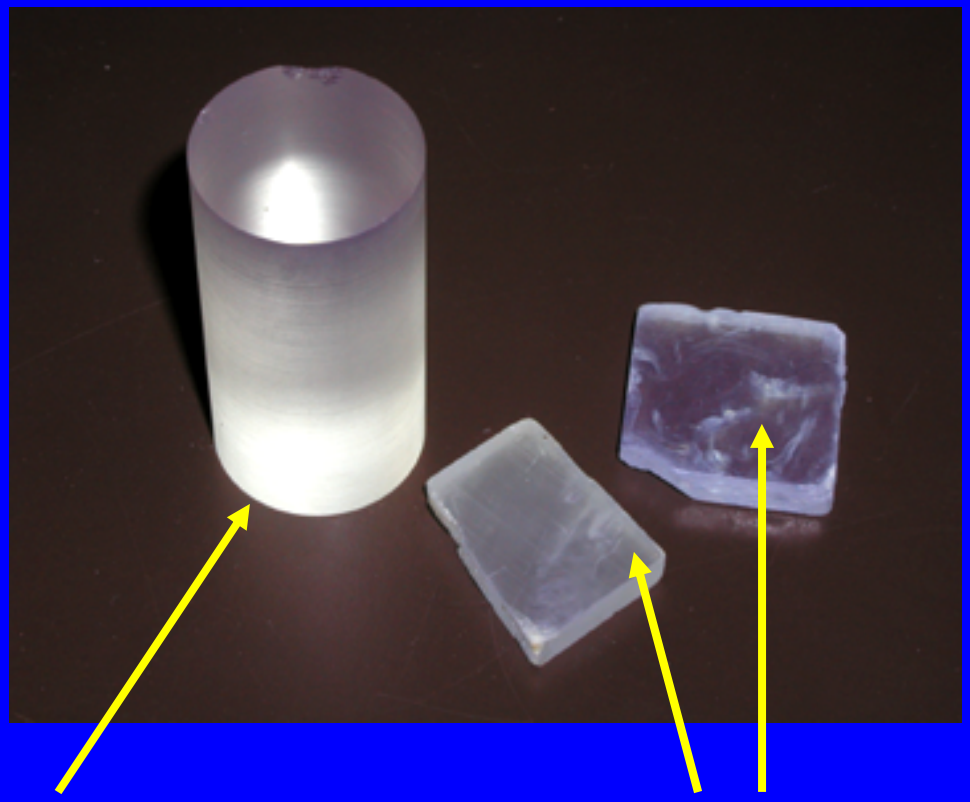
Organic Scintillators

Organic Crystals

- Only two have been used to any extent: stilbene and anthracene.
- Naphthalene has been used to a lesser extent
- They are fragile, not available in large sizes and have poor resolution
- As such, they are rarely used today

Organic Scintillators

Organic Crystals vs Inorganic Crystals



Calcium Fluoride
Inorganic

Anthracene
Organic

Organic Scintillators

Plastic Scintillators

- The organic scintillator is mixed with a plastic solvent that is then polymerized
- The most commonly used scintillator is PPO (ca. 1%) along with POPOP (ca. 0.4%)
- The most commonly employed plastics are polyvinyl toluene and polystyrene
- Detection of gamma rays, x-rays, beta particles

Organic Scintillators

Plastic Scintillators - advantages

- Plastic can be manufactured in almost any size and shape
- Rugged
- Light
- Non-hygroscopic – this means they don't have to be housed in a hermetically sealed container.
- Flat energy response when used for gamma ray and x-ray detection.

Organic Scintillators

Plastic Scintillators - disadvantages

- Plastic scintillators are not very suitable for gamma ray or x-ray spectroscopy since only a fraction of the photon energy is absorbed in the scintillator.

  Plastic's low atomic number means photons are much more likely to interact via compton scattering than the photoelectric effect.

  The spectrum shape, especially the compton edge, conveys some information about photon energy. It is possible to determine the general energy range of the photons, e.g., high, medium or low.

Scintillator Housing and Optical Coupling

Scintillator Housing and Optical Coupling

Scintillator Housing

- The scintillator must be protected from ambient light. In some cases it must also be shielded from specific types of radiation (e.g., beta particles).

- If the scintillator is not hygroscopic (e.g., a plastic scintillator), it does not need to be protected in a moisture proof container. The PMT might be coupled directly to the scintillator.

Scintillator Housing and Optical Coupling

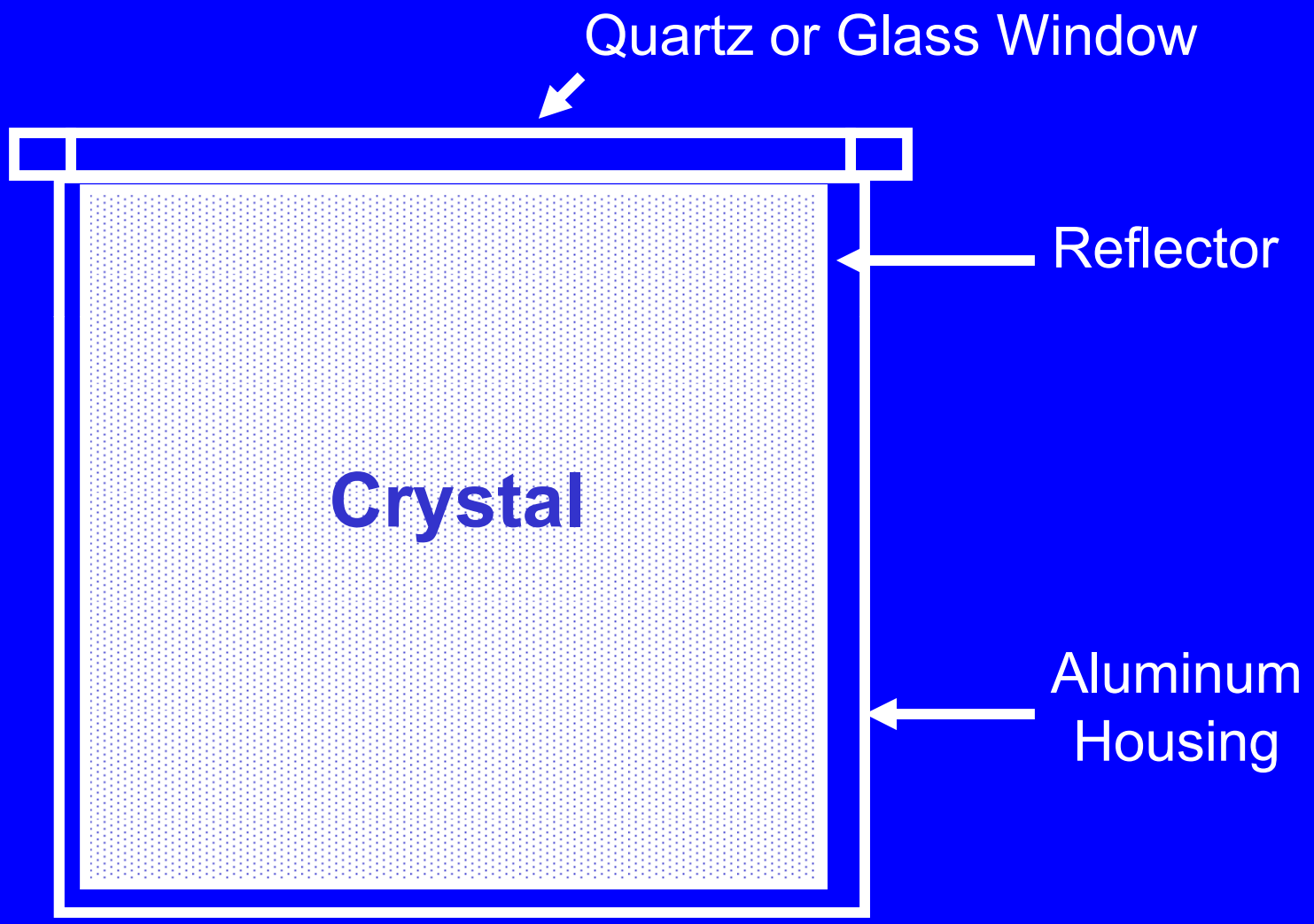
Scintillator Housing

- If the scintillator is hygroscopic, it must be housed in a hermetically sealed container (e.g., a NaI crystal in an aluminum “can”).
- When the scintillator and PMT cannot be in physical contact because the former is hermetically sealed, the housing must have a transparent window to transmit the emitted light.

  Such a container is usually lined with a white paint or powder to reflect light through the window.

Scintillator Housing and Optical Coupling

Hermetically Sealed NaI Crystal



Scintillator Housing and Optical Coupling

Scintillator Housing

- If it is desirable to detect beta particles, a thin aluminized mylar window might be incorporated into the scintillator housing/covering.
- If it is necessary to detect low energy photons, the housing might incorporate a thin window made of low Z material (e.g., beryllium).

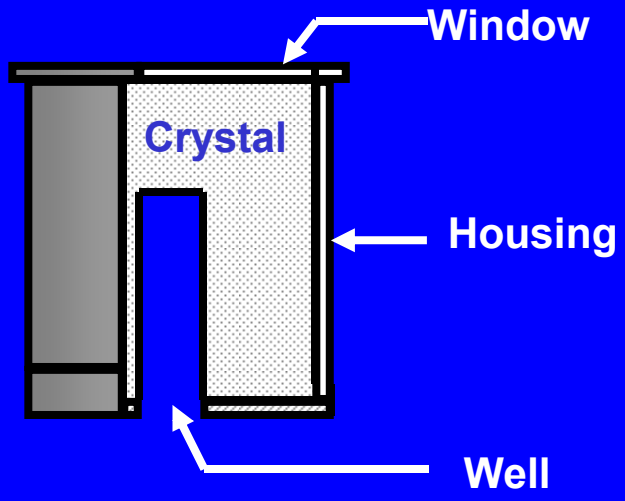
Scintillator Housing and Optical Coupling

Scintillator Housing

- To maximize the detector's efficiency for small samples, a hole might be drilled all or part way through the scintillator. During the count, the sample is positioned in the hole.
- Although the detection efficiency would be high, the analysis is limited to small samples. As such, the sample count rate might still be low.
- Such a configuration can be unsuitable for gamma spectroscopy because surrounding the sample with the scintillator can dramatically increase coincident (summation) losses.

Scintillator Housing and Optical Coupling

Well Detector



Scintillator Housing and Optical Coupling

Optical Coupling

- In most cases, the window of the scintillator housing is directly coupled (in direct contact) to the photocathode of the photomultiplier tube.

  An optical coupling grease or gel is almost always applied to the scintillator window - PMT interface to minimize reflection.

Scintillator Housing and Optical Coupling

Optical Coupling

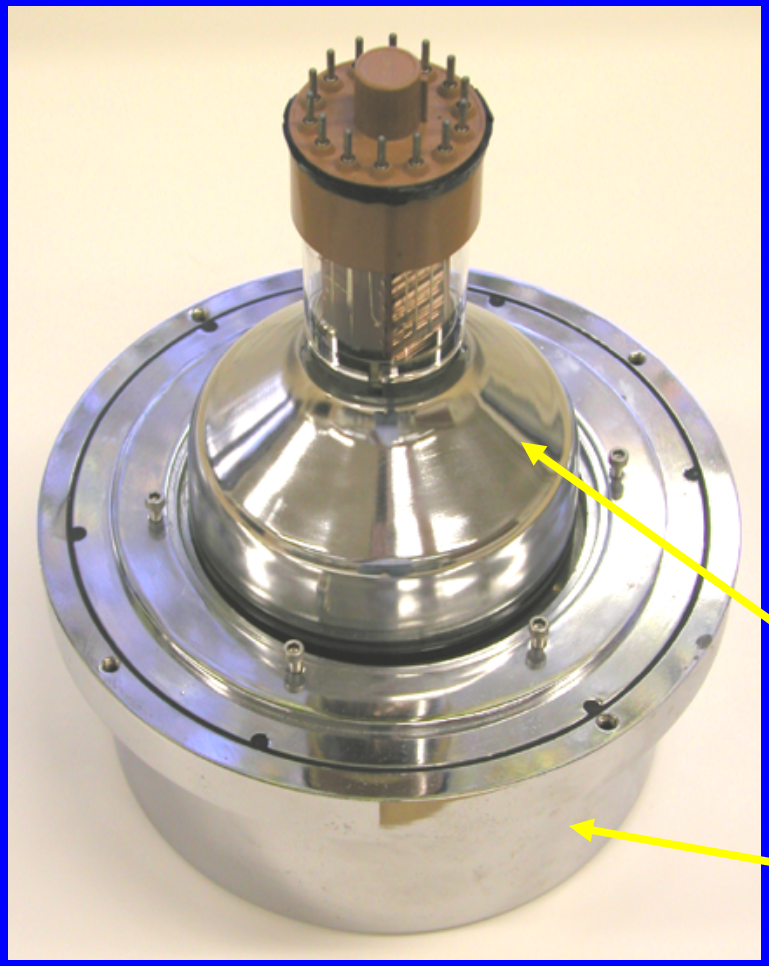
- All sorts of scintillator-PMT arrangements are possible. For example:

  One photomultiplier tube might be coupled to one or more scintillating crystals.

  Multiple photomultiplier tubes might be coupled to a single crystal

Scintillator Housing and Optical Coupling

Optical Coupling



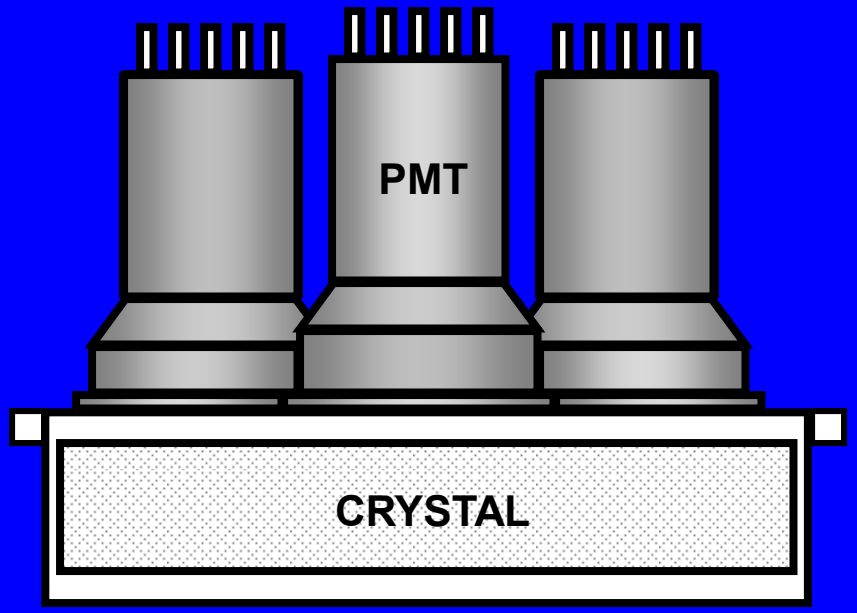
Typical arrangement: a single NaI crystal coupled directly to a single photomultiplier tube.

Photomultiplier tube

NaI Crystal

Scintillator Housing and Optical Coupling

Optical Coupling



Multiple PMTs connected to single large crystal

Scintillator Housing and Optical Coupling

Light Pipes

- A scintillator can also be coupled to a “remote” photomultiplier tube via a light pipe (typically an acrylic plastic).
- One end of the light pipe is connected to the scintillator and the other end is connected to the photomultiplier tube.
- Optical cement is often used to connect the scintillator to the light pipe.

Scintillator Housing and Optical Coupling

Light Pipes

Example light pipes (guides) for transmitting light from the scintillator to a remote PMT.

Teledyne

Photomultiplier Tubes

Photomultiplier Tubes

General

- The photomultiplier tube (PMT) converts each flash of light (scintillation) from the detector into an electronic pulse
- Photodiodes are less frequently used for this purpose. For photodiodes to be employed, the light emitted by the scintillator should be in the 500 to 600 nm range.
- PMTs are fragile

Photomultiplier Tubes

General

- PMTs are affected by magnetic fields
- The pins (electrical contacts) on the end of the PMT should be kept clean – do not touch with bare hands.
- PMT's are usually round in cross section but might be square if multiple tubes must be packed close together.

Photomultiplier Tubes

Photocathode

- The photocathode is a thin metallic deposit (e.g., Sb-Cs, Sb-Rb-Cs) on the inside of the window of the PMT.
- It is usually flat and circular
- The photo cathode is usually on one end of the PMT (end-on) but some PMTs have the photocathode on the side (side-on).

Photomultiplier Tubes

Photocathode

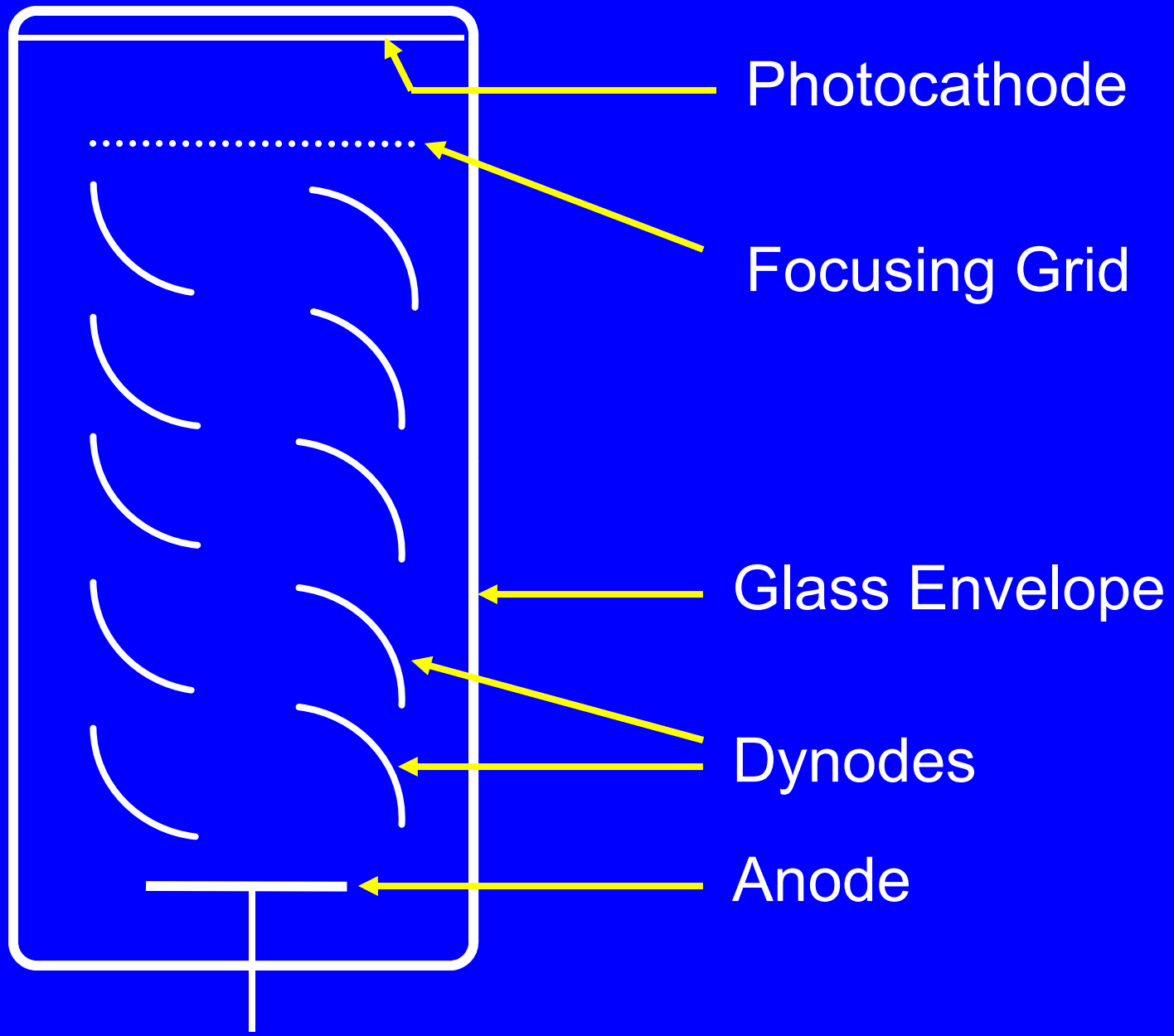
- The absorption of light photons from the scintillator knocks electrons off the photocathode
- 20 to 30% of the light photons incident on the photocathode result in the freeing of electrons. This is known as the “quantum efficiency”
- The quantum efficiency is usually greatest for light photons around 400 nm. Below a typical cutoff of 350 nm, light photons (UV), can’t penetrate the glass.

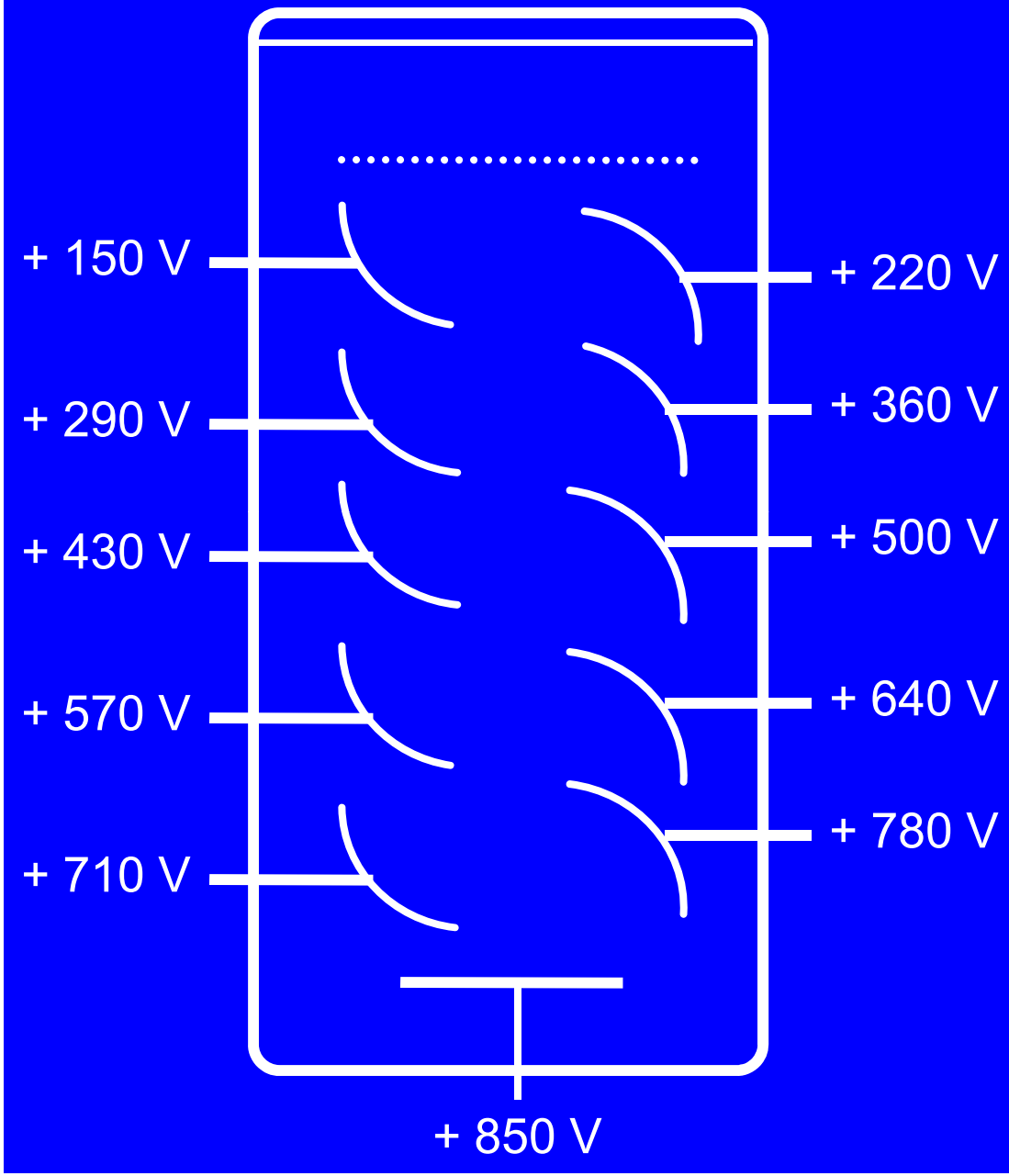
Photomultiplier Tubes

Dynodes

- Electrons from the photocathode are directed towards the first of several (usually 10) dynodes by a focusing grid

- The dynodes are curved metal plates with a positive potential that attracts and accelerates the electrons


Window
Photocathode
Focusing Grid
Glass Envelope
Dynodes
Anode

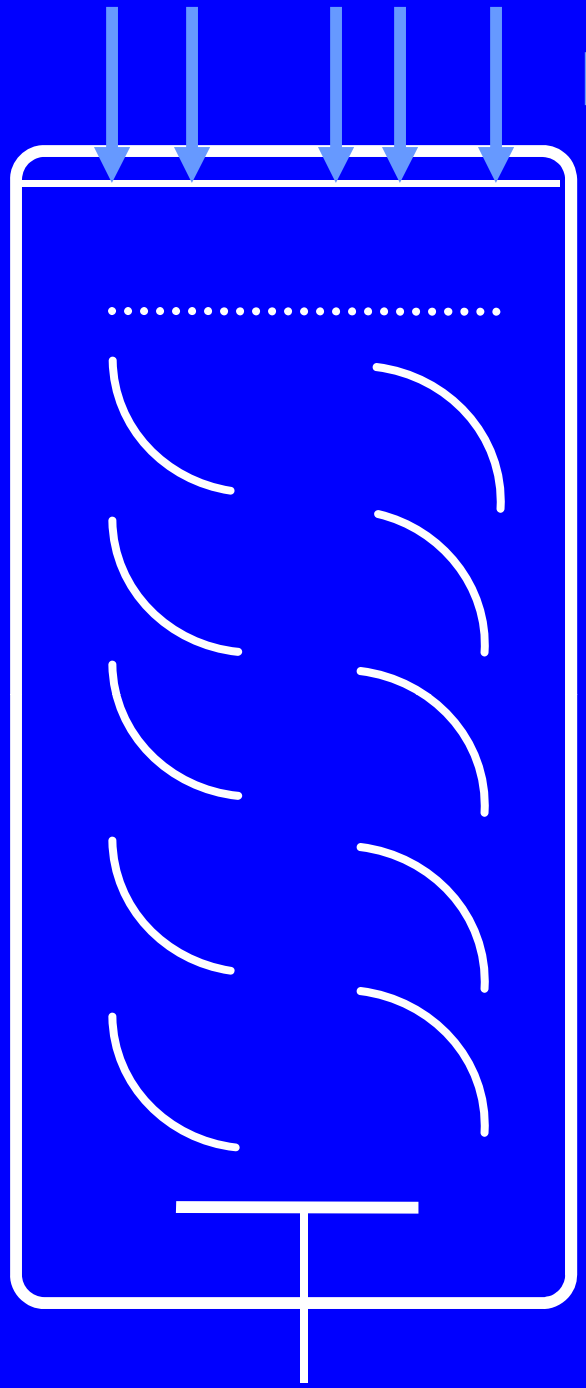


Each successive dynode has an increasingly higher potential voltage

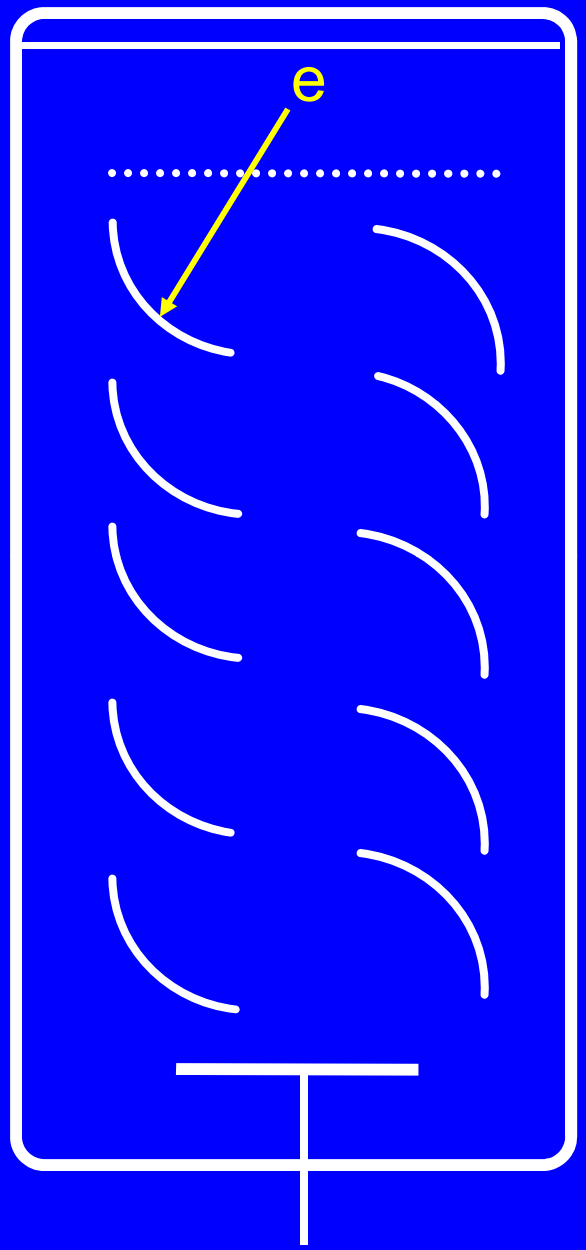
Photomultiplier Tubes

Dynodes

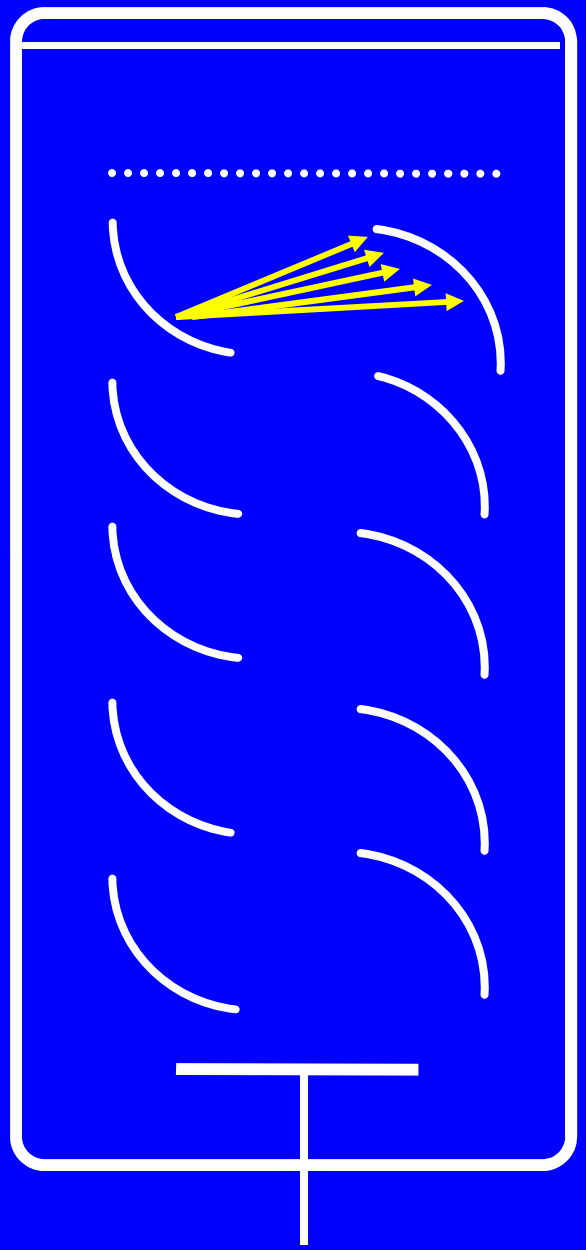
- Each electron striking a dynode frees 4-6 electrons
- For each electron leaving the photocathode, 5 (or so) leave the first dynode, 25 leave the second dynode, 125 leave the third dynode etc.
- For every electron freed from the photocathode, over a million will eventually be collected at the anode.



Light Photons

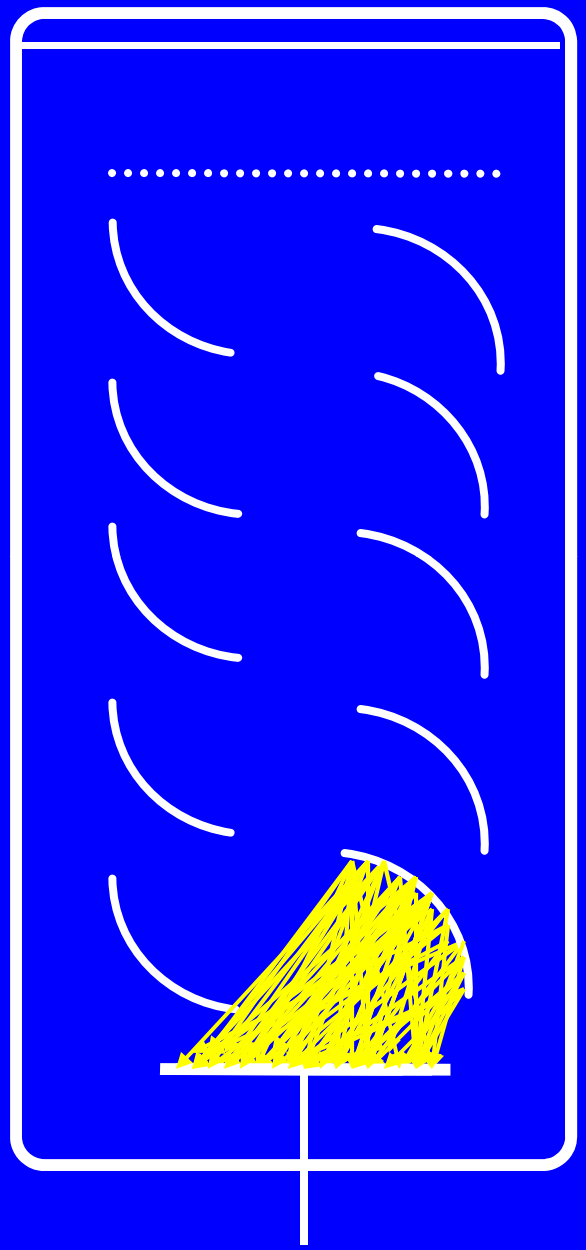


Electron ejected
from photocathode



Each electron striking first dynode causes 4 to 5 to be ejected

Each electron striking second dynode results in 4 to 5 being ejected.



Each electron freed from the photocathode results in approximately 10,000,000 electrons reaching the anode.


Photocathode
Curved dynode
Getter

Photomultiplier Tubes

Various Dynode Configurations

Venetian Blind Dynodes

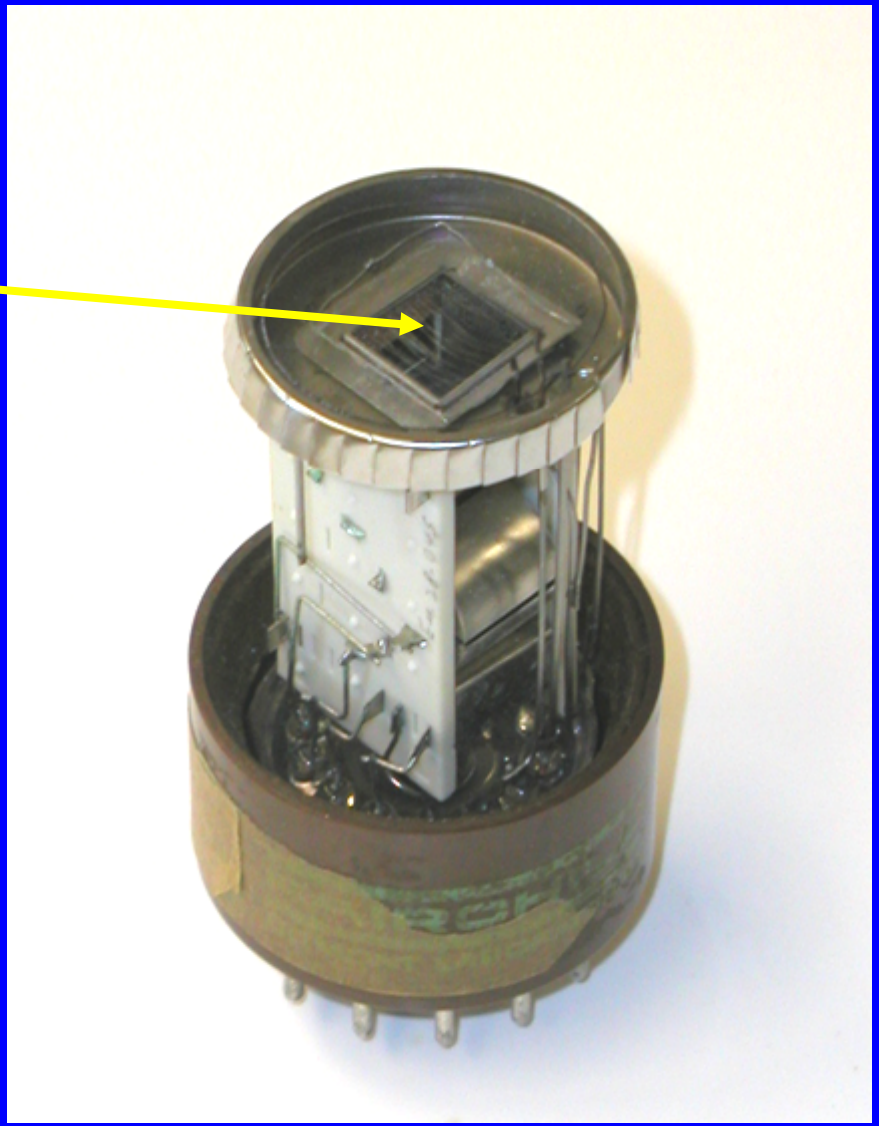
Circular Grid Dynodes

Box and Grid Dynodes

Photomultiplier Tubes

Focusing Grid

Focusing
Grid



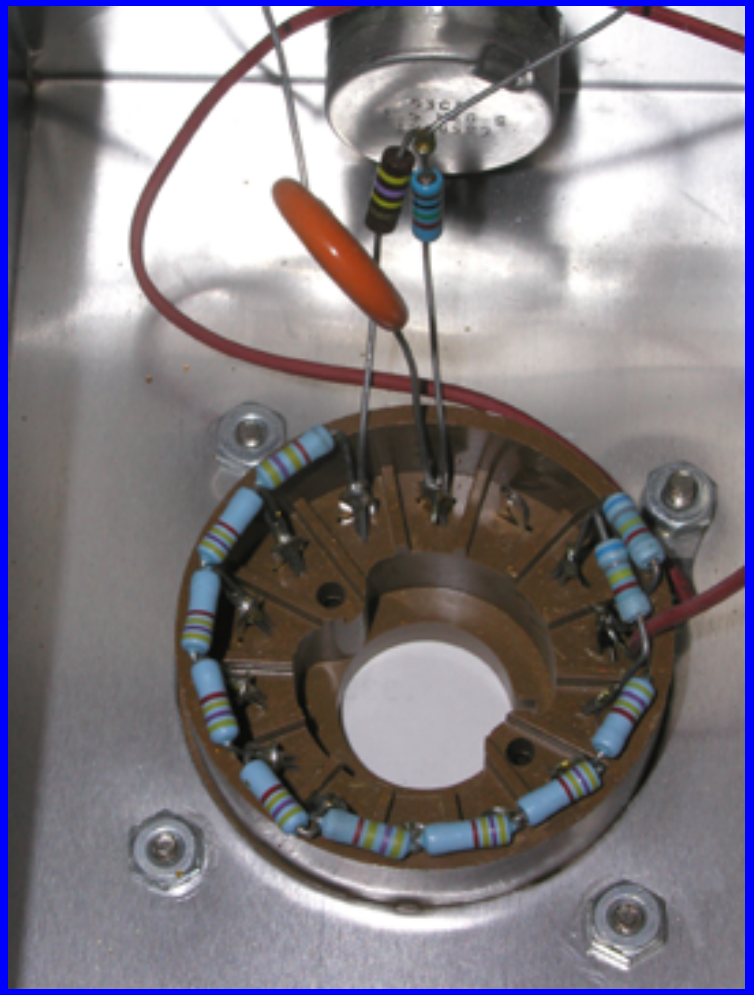
Photomultiplier Tubes

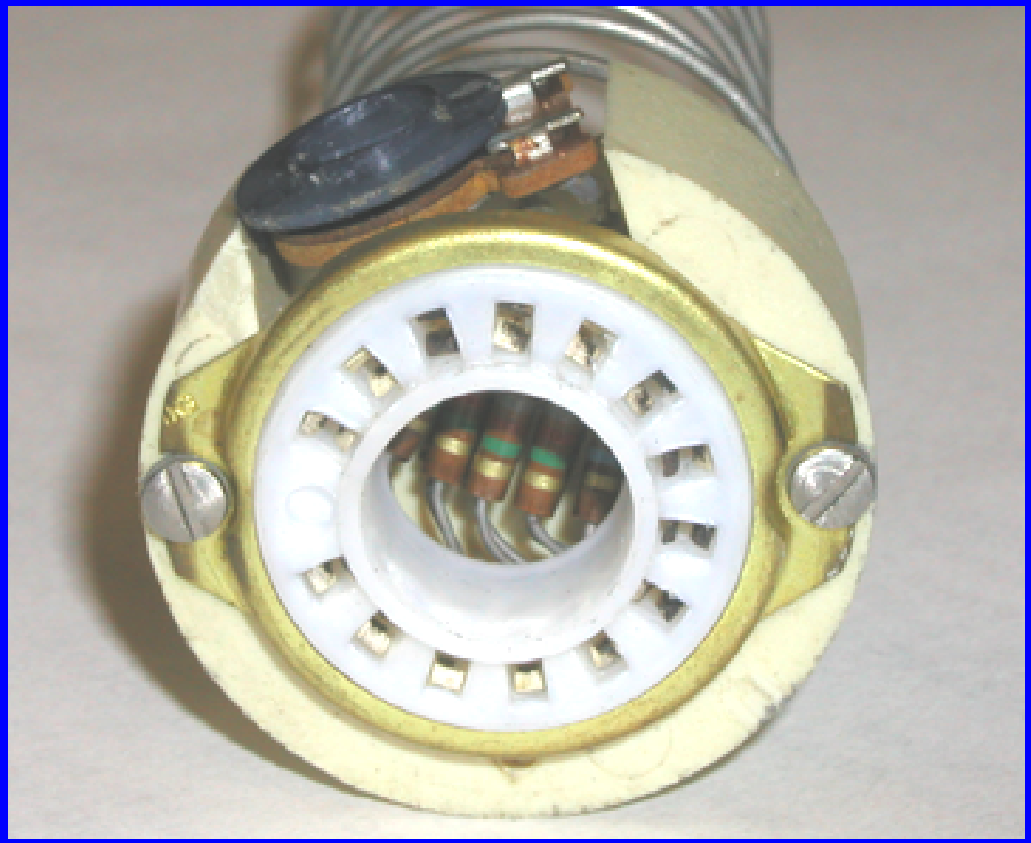
Voltage Divider

- The voltage divider is a series of resisters (and possibly some capacitors) usually located in the tube socket/base.
- The divider ensures that the photocathode, focusing grid, dynodes and the anode all have the appropriate potential

Photomultiplier Tubes

Voltage Divider

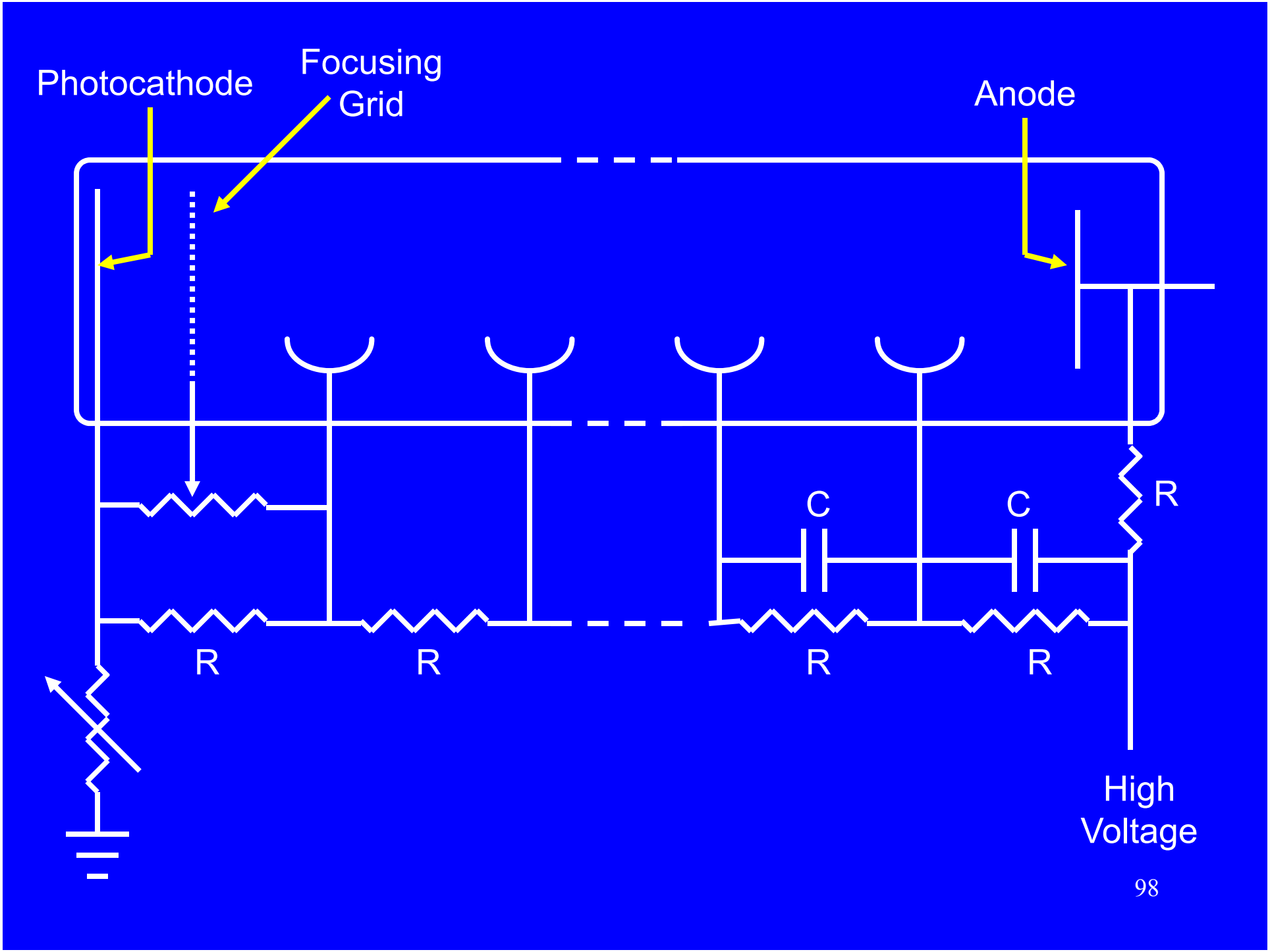




Photomultiplier Tubes

Voltage Divider

Two 5” PMTs. tubes. That on the left is directly connected to the voltage divider.


Photocathode
Focusing Grid
Anode
C
C
R
R
R
R
R
High Voltage

Potential Problems with Photomultiplier Tubes

Potential Problems with PMTs

Dark Current

- Noise
- Generally consists of small pulses that can be discriminated against
- A variety of sources: thermionic emission, field emission, ionization of residual gas, ohmic leakage, radioactive components in the tube, and luminescent effects

Potential Problems with PMTs

Magnetic Fields

- Magnetic fields can change the paths of the electrons
- The result is a decreased gain and possibly a complete loss of signal
- PMTs often shielded by “mu-metal”

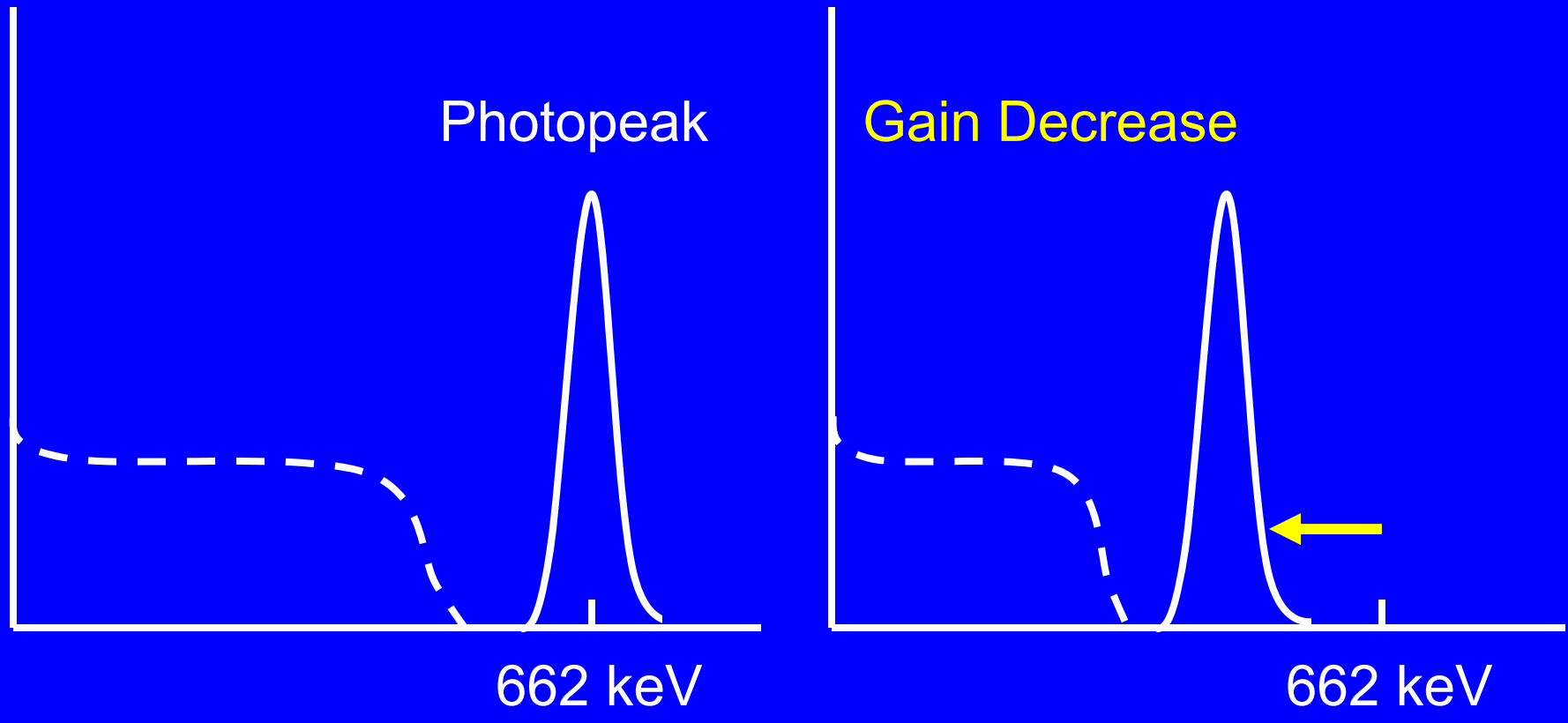
Potential Problems with PMTs

Gain Shifts

- A gain shift means that the pulse amplification (gain) has increased or decreased
- As a result, the pulses are larger or smaller than they were before the shift - not good.
- In gamma spectroscopy, this can result in the photopeak being shifted to the right or left

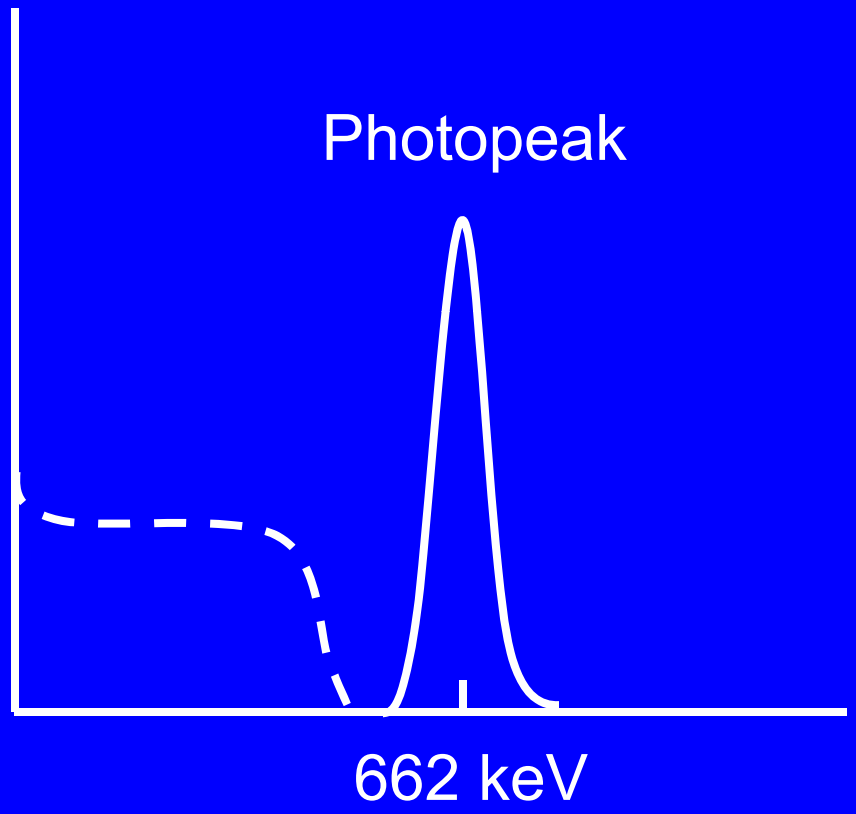
Potential Problems with PMTs

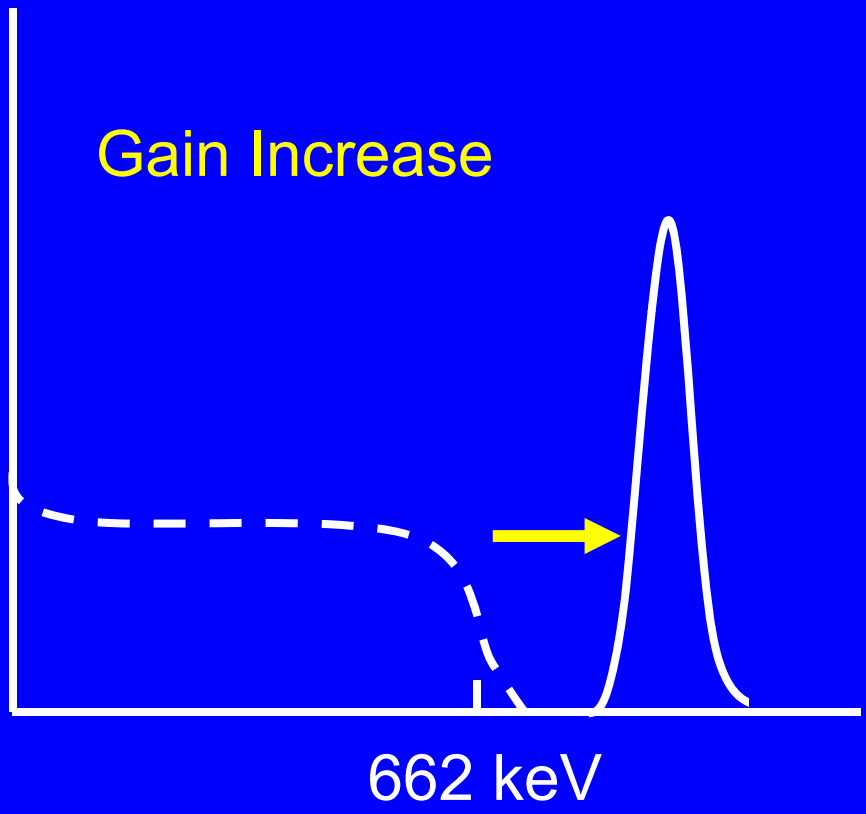
Gain Shifts



Potential Problems with PMTs

Gain Shifts





Potential Problems with PMTs

Gain Shifts

Gain shifts can occur because of a change in the potential difference between the last few dynodes of a PMT (often a 70 volt difference).

This potential is affected by the number of electrons moving across the dynodes per unit time.

When very large numbers of electrons (which carry a negative charge) move across the last few dynodes , the resulting negative electric field reduces the potential difference between the dynodes.

Potential Problems with PMTs

Gain Shifts

When the potential is reduced, the pulses become smaller and the spectrum shifts to the left.

One method that has been employed to prevent this change in potential is to run capacitors in parallel with the last few resisters in the voltage divider.

Potential Problems with PMTs

Gain Shifts

In addition to changes in count rate, changes in the gamma ray energies being counted can cause gain shifts.

This shift occur because the number of electrons moving through the PMT is directly related to the number of photons striking the photocathode ,and the latter is directly related to gamma ray energy.

The higher the count rate and the gamma ray energy, the greater the spectrum shift to the left.

Potential Problems with PMTs

Gain Shifts

Other possible causes of gain shifts include:

- bad connection between the tube base- pins and socket
- changes in the line current
- failure of HV power supply
- changes in temperature
- changes in count rate