

# Lecture: Semiconductor + Scintillator

**Semiconductor det:**

**Chapter 10.1, 10.2, 10.3, 10.4, 10.5.2, 10.5.4, 10.7.2, 10.7.3, 10.9**

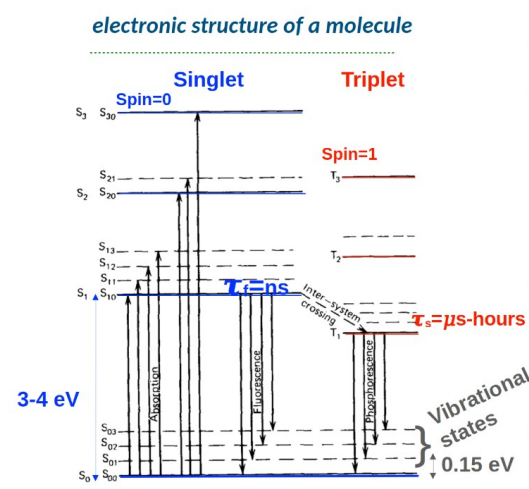
**Scintillation det:**

**Chapter 10.1, 10.2, 10.3, 10.4, 10.5.2, 10.5.4, 10.7.2, 10.7.3, 10.9**

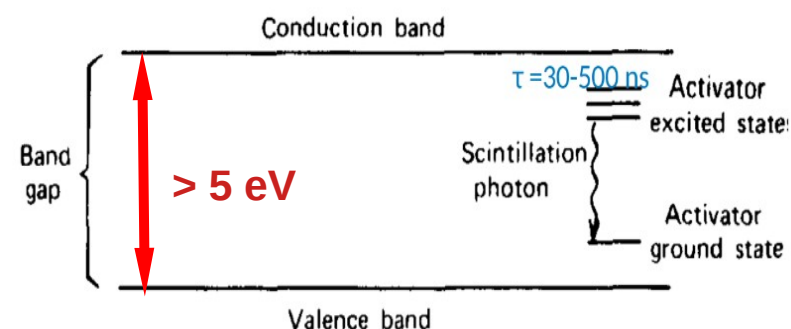
# Photocathode



## Organic



## Inorganic



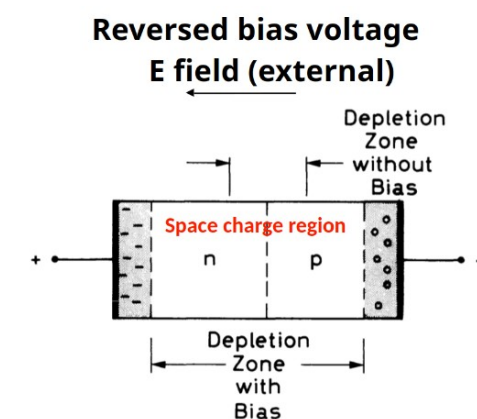
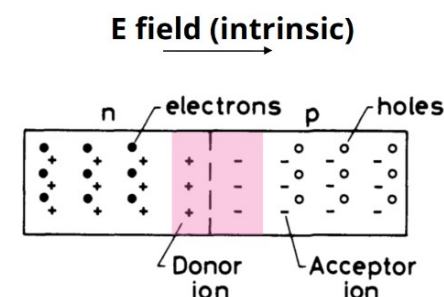
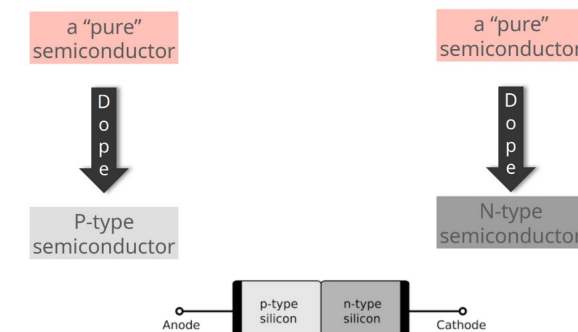
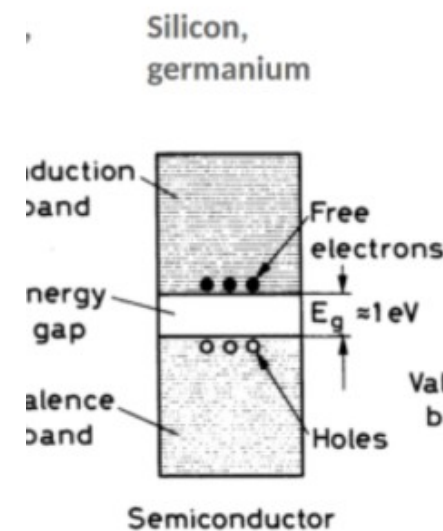
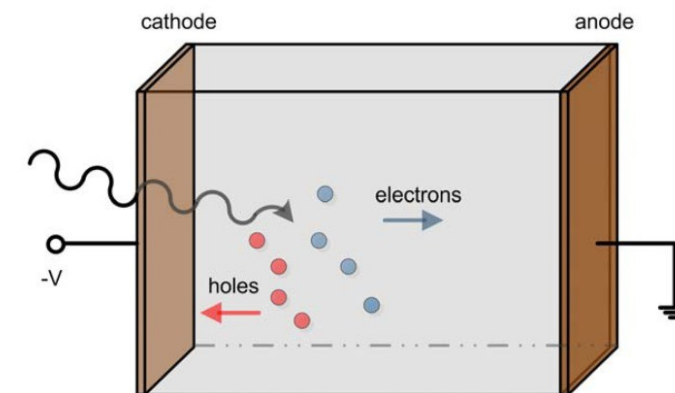
Plastic scintillators  
Charged particles  
TOF measurements, fast timing

Gamma rays  
NaI(Tl)  
CsI(Tl)  
LaBr3(Ce)

Compton suppression  
BGO

Electron hitting the organic scintillator will excite many electrons from the ground state to the excited states

Photon hitting the inorganic scintillator will give its energy to one electron via PA,CS,PP  
Now that energetic electron will excite many electrons from the ground state to the excited states



Germanium (HPGe)  
Gamma rays

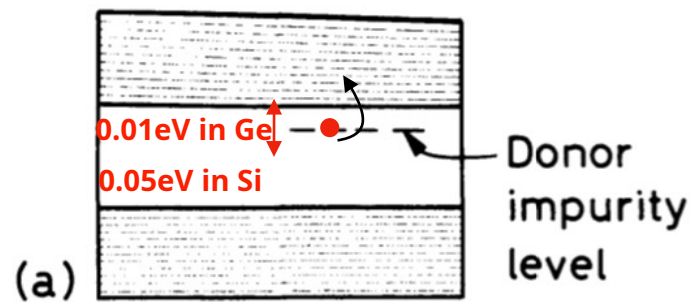
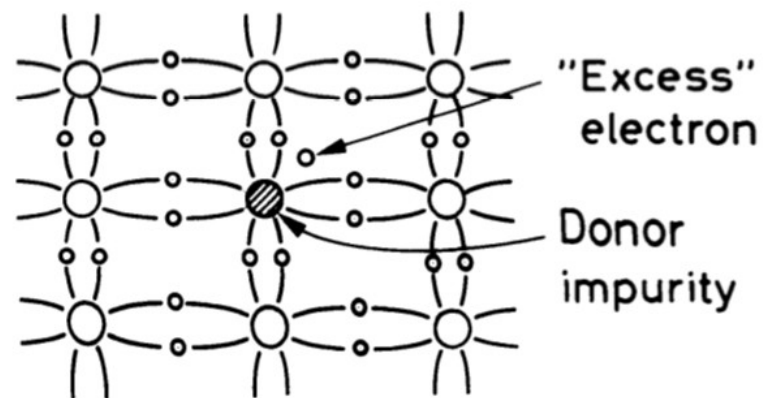
Silicon (Si)  
Heavy-charged particles  
electrons

Semiconductors are found in columns II-VI of the periodic table.

| Acceptors        |                  | Donors           |                  |                  |
|------------------|------------------|------------------|------------------|------------------|
|                  | <sup>5</sup> B   | <sup>6</sup> C   |                  |                  |
| <sup>12</sup> Mg | <sup>13</sup> Al | <sup>14</sup> Si | <sup>15</sup> P  | <sup>16</sup> S  |
| <sup>30</sup> Zn | <sup>31</sup> Ga | <sup>32</sup> Ge | <sup>33</sup> As | <sup>34</sup> Se |
| <sup>48</sup> Cd | <sup>49</sup> In | <sup>50</sup> Sn | <sup>51</sup> Sb | <sup>52</sup> Te |
| II               | III              | IV               | V                | VI               |

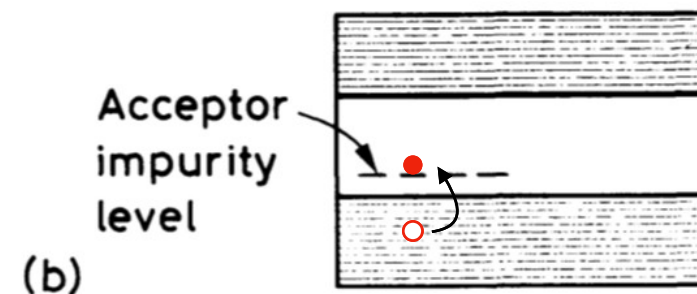
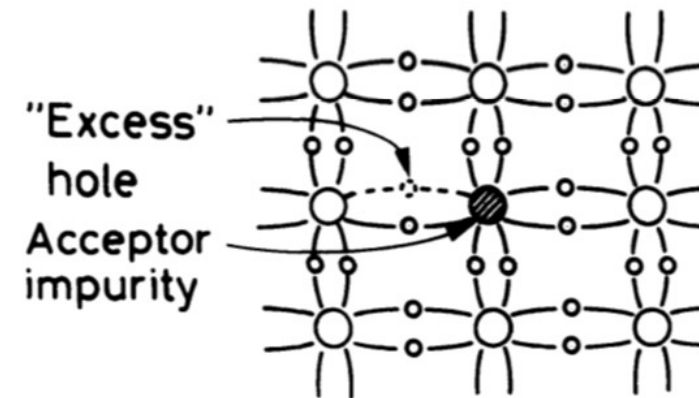
Adopted from [https://physics.bgu.ac.il/COURSES/LAB\\_C/XRAYS/Basic%20Semiconducturs.pdf](https://physics.bgu.ac.il/COURSES/LAB_C/XRAYS/Basic%20Semiconducturs.pdf)

### Donor (Pentavalent: 5 valence electrons)



$n=n_e=10^{17}$  electrons —> majority charge carriers  
 $p=n_h=10^3$  holes —> minority charge carriers  
**n-type**

### Acceptor (trivalent: 3 valence electrons)



electrons —> minority charge carriers  
**holes —> majority charge carriers**  
**p-type**

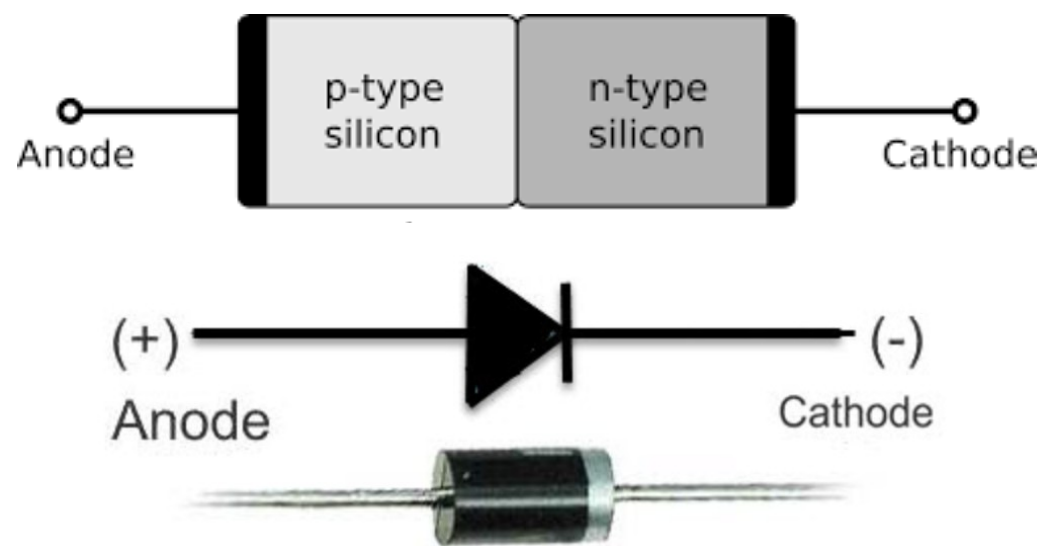
Read Leo page#221

- Amount of dopant used is usually around  $10^{13-17}$  atoms/cm<sup>3</sup>  
 This amount is very small compared to the concentration of total Ge/Si atoms ~  $10^{22}$  atoms/cm<sup>3</sup>
- Dopant amount can be higher up to  $10^{20}$  atoms/cm<sup>3</sup> and such doped materials are called heavily doped and indicated with a plus sign → p<sup>+</sup> and n<sup>+</sup>

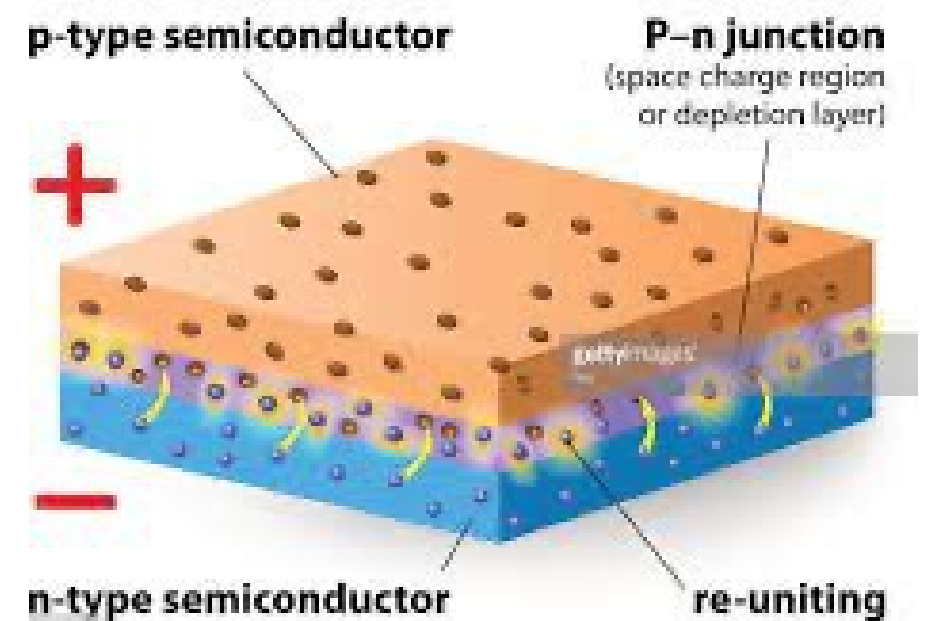
# Semiconductor junction

Once we have n- and p-type semiconductor materials, we can make a **functioning semi-conductor detector** through **Junction**

Junction provides a good depletion layer/zone/depth for the purpose of radiation detection

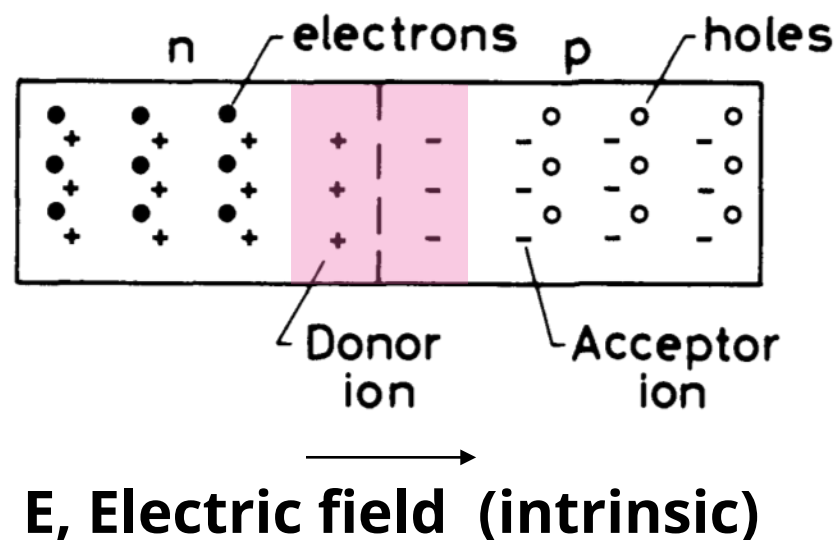


## P-N JUNCTION



# pn junction

pn junction is formed by the **juxtaposition** of a p-type semiconductor with an n-type material.



## 1- Diffusion

holes will diffuse towards n-region

electrons will towards p-region

## 2- Formation of depletion

At the junction:

Diffusing holes will recombine with the diffusing electrons. Net effect:

n-type end will become positively charged (positive donor ion)

p-type end will become negatively charged (negative acceptor ion)

a- This will create a zone of electric field across the junction which halts the diffusion, leaving a steady (immobile) space charge region.

b- potential difference across the junction, called contact potential. usually around 1 V and called depletion region

Now the the depletion region created is with no charge carriers and no current flowing through it. It is pure silicon (or germanium) material suitable for incoming radiations!!

## Depth of the depletion layer:

dielectric constant

mobility

$$d \cong (2\epsilon V \mu \rho_d)^{1/2}$$

Resistivity of the doped material

*Silicon*

$$d \simeq \begin{cases} 0.53 (\rho_n V_0)^{1/2} \mu\text{m} & \text{n-type} \\ 0.32 (\rho_p V_0)^{1/2} \mu\text{m} & \text{p-type} \end{cases}$$

*Germanium*

$$d \simeq \begin{cases} (\rho_n V_0)^{1/2} \mu\text{m} & \text{n-type} \\ 0.65 (\rho_p V_0)^{1/2} \mu\text{m} & \text{p-type} \end{cases}$$

where  $\rho$  is in  $\Omega \text{ cm}$  and  $V_0$  in Volts. If we take typical values of  $\rho \sim 20000 \Omega \text{ cm}$  for high-resistivity n-type silicon and  $V_0 = 1 \text{ V}$ , this yields  $d \simeq 75 \mu\text{m}$ , which is a rather small sensitive depth.

We want bigger depletion layer.  
We must apply bias voltage!!

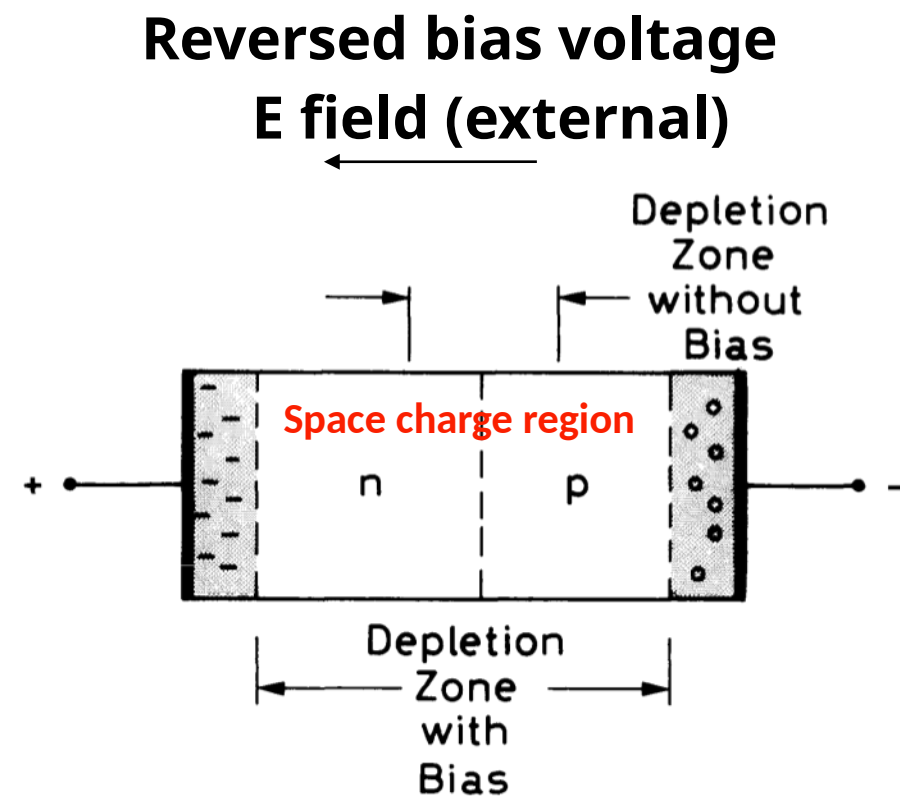
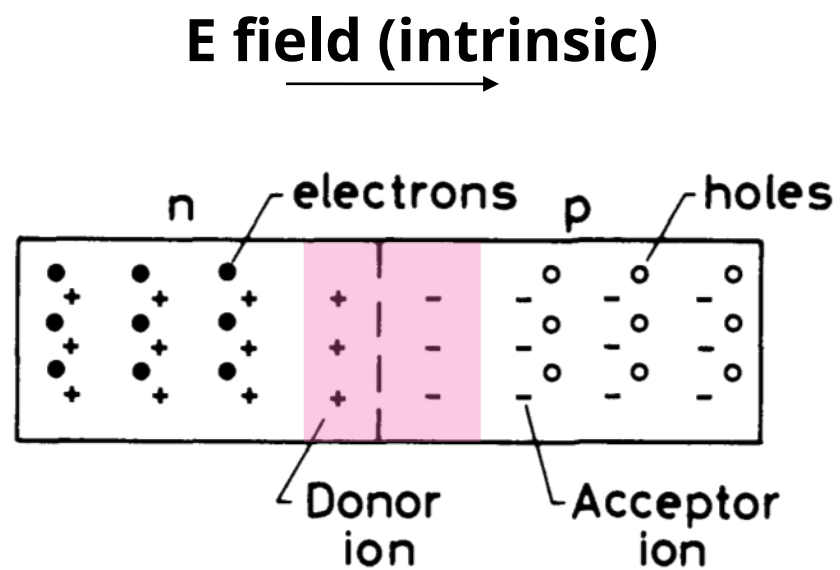
## Reversed Bias Voltage:

RB voltage is a negative voltage to the p-side

Main purpose: to increase the depletion zone

Voltage value: 4000-5000 V for germanium (less for silicon)

Negative voltage on the p-side will attract holes away from the junction  
positive voltage will attract electrons in the n-side.



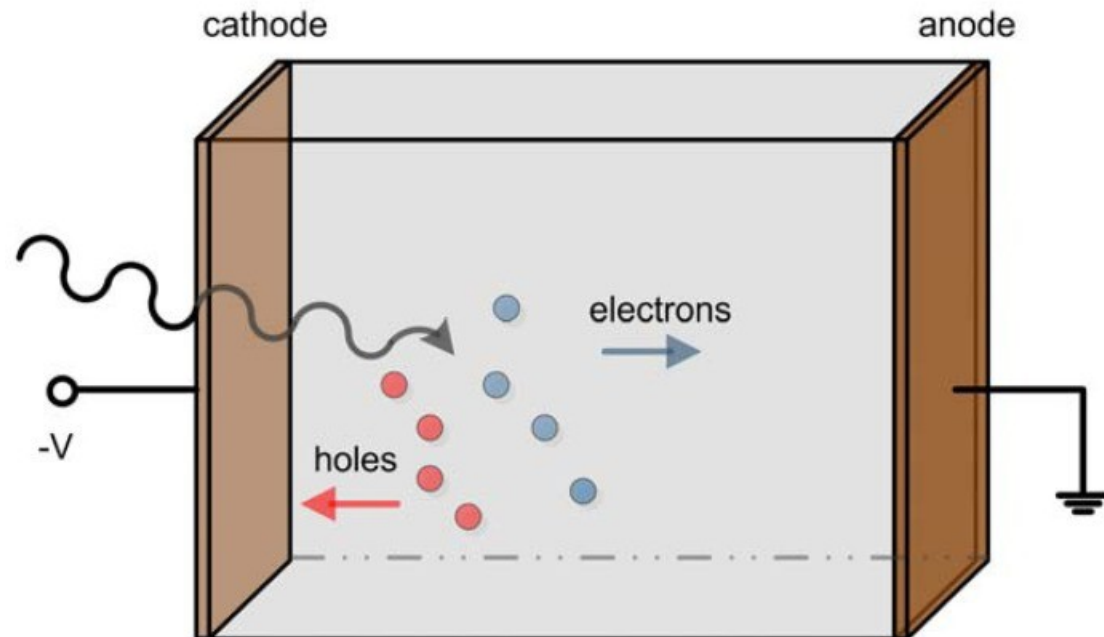
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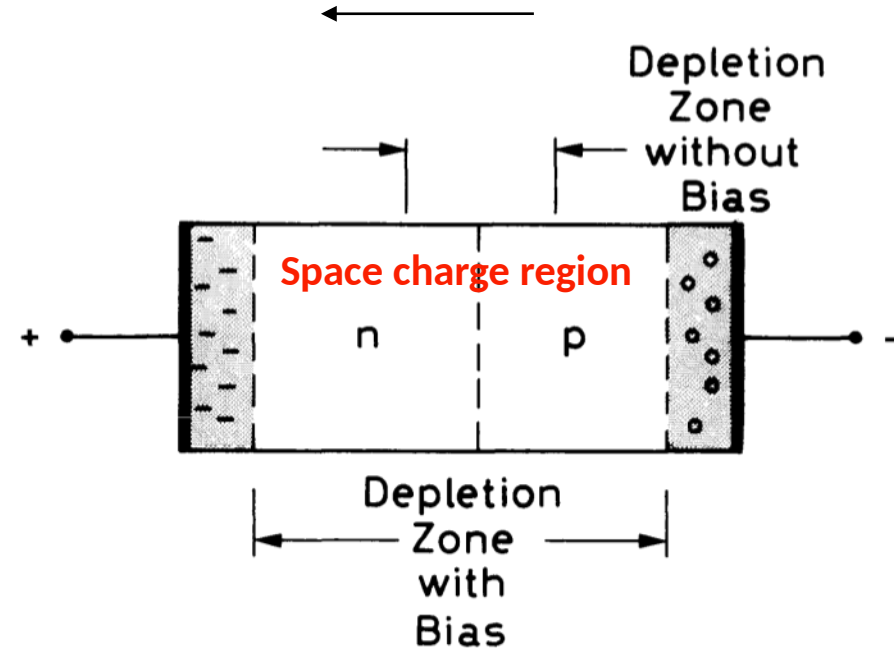
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### Reversed bias voltage E field (external)



# Characteristics of SC detectors:

## 1- Average energy per e-hole pair

**Table 10.2.** Average energy for electron-hole creation in silicon and germanium

|       | Si      | Ge      |
|-------|---------|---------|
| 300 K | 3.62 eV | —       |
| 77 K  | 3.81 eV | 2.96 eV |

## 3- Resolution + Fano factor

$F \sim 0.12$

$$R = 2.35 \sqrt{\frac{F}{J}} = 2.35 \sqrt{\frac{Fw}{E}}$$

## 2- Linearity

$$V = \frac{Q}{C} = n \frac{E}{wC}$$

$n$ : charge collection efficiency (charge collection on the electrodes)

depletion layer has to be large enough to keep linearity, i.e. should not be smaller than the range of the radiation.

## 4- cooling

( $T = 77\text{K}$  or  $-196^\circ\text{C}$ ) for Ge(Li)

( $T < 110\text{K}$  ( $< -163^\circ\text{C}$ ) for HPGe

## 5- Operating voltage

HV: 4000-5000 V



germanium detector + dewar filled with a liquid hydrogen

Please read and go through material below:

**Leakage current & Efficiency:** Leo pp: 229-230

**Bias Voltage, temperature effects, radiation damage:** Leo pp:  
243-245

## Germanium detectors

- 0 GeLi Detectors
- 0 HPGe Detectors
  - 1. Planar
  - 2. Coaxial

## Germanium detectors

- 0 GeLi Detectors

- 0 HPGe Detectors

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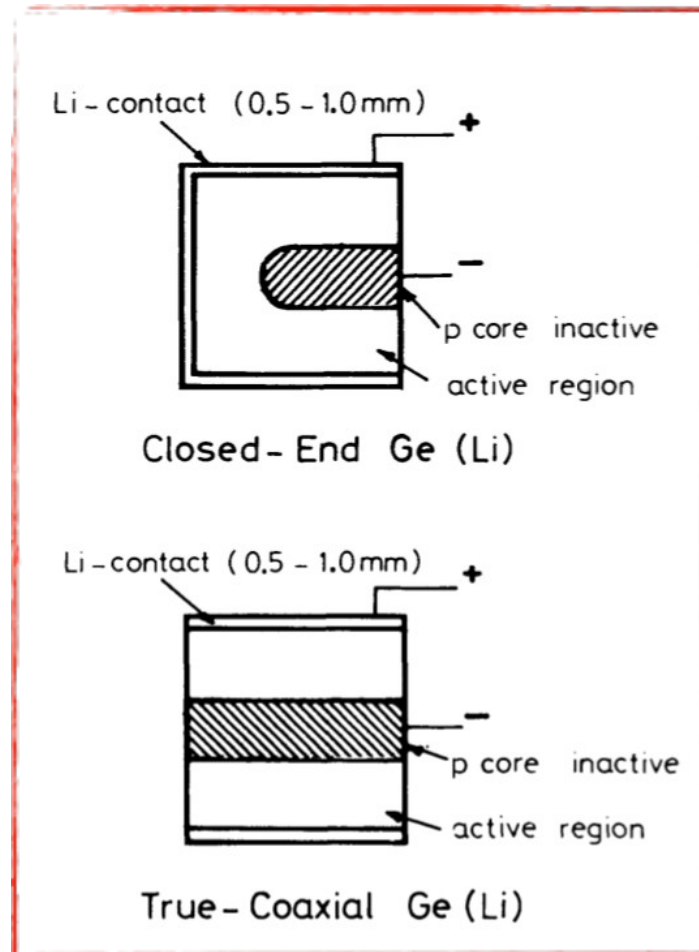
## lithium ion drifting process (Z=3 Group I element)

- In order to increase the conductivity, one could add equal amount of donor and acceptor impurities but this is a very difficult process to manage.
- Instead, in 1960 Pelle developed the lithium drifting method for compensating p-type silicon and germanium:

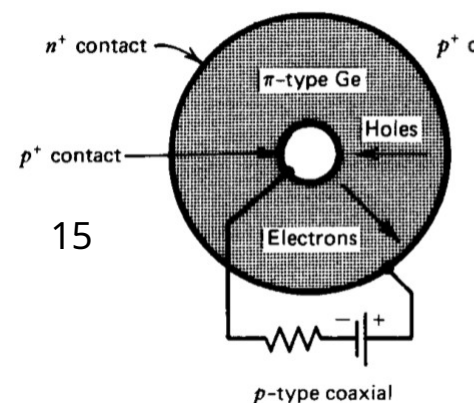
*Lithium is diffused onto the surface of a p-type material. (Note that Lithium (Z=3) acts as a donor with one valence electron.) This changes that end of the semiconductor into an n-type material. The concentration of lithium drops off in a Gaussian manner so that the junction between the n-type and p-type regions lies at some depth under the surface.*

## Ge(Li) detectors

pronounced as “jelly”



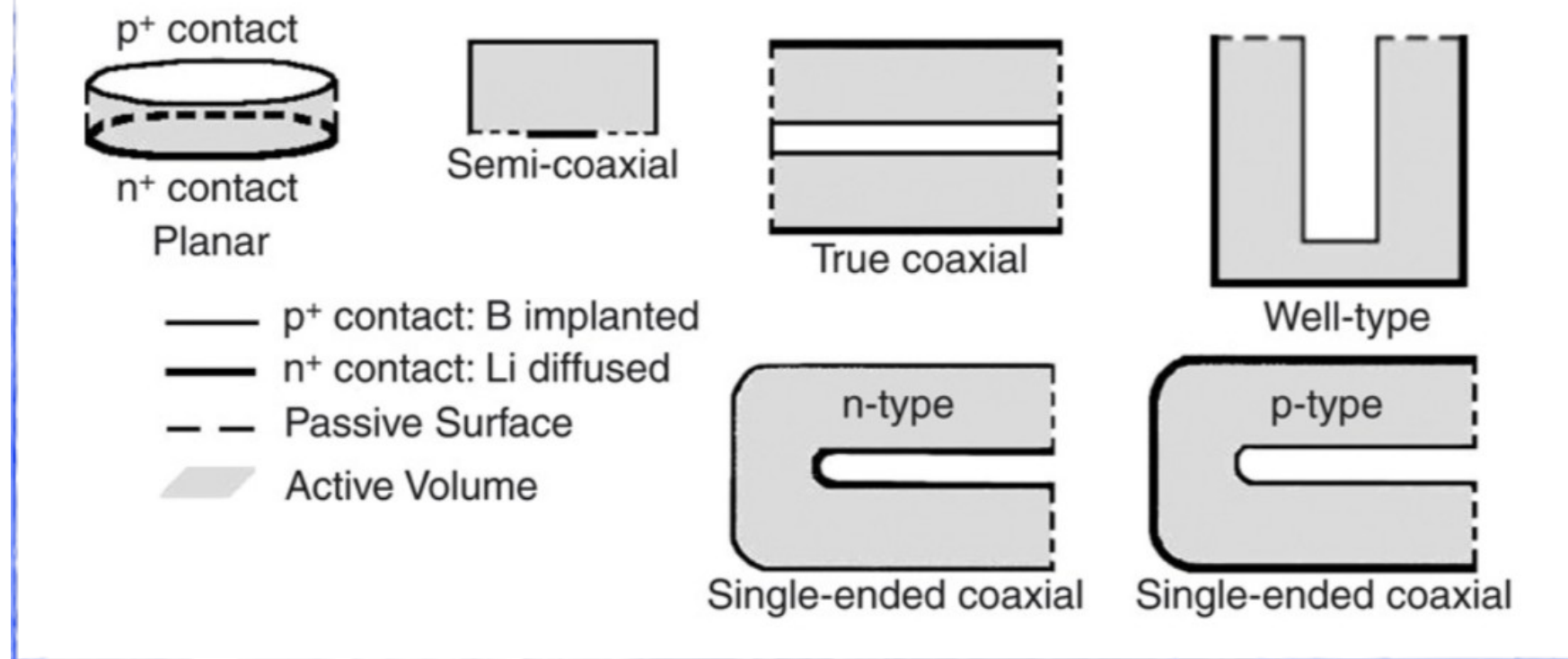
- Year 1960 was innovative for a new doping method
- Lithium was used as doping
- Li has 1 valence electron and acts as donor in Ge
- Ge is doped by “diffusion” of Li (high mobility)
- After a drifting time of weeks or months a thickness of the compensated layer of up to 35 mm can be achieved for a coaxial detector.
- Creating Ge(Li) type detector material takes time.



## Germanium detectors

- 0 GeLi Detectors
- 0 HPGe Detectors
  - 1. Planar
  - 2. Coaxial

## HPGe detectors



- In the late 1970s
- Pure samples of the detector material could be prepared only for germanium material
- The production process of a detector is much faster since no time-consuming drifting process is needed.
- The commercial production of Ge(Li) detectors was given up around 1980 when the volume of HPGe detectors became competitive with the volume of Ge(Li) detectors
- The size of pure crystals is limited to approximately 5 cm in diameter by 1 cm thick (it is much more improved at present: 9 cm length 8 cm circular diameter for the most advance **HPGe detectors**. But still smaller compared to scintillators!!)
- Quite expensive

# What is High Purity exactly?

## Internal impurities

$$d \cong \left( \frac{2\epsilon V}{eN} \right)^{1/2}$$

d: depletion layer

V: applied High voltage

N: internal impurity concentration

€: dielectric constant

For a typical intrinsic germanium material,  $N=10^{13}$  atoms/cm<sup>3</sup>

For HPGe-->  $N=10^{10}$  atoms/cm<sup>3</sup>

Because of that the germanium material should be as pure as possible. Such material is then called High Purity Germanium material. Silicon cannot be purified that much.

## External impurities (Dopant)

$$d \cong (2\epsilon V \mu \rho_d)^{1/2}$$

$$\text{where } \rho_d = \frac{1}{e \mu N_D}$$

$N_D$ : dopant concentration

$\rho_d$ : resistivity of the doped semiconductor, opposition to the conductivity ( $\sigma$ )

$\mu$ : mobility of the major charge carrier

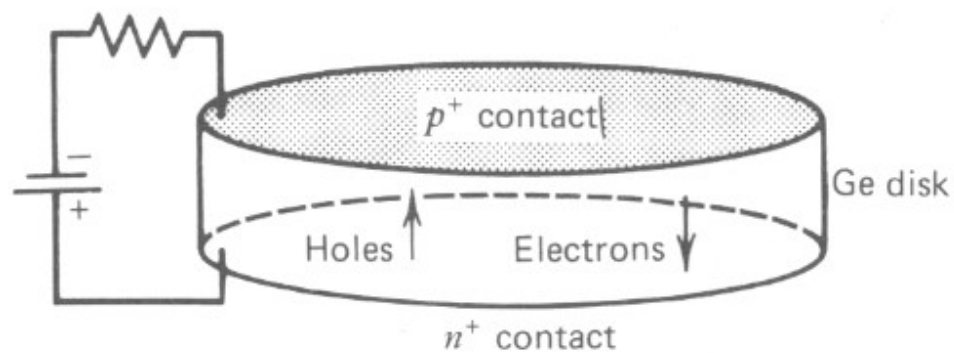
High voltage value is necessary for a larger depletion region (4000-5000 V for germanium material).

This high voltage value requires higher resistivity of the doped material which is limited by the (internal) impurity concentration before doping.

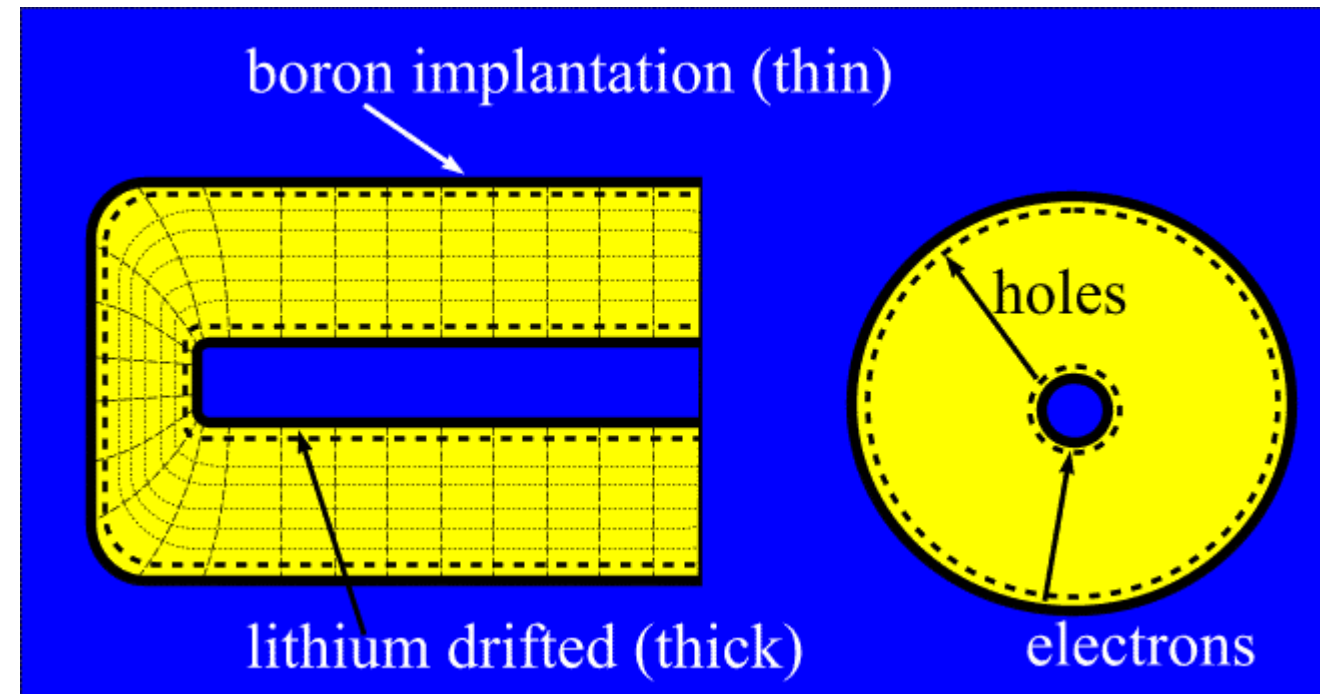
The dopant concentration cannot be too small but sufficient to override the nonuniform effects of the residual impurities (internal).

Operated at 77 Kelvin using liquid nitrogen.

## Planar



## Coaxial



In Coaxial crystals:

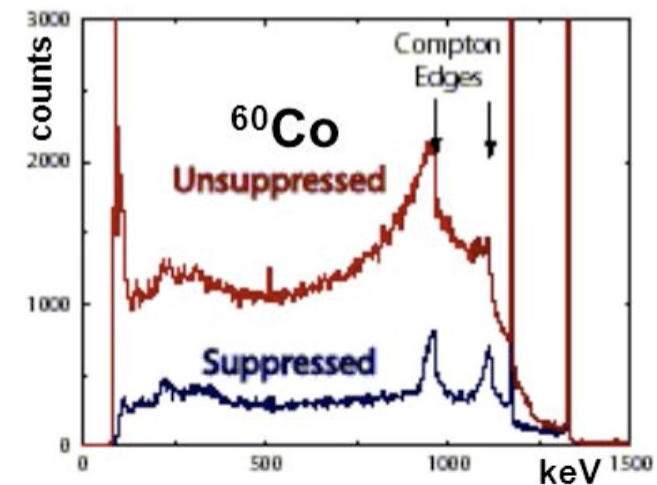
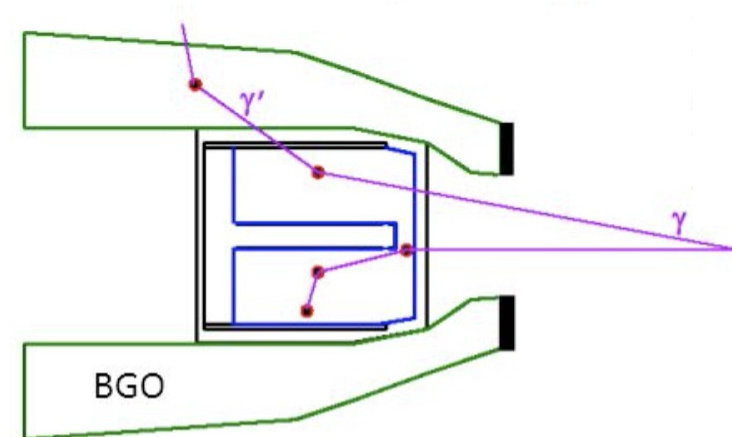
|         | Outer Contact | Inner |
|---------|---------------|-------|
| Contact |               |       |
| p-type  | n(Li)         | p(B)  |
| n-type  | p(B)          | n(Li) |

The n  $\sim$  600  $\mu\text{m}$  - 1 mm, p contact is very thin  $\sim$  0.3  $\mu\text{m}$ .

## *BGO Compton suppression*



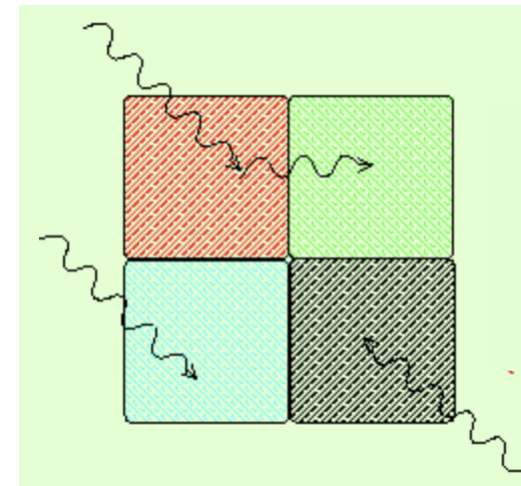
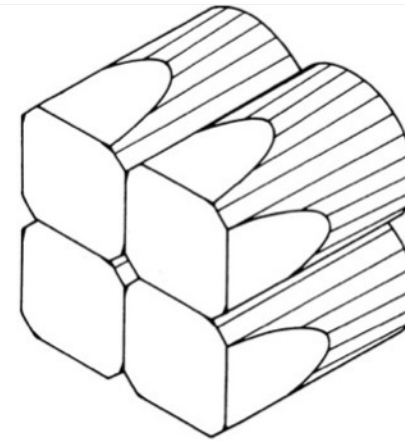
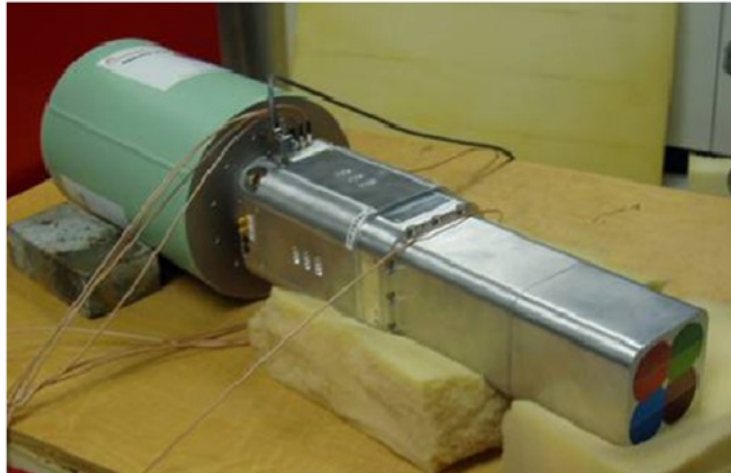
ROSPHERE at Bucharest, Romania



For large Ge arrays: **P/T (Peak to Total) Ratio** improves from 20% to 60%

# $4\pi$ -Ge Arrays: Segmented crystals

Clover (4-fold segmentation)



Addback

Fig. 15. Eurogam II at IReS Strasbourg.

# MINIBALL at CERN/ISOLDE

## 6-fold segmentation

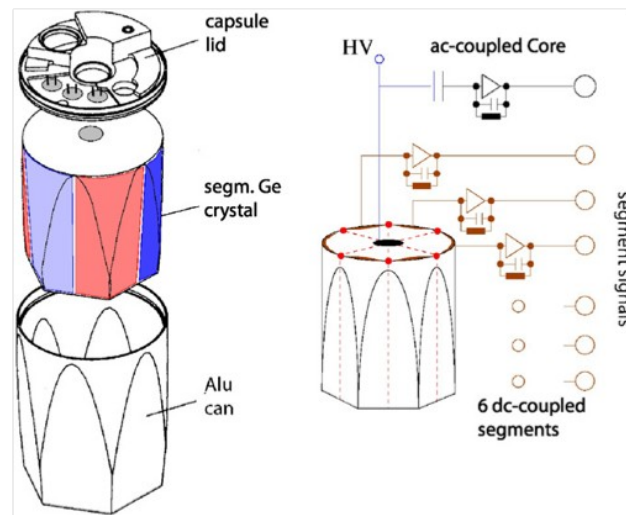
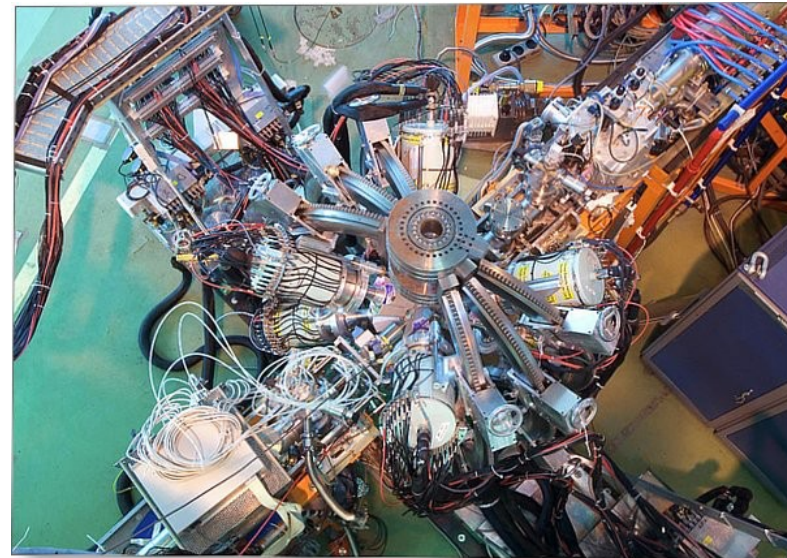
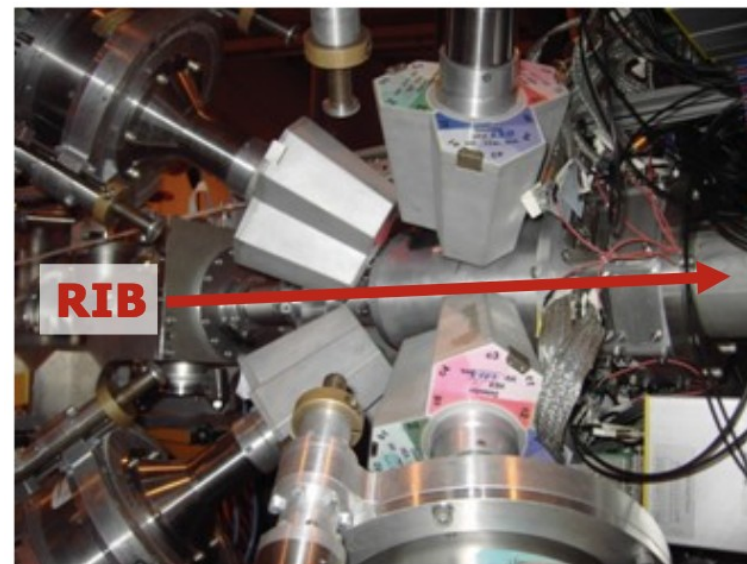
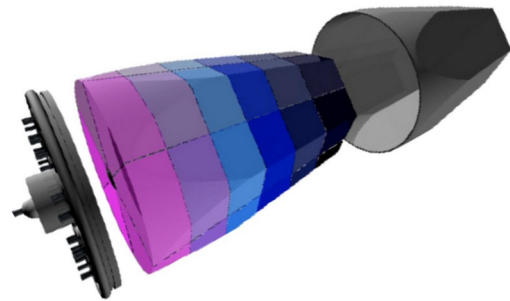


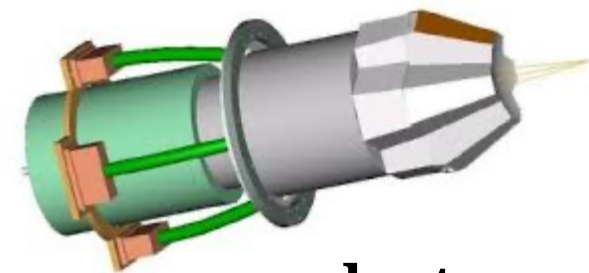
Fig. 23. The segmented MINIBALL detector.



# $4\pi$ -Ge Arrays: Highly segmented *HPGe* arrays



triple clusters



seven clusters

36-fold segmentation

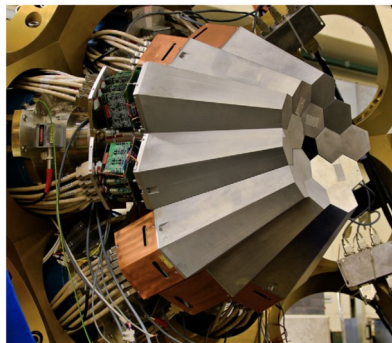
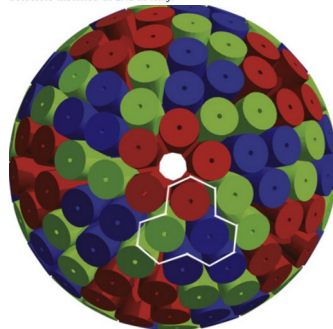
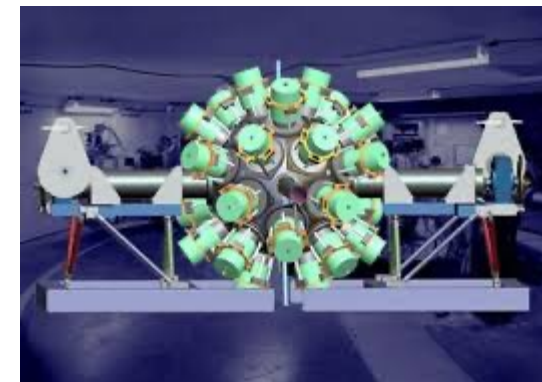
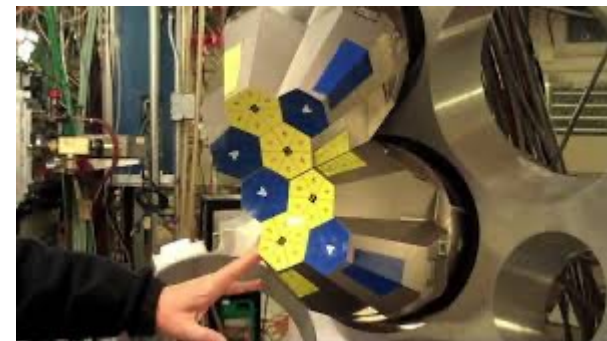


Fig. 6. (Colour online) Photograph of the setup with five AGATA triple cluster detectors installed at LNL in Italy.

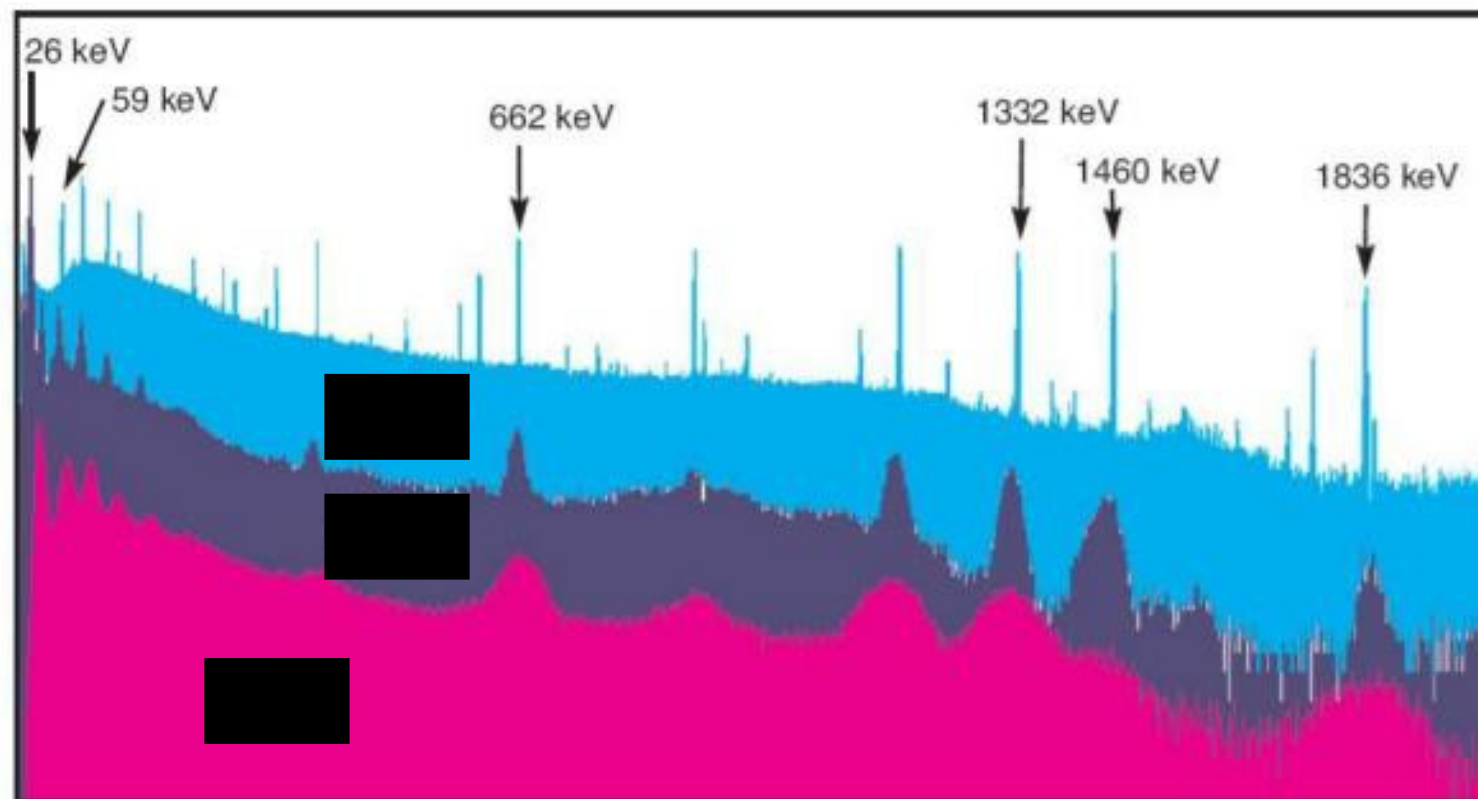


AGATA, Europe



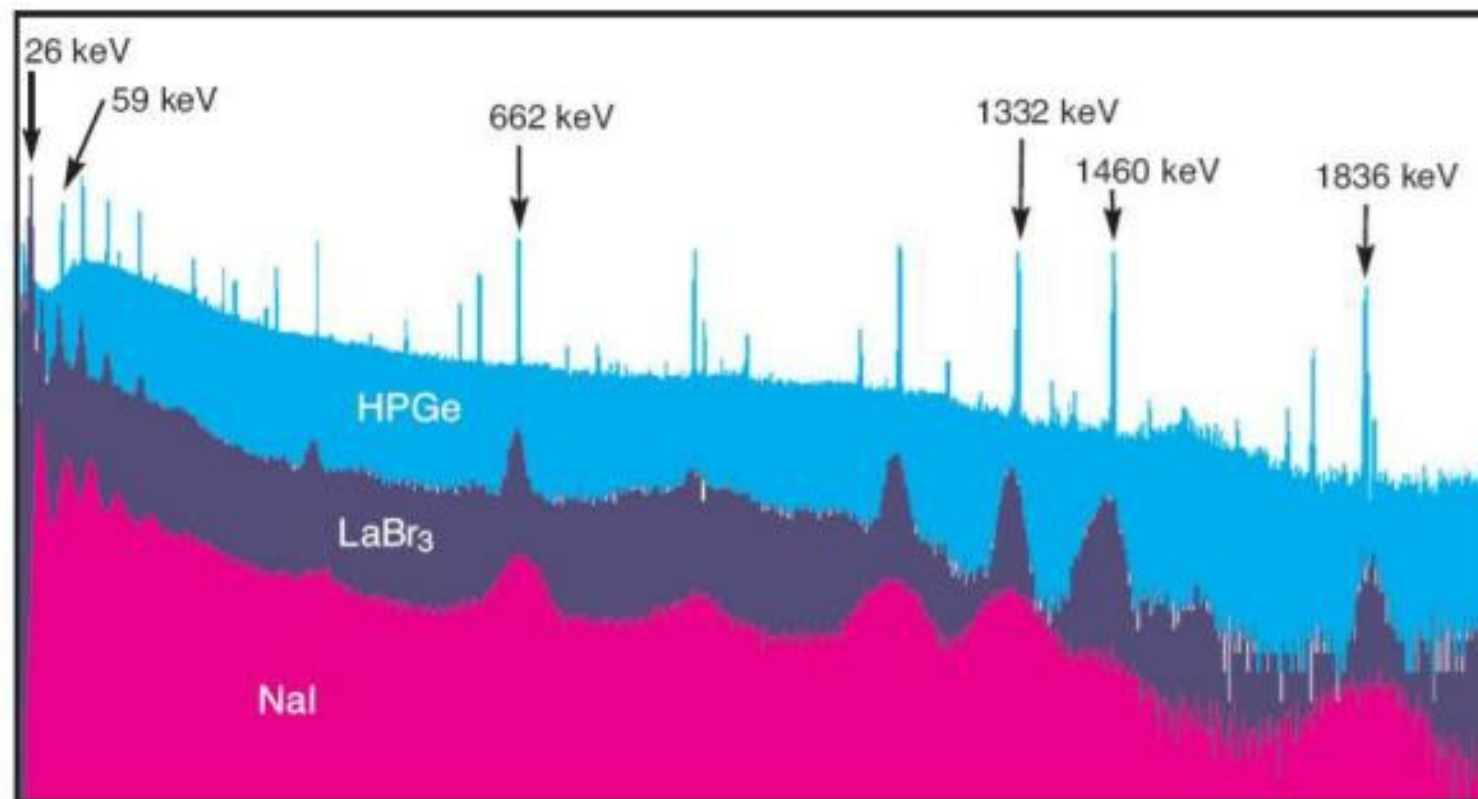
GRETA, USA

## Comparison of HPGe, NaI, and LaBr



Match colours to each detector type!!

## Comparison of HPGe, NaI, and LaBr



## High Count Rate Compatibility

Lanthanum bromide detectors can operate over wide dynamic ranges of count rate with little variation in energy resolution.

| Detector Type          | Resolution @622 keV (%) | Density (g/cc) | Photoelectron Yield Relative to NaI | Primary Decay Time (usec) |
|------------------------|-------------------------|----------------|-------------------------------------|---------------------------|
| LaBR <sub>3</sub> (Ce) | 2.8 - 4.0               | 5.29           | 130                                 | 0.026                     |
| NaI(Tl)                | 7                       | 3.7            | 100                                 | 0.230                     |
| HPGe                   | 0.2 (1.3 keV)           | 5.35           | N/A                                 | N/A                       |

# Questions to you

- o Why do we prefer germanium ( $Z=32$ ) to silicon ( $Z=14$ ) for gamma-ray detection? Can you explain by giving numerical values?
- o How do semi-conductor detectors work? Draw and explain the concept of energy bands in this context. What are the charge carriers in semi-conductor materials?
- o What type of preamplifier would you suggest for Germanium detectors? Explain reasoning. (Hint: Get help from Lecture 8 pulse signal processing. )
- o Should Preamplifier amplify the signal from the detector output significantly? Why should Preamplifier should stay very close to the germanium detector output?
- o How does a Germanium detector work (depletion layer, pn junction)?
- o Why do you have to cool Germanium detectors? Explain why it is important to increase the bias voltage in small steps.
- o What is the effect of Compton suppression? What type of detectors are used for Compton suppression? And why?

# Today

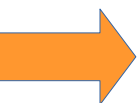
- Scintillation
  - Organic scintillators
    - Anthracene
    - Stilbene
    - Plastic
    - Liquid
  - Inorganic scintillators
    - NaI(Tl)
    - CsI(Tl)
    - LaBr<sub>3</sub>(Ce)
    - BGO
- PMTs (Photomultiplier Tubes)
  - Mechanism
  - Photocathode
  - Quantum efficiency
- Time response
  - Organic
  - Inorganic
- Pulse shape discrimination
  - Organic
- Light output
  - Organic
  - Inorganic
- Energy resolution
  - Inorganic
- Detector efficiency
  - Heavy charged particle
  - Electrons
  - Gamma rays
  - Neutrons

**Table 7.3.** Average energy loss per scintillator photon for electrons

| Material   | $\epsilon$ [eV/photon] |
|------------|------------------------|
| Anthracene | 60                     |
| NaI        | 25                     |
| Plastic    | 100                    |
| BGO        | 300                    |

- The light output of a scintillator refers more specifically to its efficiency for converting ionization energy to photons.
- The fraction of all incident particle energy which is converted into visible light is called “*scintillation efficiency*” or “*light output*”
- *Light output depends on the type of the radiation and energy*

Q: Can you tell the which type has the largest light output in Table 7.3?



## Examples of light output for inorganic scintillators

- Deviations from linearity are less for inorganic scintillators.
- Non-linearity starts from 400 keV down to zero energy value
- We have to take care of this non-linearity (in the step of energy calibration of the detectors)

*Perfectly linear response would correspond to a horizontal line*

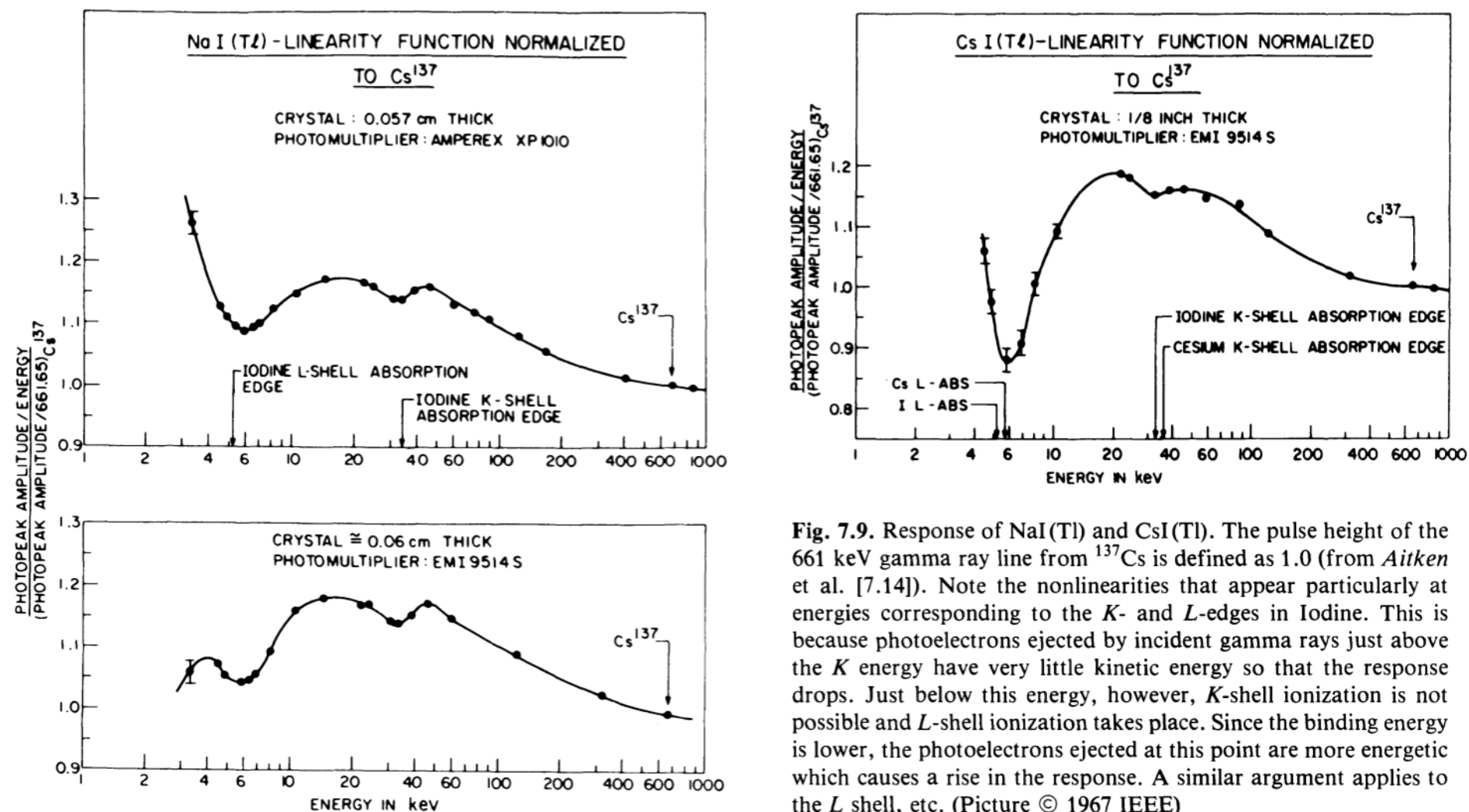


Fig. 7.9. Response of NaI(Tl) and CsI(Tl). The pulse height of the 661 keV gamma ray line from  $^{137}\text{Cs}$  is defined as 1.0 (from Aitken et al. [7.14]). Note the nonlinearities that appear particularly at energies corresponding to the  $K$ - and  $L$ -edges in Iodine. This is because photoelectrons ejected by incident gamma rays just above the  $K$  energy have very little kinetic energy so that the response drops. Just below this energy, however,  $K$ -shell ionization is not possible and  $L$ -shell ionization takes place. Since the binding energy is lower, the photoelectrons ejected at this point are more energetic which causes a rise in the response. A similar argument applies to the  $L$  shell, etc. (Picture © 1967 IEEE)

## Examples of light output for plastic (organic) scintillator

- Light output decreases for heavier particles
- Linearity is worsen for heavier particles.

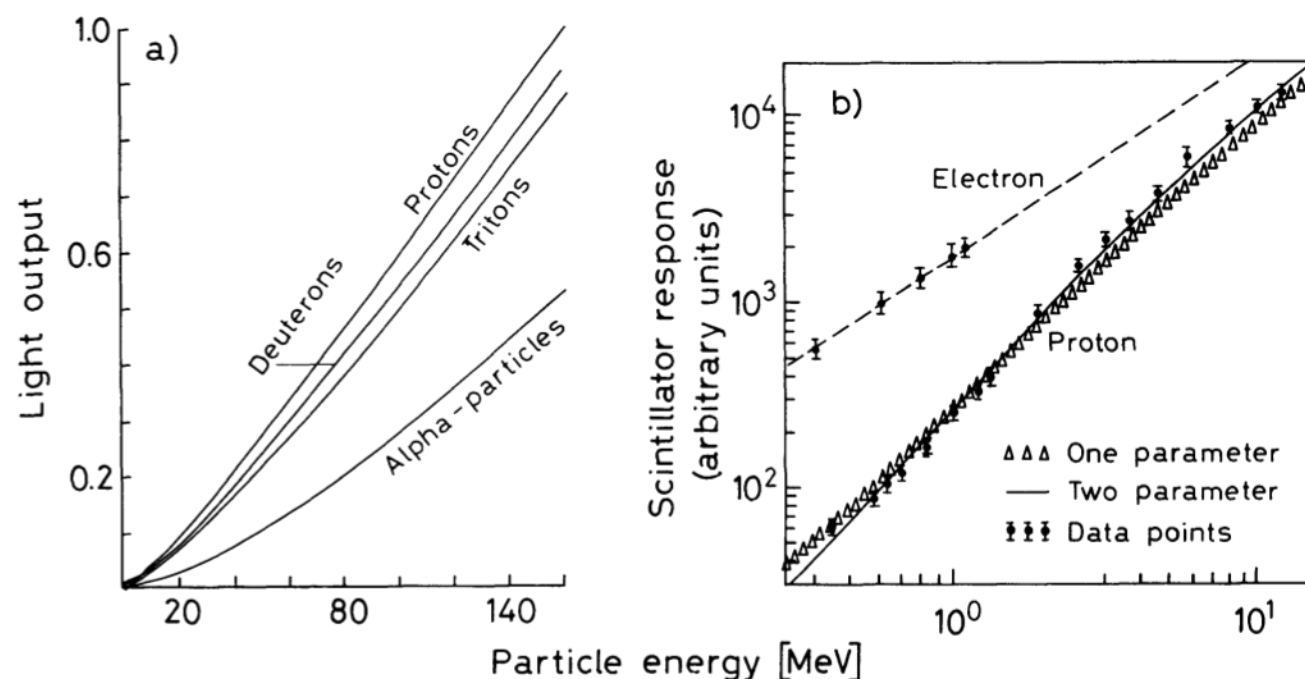


Fig. 7.8a, b. Response of NE102 plastic scintillator to different particles ((a) from Gooding and Pugh [7.6]; (b) from Craun and Smith [7.7])

**Quenching interactions:** Some energy loss is dissipated non-radiatively, primarily in the form of lattice “vibrations” or “heat”. These radiationless de-excitation processes are called “**quenching**”

Since a higher ionizing power (alphas for example) produces a higher density of excited molecules, more quenching interactions will take place for these particles.

# Temperature dependence

The plot shows how sensitive is the decay time with temperature changes

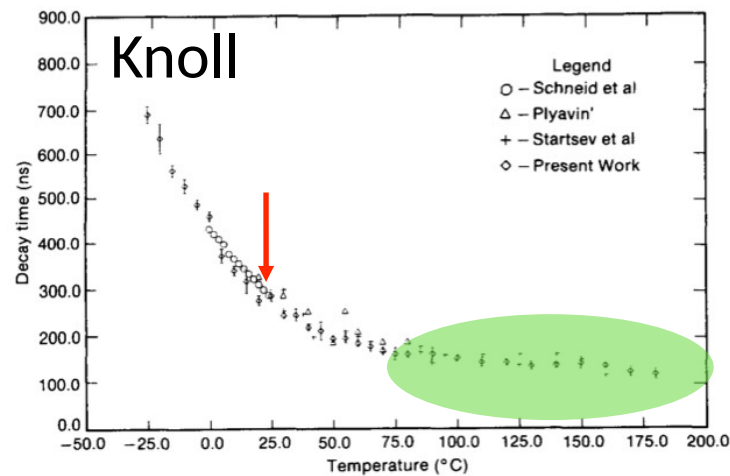
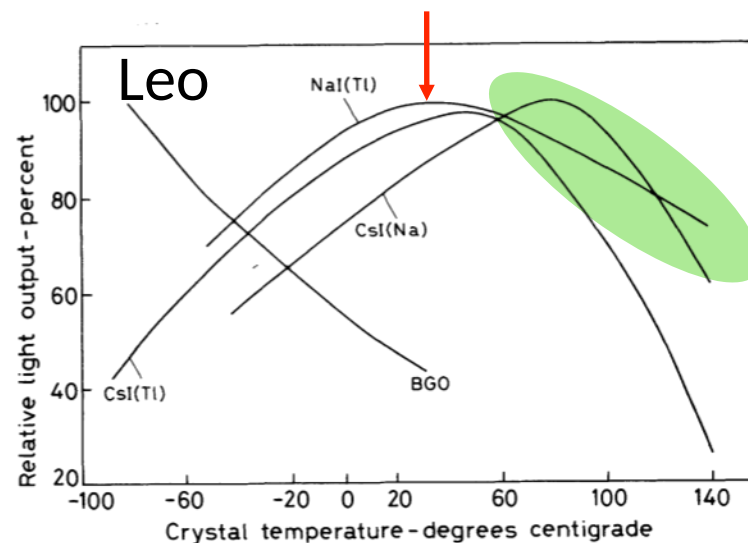


**Figure 8.10** Temperature dependence of the scintillation decay time in NaI(Tl). (From Schweitzer and Ziehl.<sup>83</sup>)



Inorganic scintillators work mostly in room temperatures.

- For some applications low decay time is desired.
- Can be obtained via high temperature
- However, light yield decreases significantly.

Organic scintillators have the same light output between the temperatures -60 to 20 °C i.e. less temperature dependent

# Today

- Scintillation
  - Organic scintillators
    - Anthracene
    - Stilbene
    - Plastic
    - Liquid
  - Inorganic scintillators
    - NaI(Tl)
    - CsI(Tl)
    - LaBr<sub>3</sub>(Ce)
    - BGO
- PMTs (Photomultiplier Tubes)
  - Mechanism
  - Photocathode
  - Quantum efficiency
- Time response
  - Organic
  - Inorganic
- Pulse shape discrimination
  - Organic
- Light output
  - Organic
  - Inorganic
- Energy resolution
  - Inorganic
- Detector efficiency
  - Heavy charged particle
  - Electrons
  - Gamma rays
  - Neutrons

## Let's calculate energy resolution for a 662 keV gamma ray on a NaI(Tl) Detector

**Table 7.3.** Average energy loss per scintillator photon for electrons

| Material   | $\epsilon$ [eV/photon] |
|------------|------------------------|
| Anthracene | 60                     |
| NaI        | 25                     |
| Plastic    | 100                    |
| BGO        | 300                    |

$$E_\gamma = 662 \text{ keV}$$

$$N_{\text{photons}} = J = \frac{E_0}{\epsilon} = \frac{E_0}{W}$$

$$= \frac{662 \text{ keV}}{25 \text{ eV}}$$

$$= 26480 \text{ photons}$$

What about Fano factor?

### Case 1:

For a detector in which the radiation energy is **not totally absorbed**, the number of signals producing reactions is given by a **Poisson distribution**. Fano factor=1

**Scintillator**

### Case 2:

If the energy of the radiation is **fully absorbed** as is the case for detectors used in spectroscopy experiments, the Poisson statistics is incorrect. Fano factor  $\ll 1$

**Gas  
Solid-state  
detectors**

## Let's calculate energy resolution for a 662 keV gamma ray on a NaI(Tl) Detector

**Table 7.3.** Average energy loss per scintillator photon for electrons

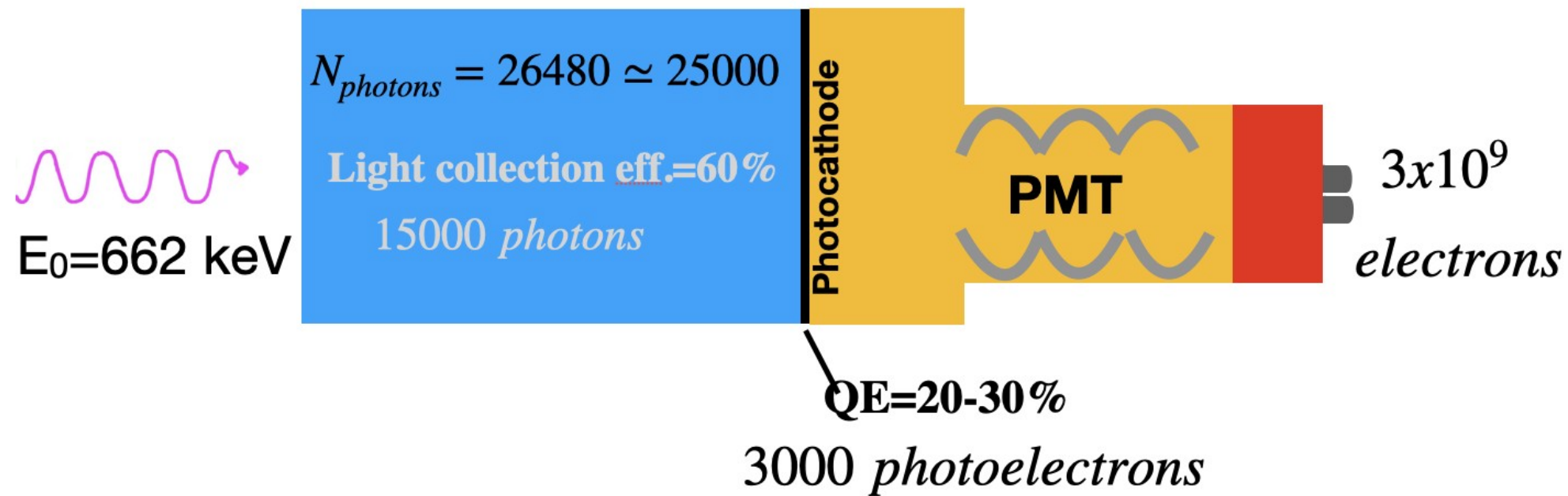
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$$N_{photons} = J = \frac{E_0}{\epsilon} = \frac{E_0}{w}$$

$$= \frac{662 \text{ keV}}{25 \text{ eV}}$$

$$= 26480 \text{ photons}$$



$$\frac{\Delta E_{FWHM}}{E_0} = 2.35 \frac{\sigma_J}{J} = 2.35 \frac{\sqrt{(3000)}}{3000} = 0.043 = 4.3\%$$

Light output or light yield has affect on the energy resolution.  
While density of the scintillator has affect on its efficiency.

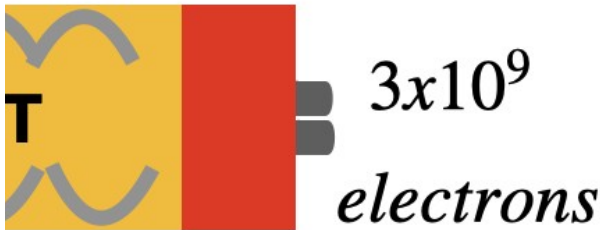
$$N_{photons} = 26480 \simeq 25000$$

**Table 7.3.** Average energy loss per scintillator photon for electrons

| Material   | $\epsilon$ [eV/photon] |
|------------|------------------------|
| Anthracene | 60                     |
| NaI        | 25                     |
| Plastic    | 100                    |
| BGO        | 300                    |

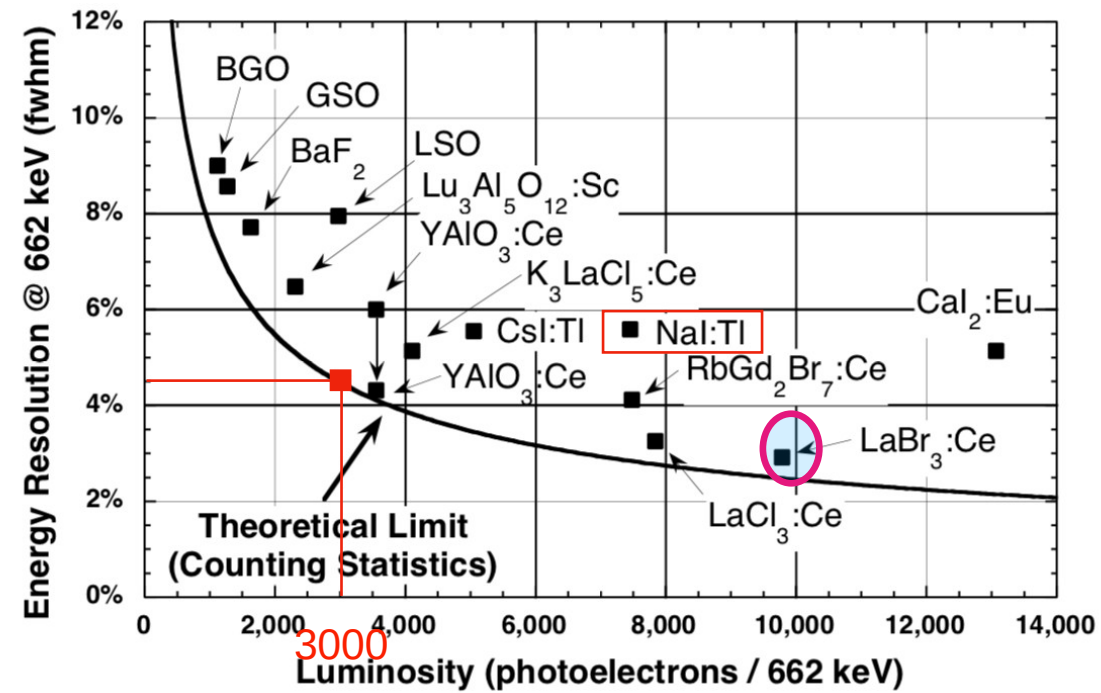
→ Best resolution

→ Highest efficiency



trons

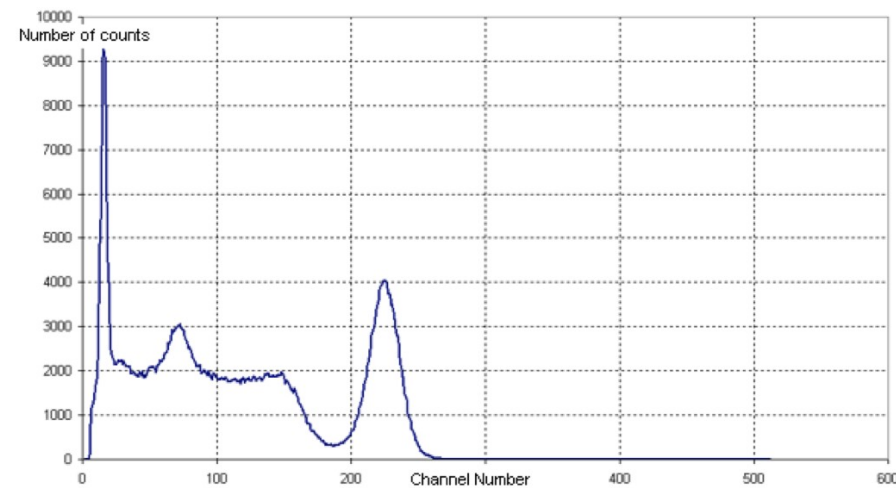
Light output or light yield has affect on the energy resolution.  
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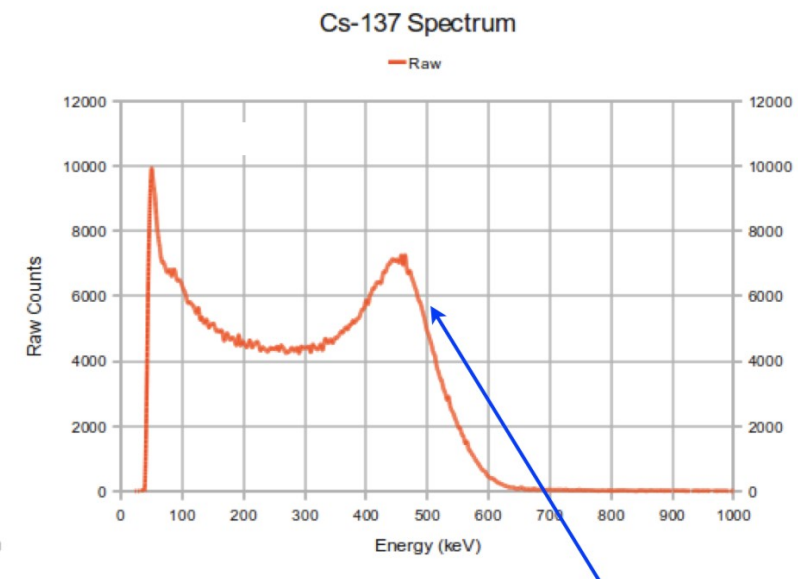
Resolution is never reached to the optimum value due to different losses in Scint. detectors.

# Inorganic vs Organic

- $^{137}\text{Cs}$  spectrum in NaI crystal



same in plastic scintillator



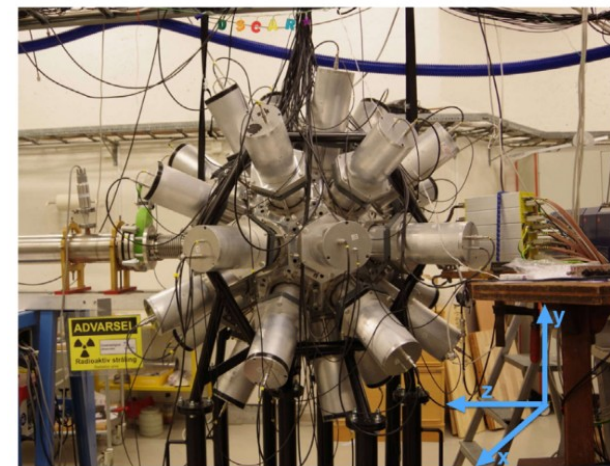
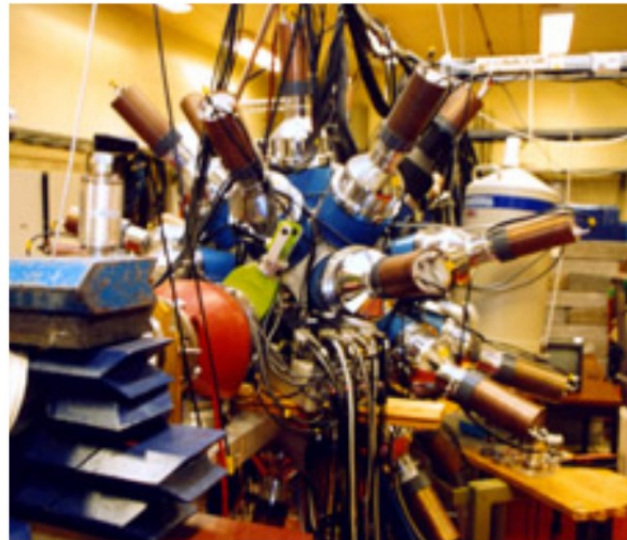
Compton edge or full peak?

Organic scintillators have low density (low-Z) (C and H only) while Photoelectric absorption is proportional to  $Z^4$  or  $Z^5$

# CACTUS vs OSCAR

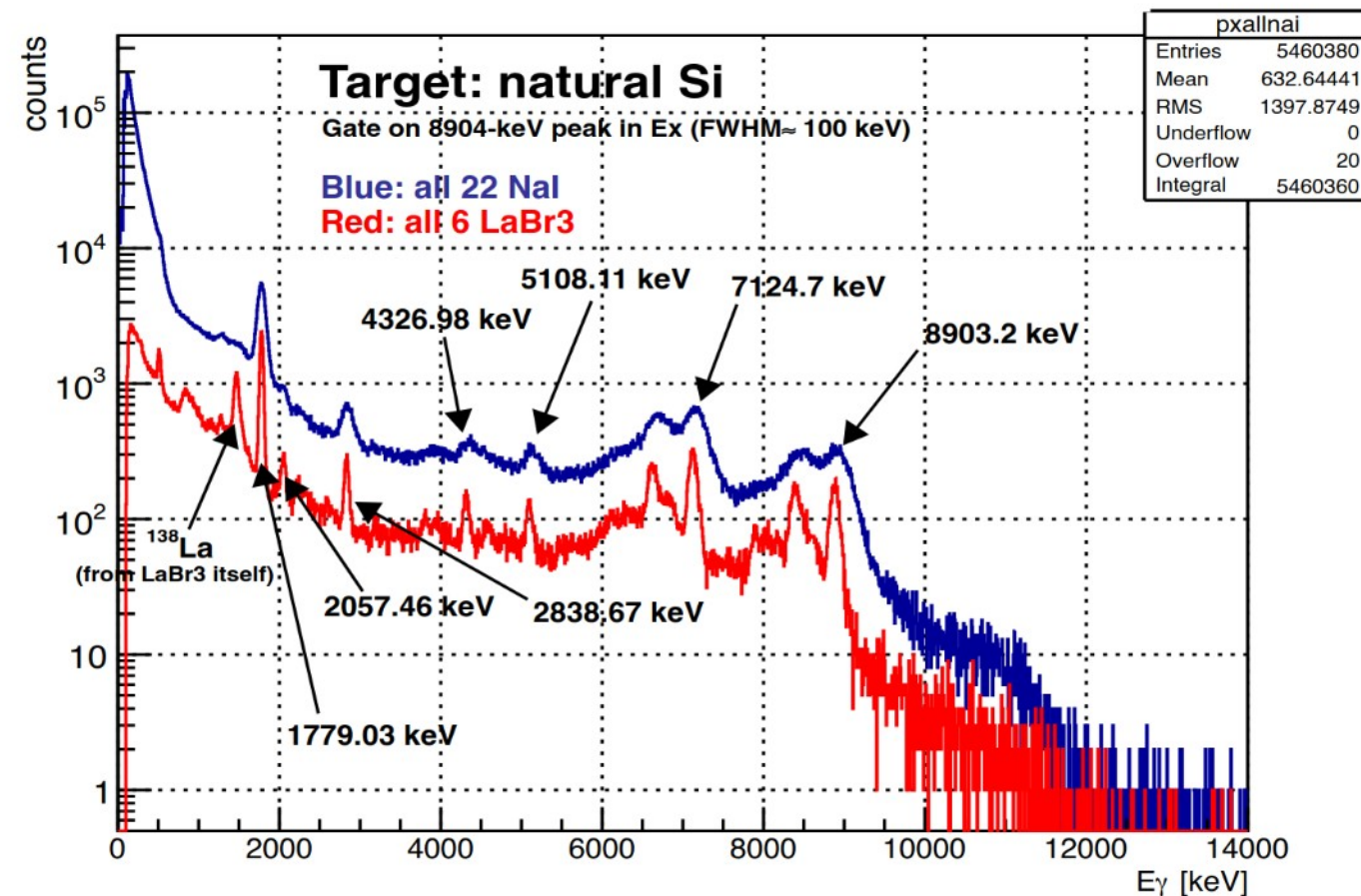
## CACTUS Array

- 0 30 large volume NaI (Tl) detectors.
- 0 Dimension: ( $\varnothing$  5 × 5 inches)



## Oslo Scintillator Array (OSCAR)

- 0 30 large volume LaBr3(Ce) detectors.
- 0 Dimension: ( $\varnothing$  3.5 × 8 inches)



Comparison of energy resolutions

| Detector Type          | Resolution @622 keV (%)<br>Resolution | Density (g/cc)<br>Efficiency | Photoelectron Yield Relative to NaI | Primary Decay Time (usec) | W (eV/photon) |
|------------------------|---------------------------------------|------------------------------|-------------------------------------|---------------------------|---------------|
| LaBr <sub>3</sub> (Ce) | 2.8 - 4.0                             | 5.29                         | 130                                 | 0.026                     | 16            |
| NaI(Tl)                | 7                                     | 3.7                          | 100                                 | 0.230                     | 25            |
| HPGe                   | 0.2 (1.3 keV)                         | 5.35                         | N/A                                 | N/A                       |               |

LaBr<sub>3</sub>(Ce) crystals is better than that of NaI(Tl) crystals in terms of “internal homogeneity”. In other words, LaBr<sub>3</sub>(Ce) has much smaller variation in energy response across the detector than NaI(Tl).

This uniformity is crucial for a more accurate energy measurement and helps avoid broadening of the energy peaks

Crystal structure, losses due to quenching interactions

# Not Today



- Scintillation
  - Organic scintillators
    - Anthracene
    - Stilbene
    - Plastic
    - Liquid
  - Inorganic scintillators
    - NaI(Tl)
    - CsI(Tl)
    - LaBr<sub>3</sub>(Ce)
    - BGO
- PMTs (Photomultiplier Tubes)
  - Mechanism
  - Photocathode
  - Quantum efficiency
- Time response
  - Organic
  - Inorganic
- Pulse shape discrimination
  - Organic
- Light output
  - Organic
  - Inorganic
- Energy resolution
  - Inorganic
- Detector efficiency
  - Heavy charged particle
  - Electrons
  - Gamma rays
  - Neutrons

# In-class activity

Figure out detection efficiency for different types of radiation (for scintillation detectors).

Heavy-ions

Electrons

Gammas

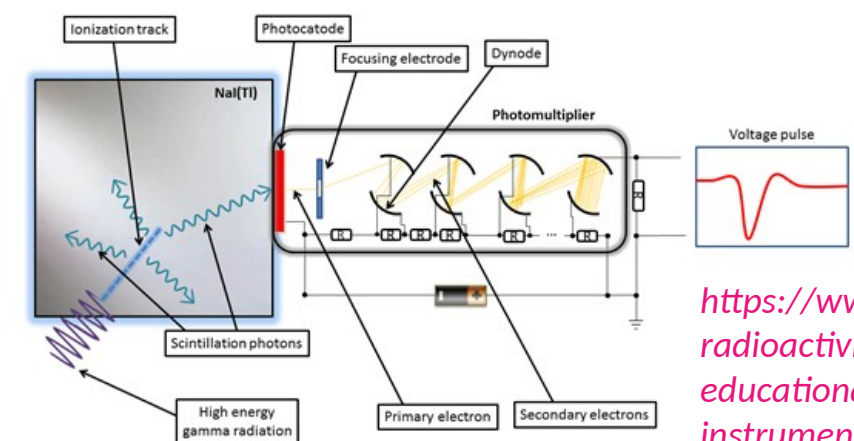
Neutrons

# Questions to you

- 0 How do scintillator detectors work? What is the mechanism of a scintillator detector independent from its type? What properties are important to look at when comparing various types of scintillator materials?
- 0 Explain how scintillation light is produced in inorganic scintillator materials and why we dope inorganic scintillators.
- 0 Explain how an organic scintillator produces light. What is the desired process?
- 0 Compare organic and inorganic scintillators. List main differences.
- 0 How can you estimate the energy resolution of an inorganic scintillator detector? Feel free to give numerical explanations.

- 0 Which scintillator detector is optimum for:

- beta particles
- alpha particles
- gamma rays
- Neutrons



- 0 What are the advantages of LaBr<sub>3</sub> detectors compared to NaI(Tl) detectors?
- 0 Compare a typical gamma-ray pulse-height spectrum in organic and inorganic scintillator detector. Which one would you choose?
- 0 Explain how a PMT works and what it is used for. Draw and explain.

## Pulse shape discrimination

**Slow light output component as a function of time** produces a long tail which depends on the nature of the exciting particle/radiation.

The slow component fraction should depend primarily on the rate of energy loss  $dE/dx$  of the exciting particle and should be greatest for particles with large  $dE/dx$ . ( $\alpha > \beta > \gamma$ )

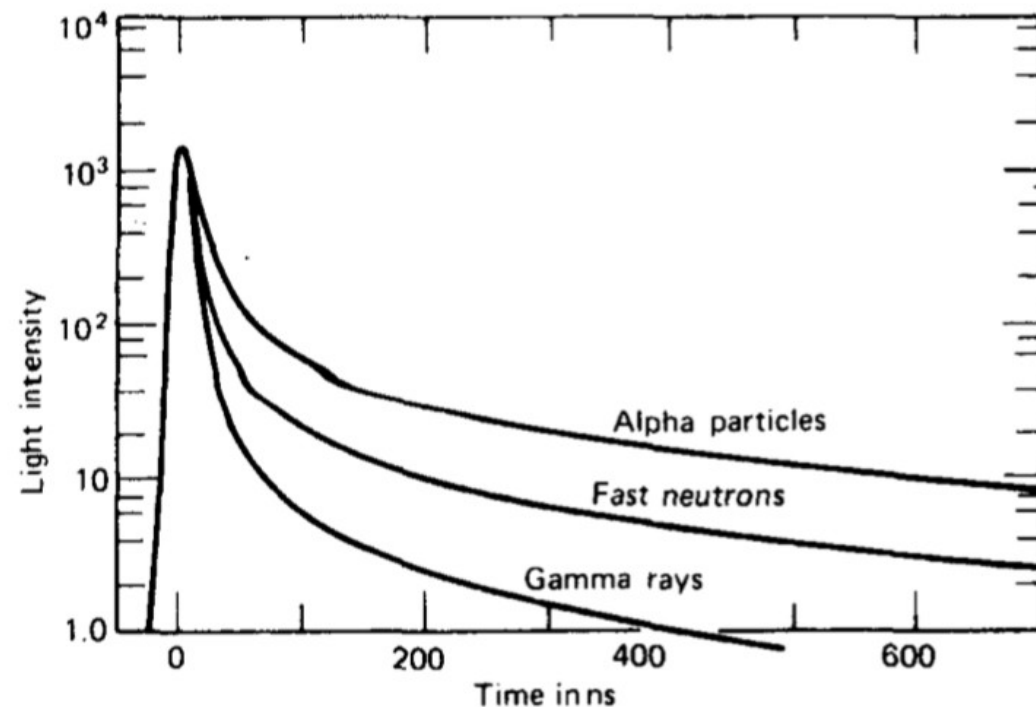
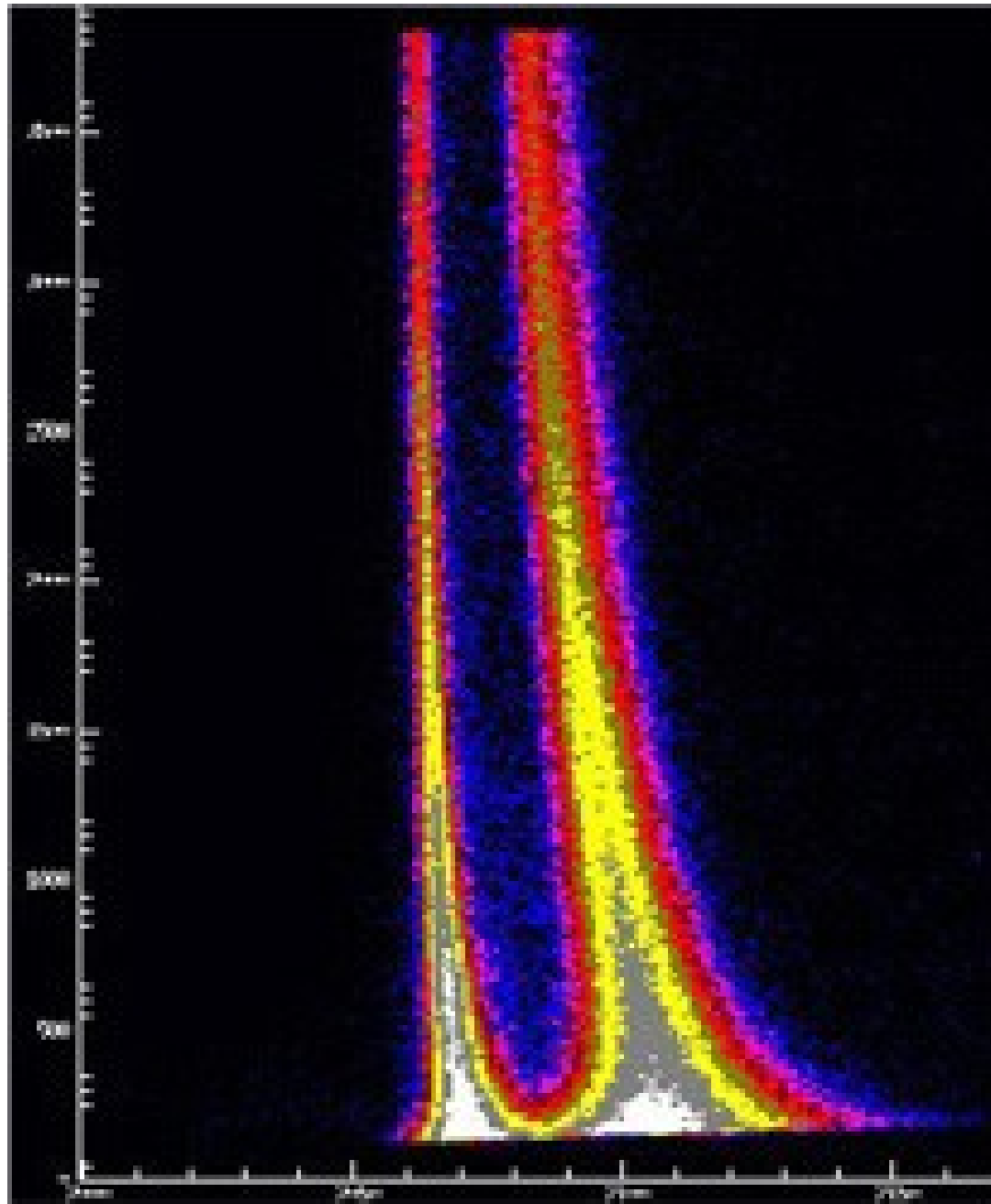


**Figure 8.5** The time dependence of scintillation pulses in stilbene (equal intensity at time zero) when excited by radiations of different types. (From Bollinger and Thomas.<sup>60</sup>)

PSD is used to **eliminate gamma-ray-induced events when organic scintillators are used as neutron detectors.**

**stilbene and liquid scintillators**

## What about inorganic scintillators?



Otherway around:

LaBr<sub>3</sub>(Ce) detectors have fast timing, i.e. good time resolution, compared to NaI(Tl).

We can then use them to **eliminate neutron induced events as LaBr<sub>3</sub>(Ce) is used as gamma-ray detectors (OSCAR array at OCL).**

**Example:** Fission reaction produces a lot of neutrons in addition to gamma rays from the reaction products

# Lecture: Semiconductor + Scintillator

**Semiconductor det:**

**Chapter 10.1, 10.2, 10.3, 10.4, 10.5.2, 10.5.4, 10.7.2, 10.7.3, 10.9**

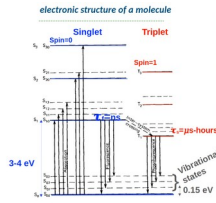
**Scintillation det:**

**Chapter 10.1, 10.2, 10.3, 10.4, 10.5.2, 10.5.4, 10.7.2, 10.7.3, 10.9**

## Photocathode



### Organic

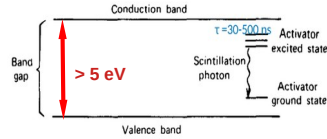


Plastic scintillators  
Charged particles  
TOF measurements, fast timing

Liquid scintillators  
Neutron detection

Electron hitting the organic scintillator will excite many electrons from the ground state to the excited states

### Inorganic

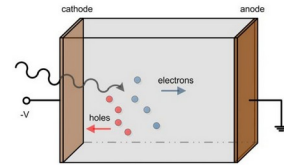


Gamma rays  
NaI(Tl)  
CsI(Tl)  
LaBr3(Ce)

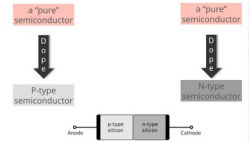
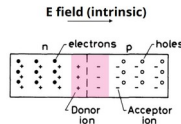
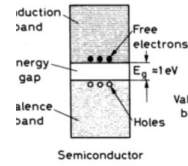
Compton suppression  
BGO

Photon hitting the inorganic scintillator will give its energy to one electron via PA, CS, PP

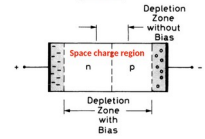
Now that energetic electron will excite many electrons from the ground state to the excited states



Silicon, germanium



Reversed bias voltage  
E field (external)



Germanium (HPGe)  
Gamma rays

Silicon (Si)  
Heavy-charged particles  
electrons

Semiconductors are found in columns II-VI of the periodic table.

| Acceptors |                | Donors         |          |          |
|-----------|----------------|----------------|----------|----------|
|           | <sup>5</sup> B | <sup>6</sup> C |          |          |
| 12<br>Mg  | 13<br>Al       | 14<br>Si       | 15<br>P  | 16<br>S  |
| 30<br>Zn  | 31<br>Ga       | 32<br>Ge       | 33<br>As | 34<br>Se |
| 48<br>Cd  | 49<br>In       | 50<br>Sn       | 51<br>Sb | 52<br>Te |
| II        | III            | IV             | V        | VI       |

Adopted from [https://physics.bgu.ac.il/COURSES/LAB\\_C/XRAYS/Basic%20Semiconducturs.pdf](https://physics.bgu.ac.il/COURSES/LAB_C/XRAYS/Basic%20Semiconducturs.pdf)

**Donor (Pentavalent: 5 valence electrons)**

(a)

$n = n_e = 10^{17}$  electrons  $\rightarrow$  majority charge carriers  
 $p = n_h = 10^3$  holes  $\rightarrow$  minority charge carriers  
**n-type**

**Acceptor (trivalent: 3 valence electrons)**

(b)

electrons  $\rightarrow$  minority charge carriers  
**holes  $\rightarrow$  majority charge carriers**  
**p-type**

Read Leo page#221

- Amount of dopant used is usually around  $10^{13-17}$  atoms/cm<sup>3</sup>  
 This amount is very small compared to the concentration of total Ge/Si atoms  $\sim 10^{22}$  atoms/cm<sup>3</sup>
- Dopant amount can be higher up to  $10^{20}$  atoms/cm<sup>3</sup> and such doped materials are called heavily doped and indicated with a plus sign  $\rightarrow p^+$  and  $n^+$

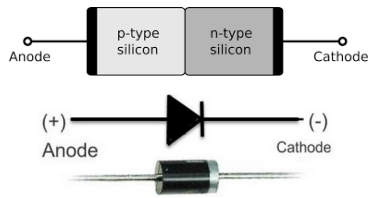
At normal temperatures, therefore, the extra electron is easily excited into the conduction band where it will enhance the conductivity of the semiconductor.

If the concentration of the impurity atom is  $N_D$  (D: donor), the extra atom of each impurity atom will be excited to the conduction band, becoming a conduction electron. That also means that  $N_D \cong n$  !!

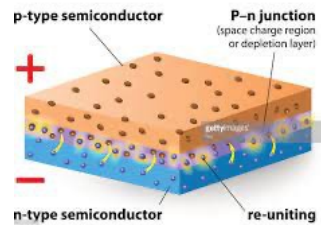
## Semiconductor junction

Once we have n- and p-type semiconductor materials, we can make a **functioning semi-conductor detector** through **Junction**

Junction provides a good depletion layer/zone/depth for the purpose of radiation detection

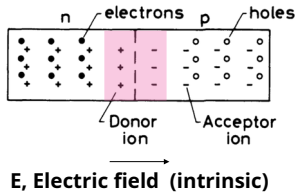


## P-N JUNCTION



## pn junction

pn junction is formed by the **juxtaposition** of a p-type semiconductor with an n-type material.



### 1- Diffusion

holes will diffuse towards n-region  
electrons will towards p-region

### 2- Formation of depletion

At the junction:

Diffusing holes will recombine with the diffusing electrons. Net effect:

n-type end will become positively charged (positive donor ion)

p-type end will become negatively charged (negative acceptor ion)

a- This will create a zone of electric field across the junction which halts the diffusion, leaving a steady (immobile) space charge region.

b- potential difference across the junction, called contact potential.  
usually around 1 V and called depletion region

Now the the depletion region created is with no charge carriers and no current flowing through it. It is pure silicon (or germanium) material suitable for incoming radiations!!

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Now the the depletion region created is with no charge carriers and no current flowing through it. It is pure silicon (or germanium) material suitable for incoming radiations!!

### Depth of the depletion layer:

$$d \cong (2\epsilon V \mu \rho_d)^{1/2}$$

dielectric constant     mobility  
Resistivity of the doped material

*Silicon*

$$d \cong \begin{cases} 0.53(\rho_n V_0)^{1/2} \mu\text{m} & \text{n-type} \\ 0.32(\rho_p V_0)^{1/2} \mu\text{m} & \text{p-type} \end{cases}$$

*Germanium*

$$d \cong \begin{cases} (\rho_n V_0)^{1/2} \mu\text{m} & \text{n-type} \\ 0.65(\rho_p V_0)^{1/2} \mu\text{m} & \text{p-type} \end{cases}$$

We want bigger depletion layer.  
We must apply bias voltage!!

where  $\rho$  is in  $\Omega \text{ cm}$  and  $V_0$  in Volts. If we take typical values of  $\rho \sim 20000 \Omega \text{ cm}$  for high-resistivity n-type silicon and  $V_0 = 1 \text{ V}$ , this yields  $d \approx 75 \mu\text{m}$ , which is a rather small sensitive depth.

## Reversed Bias Voltage:

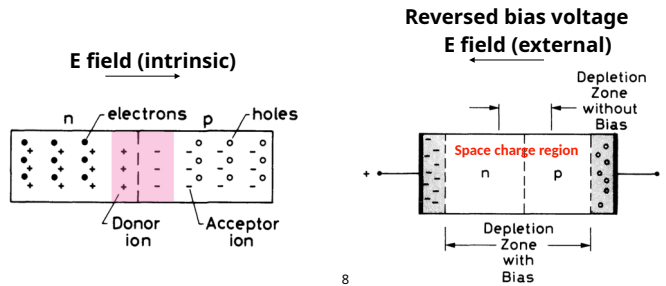
RB voltage is a negative voltage to the p-side

Main purpose: to increase the depletion zone

Voltage value: 4000-5000 V for germanium (less for silicon)

Negative voltage on the p-side will attract holes away from the junction

positive voltage will attract electrons in the n-side.



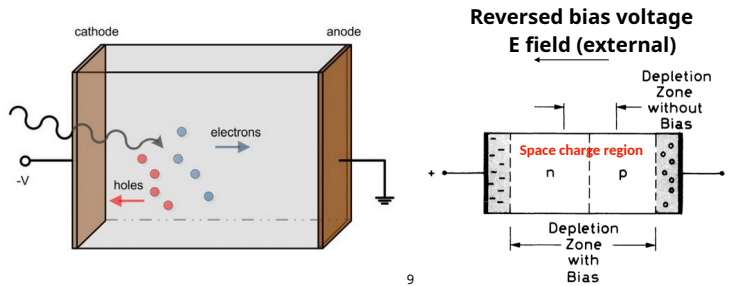
### Reversed Bias Voltage:

RB voltage is a negative voltage to the p-side

Main purpose: to increase the depletion zone

Voltage value: 4000-5000 V for germanium (less for silicon)

Negative voltage on the p-side will attract holes away from the junction  
positive voltage will attract electrons in the n-side.



Now we have built our detector with a sensitive volume, i.e. depletion layer!

What happens next?

1-Ionizing radiation entering this zone will liberate electron-hole pairs

2-The pairs will be swept out by the electric field.

3-If electrical contacts (cathode and anode) are placed on either end of the junction device, a current signal proportional to the ionization will then be detected. Energy information of the incoming radiation will be obtained!

## Characteristics of SC detectors:

### 1- Average energy per e-hole pair

**Table 10.2.** Average energy for electron-hole creation in silicon and germanium

|       | Si      | Ge      |
|-------|---------|---------|
| 300 K | 3.62 eV | —       |
| 77 K  | 3.81 eV | 2.96 eV |

### 3- Resolution + Fano factor

$F \sim 0.12$

$$R = 2.35 \sqrt{\frac{F}{J}} = 2.35 \sqrt{\frac{Fw}{E}}$$

### 2- Linearity

$$V = \frac{Q}{C} = n \frac{E}{wC}$$

$n$ : charge collection efficiency (charge collection on the electrodes)

depletion layer has to be large enough to keep linearity, i.e. should not be smaller than the range of the radiation.

### 4- cooling

( $T = 77\text{K}$  or  $-196^\circ\text{C}$ ) for Ge(Li)

( $T < 110\text{K}$  ( $< -163^\circ\text{C}$ ) for HPGe)

### 5- Operating voltage

HV: 4000-5000 V



germanium detector + dewar filled with a liquid hydrogen

Please read and go through material below:

**Leakage current & Efficiency:** Leo pp: 229-230

**Bias Voltage, temperature effects, radiation damage:** Leo pp:  
243-245

## Germanium detectors

- 0 GeLi Detectors

- 0 HPGe Detectors

  - 1. Planar

  - 2. Coaxial

## Germanium detectors

- 0 GeLi Detectors

- 0 HPGe Detectors

1. Planar
2. Coaxial

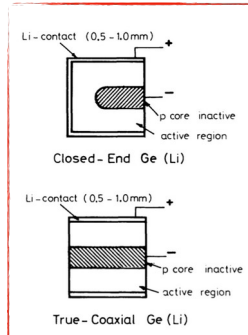
## **lithium ion drifting process (Z=3 Group I element)**

- In order to increase the conductivity, one could add equal amount of donor and acceptor impurities but this is a very difficult process to manage.
- Instead, in 1960 Pelle developed the lithium drifting method for compensating p-type silicon and germanium:

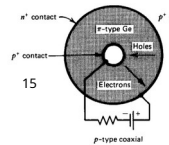
*Lithium is diffused onto the surface of a p-type material. (Note that Lithium (Z=3) acts as a donor with one valence electron.) This changes that end of the semiconductor into an n-type material. The concentration of lithium drops off in a Gaussian manner so that the junction between the n-type and p-type regions lies at some depth under the surface.*

## Ge(Li) detectors

pronounced as "jelly"



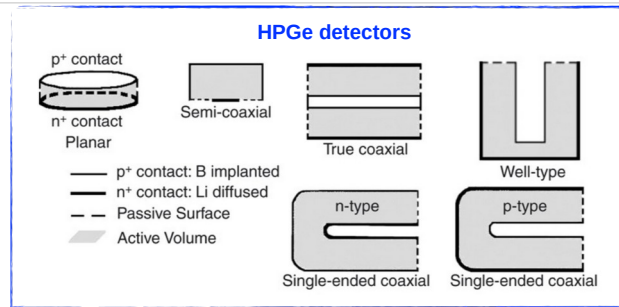
- Year 1960 was innovative for a new doping method
- Lithium was used as doping
- Li has 1 valence electron and acts as donor in Ge
- Ge is doped by "diffusion" of Li (high mobility)
- After a drifting time of weeks or months a thickness of the compensated layer of up to 35 mm can be achieved for a coaxial detector.
- Creating Ge(Li) type detector material takes time.



obtain figures of Ge(Li) detectors

## Germanium detectors

- 0 GeLi Detectors
- 0 HPGe Detectors
  - 1. Planar
  - 2. Coaxial



- In the late 1970s
- Pure samples of the detector material could be prepared only for germanium material
- The production process of a detector is much faster since no time-consuming drifting process is needed.
- The commercial production of Ge(Li) detectors was given up around 1980 when the volume of HPGe detectors became competitive with the volume of Ge(Li) detectors
- The size of pure crystals is limited to approximately 5 cm in diameter by 1 cm thick (it is much more improved at present: 9 cm length 8 cm circular diameter for the most advance **HPGe detectors**. But still smaller compared to scintillators!!)
- Quite expensive

## What is High Purity exactly?

### Internal impurities

$$d \cong \left( \frac{2\epsilon V}{eN} \right)^{1/2}$$

d: depletion layer  
V: applied High voltage  
N: internal impurity concentration  
 $\epsilon$ : dielectric constant

For a typical intrinsic germanium material,  $N=10^{13}$  atoms/cm<sup>3</sup>

For HPGe-->  $N=10^{10}$  atoms/cm<sup>3</sup>

Because of that the germanium material should be as pure as possible. Such material is then called High Purity Germanium material. Silicon cannot be purified that much.

### External impurities (Dopant)

$$d \cong (2\epsilon V \mu \rho_d)^{1/2}$$

$$\text{where } \rho_d = \frac{1}{e \mu N_D}$$

$N_D$ : dopant concentration  
 $\rho_d$ : resistivity of the doped semiconductor, opposition to the conductivity ( $\sigma$ )  
 $M$ : mobility of the major charge carrier

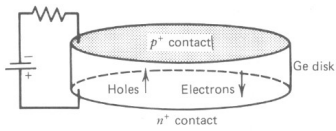
High voltage value is necessary for a larger depletion region (4000-5000 V for germanium material).

This high voltage value requires higher resistivity of the doped material which is limited by the (internal) impurity concentration before doping.

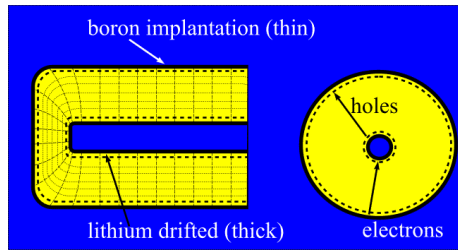
The dopant concentration cannot be too small but sufficient to override the nonuniform effects of the residual impurities (internal).

Operated at 77 Kelvin using liquid nitrogen.

Planar



Coaxial



In Coaxial crystals:

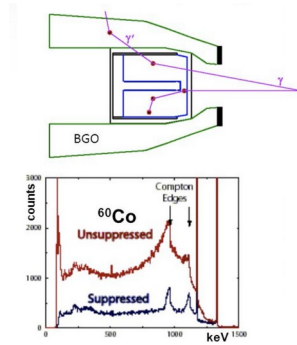
|         | Outer Contact | Inner |
|---------|---------------|-------|
| Contact |               |       |
| p-type  | n(Li)         | p(B)  |
| n-type  | p(B)          | n(Li) |

The  $n \sim 600 \mu\text{m} - 1 \text{ mm}$ , p contact is very thin  $\sim 0.3 \mu\text{m}$ .

## BGO Compton suppression



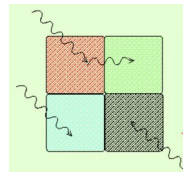
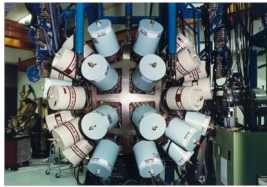
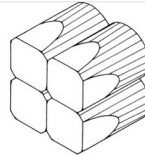
ROSPHERE at Bucharest, Romania



For large Ge arrays: **P/T (Peak to Total) Ratio** improves from 20% to 60%

## 4 $\Pi$ -Ge Arrays: Segmented crystals

Clover (4-fold segmentation)



Addback

Fig. 15. Eurogam II at IReS Strasbourg.

## MINIBALL at CERN/ISOLDE

### 6-fold segmentation

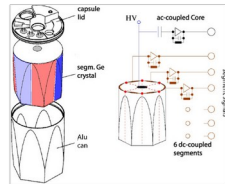
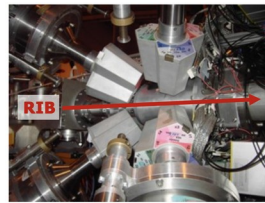
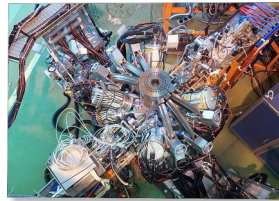
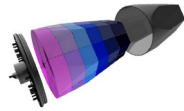


Fig. 23. The segmented MINIBALL detector.



## $4\pi$ -Ge Arrays: Highly segmented *HPGe* arrays



triple clusters

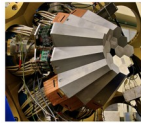
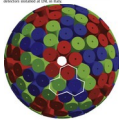


Fig. 4. (Color online) Photograph of the array with four HPGe crystal units.  
 (Source: [1])

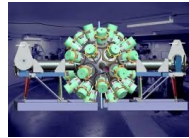
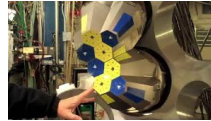


AGATA, Europe

36-fold segmentation

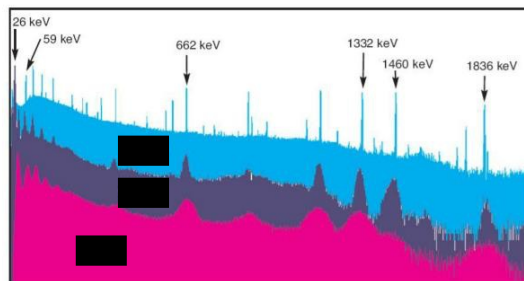


seven clusters



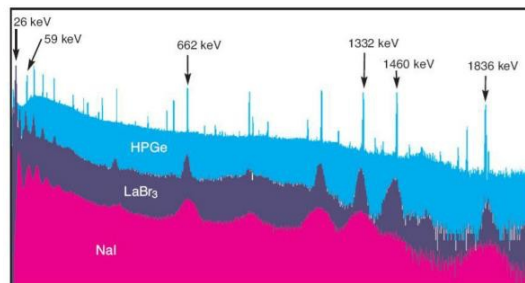
GRETA, USA

### Comparison of HPGe, NaI, and LaBr



Match colours to each detector type!!

## Comparison of HPGe, NaI, and LaBr



### High Count Rate Compatibility

Lanthanum bromide detectors can operate over wide dynamic ranges of count rate with little variation in energy resolution.

| Detector Type          | Resolution @622 keV (%) | Density (g/cc) | Photoelectron Yield Relative to NaI | Primary Decay Time (usec) |
|------------------------|-------------------------|----------------|-------------------------------------|---------------------------|
| LaBr <sub>3</sub> (Ce) | 2.8 - 4.0               | 5.29           | 130                                 | 0.026                     |
| NaI(Tl)                | 7                       | 3.7            | 100                                 | 0.230                     |
| HPGe                   | 0.2 (1.3 keV)           | 5.35           | N/A                                 | N/A                       |

## Questions to you

- Why do we prefer germanium ( $Z=32$ ) to silicon ( $Z=14$ ) for gamma-ray detection? Can you explain by giving numerical values?
- How do semi-conductor detectors work? Draw and explain the concept of energy bands in this context. What are the charge carriers in semi-conductor materials?
- What type of preamplifier would you suggest for Germanium detectors? Explain reasoning. (Hint: Get help from Lecture 8 pulse signal processing. )
- Should Preamplifier amplify the signal from the detector output significantly? Why should Preamplifier should stay very close to the germanium detector output?
- How does a Germanium detector work (depletion layer, pn junction)?
- Why do you have to cool Germanium detectors? Explain why it is important to increase the bias voltage in small steps.
- What is the effect of Compton suppression? What type of detectors are used for Compton suppression? And why?

# Today

- Scintillation
  - Organic scintillators
    - Anthracene
    - Stilbene
    - Plastic
    - Liquid
  - Inorganic scintillators
    - NaI(Tl)
    - CsI(Tl)
    - LaBr<sub>3</sub>(Ce)
    - BGO
- PMTs (Photomultiplier Tubes)
  - Mechanism
  - Photocathode
  - Quantum efficiency
- Time response
  - Organic
  - Inorganic
- Pulse shape discrimination
  - Organic
- Light output
  - Organic
  - Inorganic
- Energy resolution
  - Inorganic
- Detector efficiency
  - Heavy charged particle
  - Electrons
  - Gamma rays
  - Neutrons

**Table 7.3.** Average energy loss per scintillator photon for electrons

| Material   | $\epsilon$ [eV/photon] |
|------------|------------------------|
| Anthracene | 60                     |
| NaI        | 25                     |
| Plastic    | 100                    |
| BGO        | 300                    |

- The light output of a scintillator refers more specifically to its efficiency for converting ionization energy to photons.
- The fraction of all incident particle energy which is converted into visible light is called "*scintillation efficiency*" or "*light output*".
- *Light output depends on the type of the radiation and energy*

Q: Can you tell the which type has the largest light output in Table 7.3?

31

Light output response  
for inorganic and organic  
scintillators. Next slides.



Answer: The NaI(Tl) has the largest light output which gives the best energy resolution compared to Anthracene, Plastic and BGO in the table

However, we have to remember that photocathode/photomultiplier has its efficiency about 20-30% which we have to take into account for the resolution of this detector and for any given scintillator!

## Examples of light output for inorganic scintillators

- Deviations from linearity are less for inorganic scintillators.
- Non-linearity starts from 400 keV down to zero energy value
- We have to take care of this non-linearity (in the step of energy calibration of the detectors)

Perfectly linear response would correspond to a horizontal line

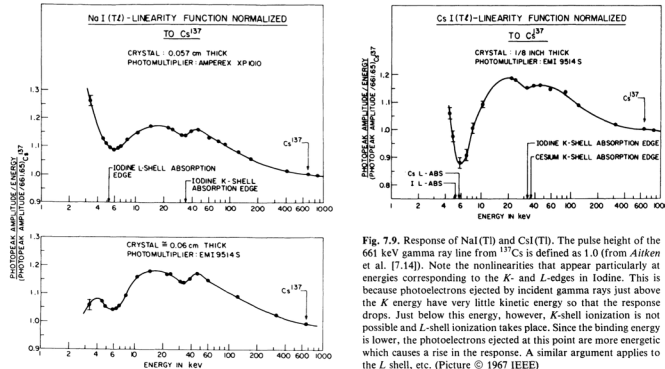


Fig. 7.9. Response of NaI(Tl) and CsI(Tl). The pulse height of the 661 keV gamma ray line from <sup>137</sup>Cs is defined as 1.0 (from Aitken et al. [7.14]). Note the nonlinearities that appear particularly at energies corresponding to the K- and L-edges in Iodine. This is because photoelectrons ejected by incident gamma rays just above the K energy have very little kinetic energy so that the response drops. Just below this energy, however, K-shell ionization is not possible and L-shell ionization takes place. Since the binding energy is lower, the photoelectrons ejected at this point are more energetic which causes a rise in the response. A similar argument applies to the L shell, etc. (Picture © 1967 IEEE)

Read page# 170 in Leo, including Figure 7.9.

### Examples of light output for plastic (organic) scintillator

- Light output decreases for heavier particles
- Linearity is worsen for heavier particles.

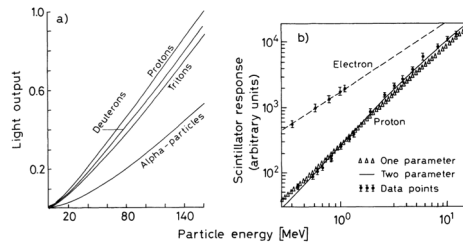


Fig. 7.8a, b. Response of NE102 plastic scintillator to different particles ((a) from Gooding and Pugh [7.6]; (b) from Craun and Smith [7.7])

**Quenching interactions:** Some energy loss is dissipated non-radiatively, primarily in the form of lattice "vibrations" or "heat". These radiationless de-excitation processes are called "**quenching**".

Since a higher ionizing power (alphas for example) produces a higher density of excited molecules, more quenching interactions will take place for these particles.

Linearity has dependency not only on the incoming energy but also the type of the particle.

Alphas have worst response: more ionizing particles = high ionization power. ( $dE/dx$  must be playing an important role)

The first successful semi-empirical model for non-linearity behaviour was proposed by Birks et al. in 1951.

He explained that the deviations as being due to quenching interactions between the excited molecules created along the path of incident particle, i.e., interactions which drain energy which would otherwise go into luminescence. Since a higher ionizing power produces a higher density of excited molecules, more quenching interactions will take place for these particles.

## Temperature dependence

The plot shows how sensitive is the decay time with temperature changes

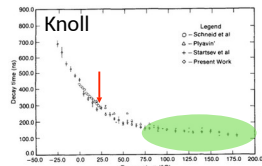
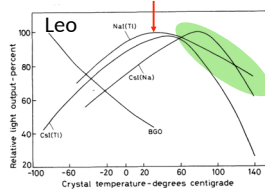


Figure 8.10 Temperature dependence of the scintillation decay time in NaI(Tl). (From Schweitzer and Ziehl<sup>10</sup>)



Inorganic scintillators work mostly in room temperatures.

- For some applications low decay time is desired.
- Can be obtained via high temperature
- However, light yield decreases significantly.

Organic scintillators have the same light output between the temperatures -60 to 20 °C i.e. less temperature dependent

# Today

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    - CsI(Tl)
    - LaBr<sub>3</sub>(Ce)
    - BGO
- PMTs (Photomultiplier Tubes)
  - Mechanism
  - Photocathode
  - Quantum efficiency
- Time response
  - Organic
  - Inorganic
- Pulse shape discrimination
  - Organic
- Light output
  - Organic
  - Inorganic
- **Energy resolution**
  - **Inorganic**
- Detector efficiency
  - Heavy charged particle
  - Electrons
  - Gamma rays
  - Neutrons

Let's calculate energy resolution for a 662 keV gamma ray on a NaI(Tl) Detector

**Table 7.3.** Average energy loss per scintillator photon for electrons

| Material   | $\epsilon$ [eV/photon] |
|------------|------------------------|
| Anthracene | 60                     |
| NaI        | 25                     |
| Plastic    | 100                    |
| BGO        | 300                    |

$E_\gamma = 662 \text{ keV}$

$$N_{photons} = J = \frac{E_0}{\epsilon} = \frac{E_0}{w}$$

$$= \frac{662 \text{ keV}}{25 \text{ eV}}$$

$$= 26480 \text{ photons}$$

36

What about Fano factor?

**Case 1:**

For a detector in which the radiation energy is **not totally absorbed**, the number of signals producing reactions is given by a **Poisson distribution**. **Fano factor=1**

**Scintillator**

**Case 2:**

If the energy of the radiation is **fully absorbed** as is the case for detectors used in spectroscopy experiments, the Poisson statistics is incorrect. Fano factor  $\ll 1$

**Gas  
Solid-state  
detectors**

Let's calculate energy resolution for a 662 keV gamma ray on a NaI(Tl) Detector

**Table 7.3.** Average energy loss per scintillator photon for electrons

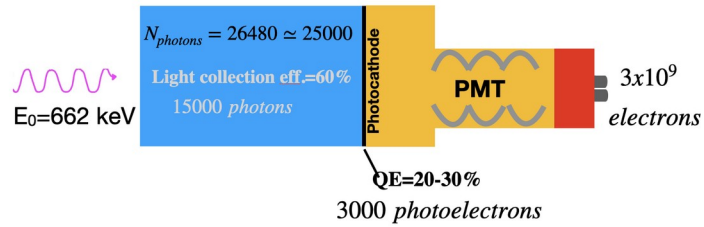
| Material   | $\epsilon$ [eV/photon] |
|------------|------------------------|
| Anthracene | 60                     |
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| Plastic    | 100                    |
| BGO        | 300                    |

$$E_\gamma = 662 \text{ keV}$$

$$N_{photons} = J = \frac{E_0}{\epsilon} = \frac{E_0}{W}$$

$$= \frac{662 \text{ keV}}{25 \text{ eV}}$$

$$= 26480 \text{ photons}$$



$$\frac{\Delta E_{FWHM}}{E_0} = 2.35 \frac{\sigma_I}{I} = 2.35 \frac{\sqrt{(3000)}}{3000} = 0.043 = 4.3\%$$

Light output or light yield has affect on the energy resolution.  
While density of the scintillator has affect on its efficiency.

$$N_{\text{photons}} = 26480 \approx 25000$$

**Table 7.3.** Average energy loss per scintillator photon for electrons

| Material   | $\epsilon$ [eV/photon] |
|------------|------------------------|
| Anthracene | 60                     |
| NaI        | 25                     |
| Plastic    | 100                    |
| BGO        | 300                    |

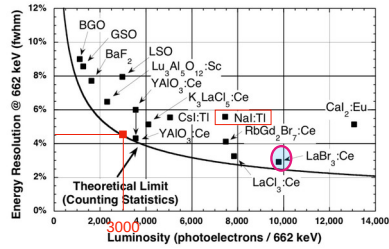
→ Best resolution

→ Highest efficiency

$3 \times 10^9$   
electrons

trons

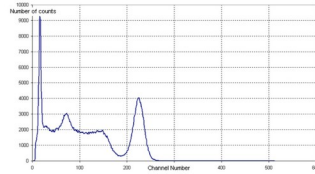
Light output or light yield has affect on the energy resolution.  
While density of the scintillator has affect on its efficiency.



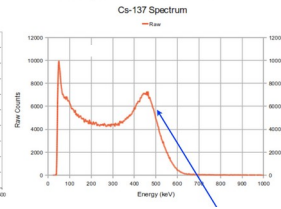
Resolution is never reached to the optimum value due to different losses in Scint. detectors.

## Inorganic vs Organic

- $^{137}\text{Cs}$  spectrum in NaI crystal



same in plastic scintillator



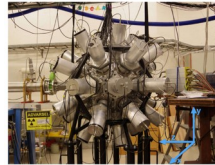
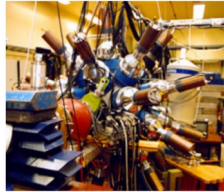
Compton edge or full peak?

Organic scintillators have low density (low-Z) (C and H only) while Photoelectric absorption is proportional to  $Z^4$  or  $Z^5$

## CACTUS vs OSCAR

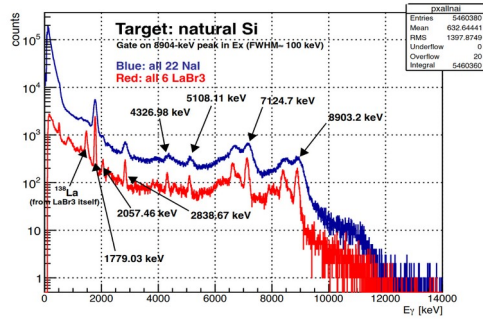
### CACTUS Array

- 0 30 large volume NaI (TI) detectors.
- 0 Dimension: ( $\varnothing$  5 × 5 inches)



### Oslo Scintillator Array (OSCAR)

- 0 30 large volume LaBr3(Ce) detectors.
- 0 Dimension: ( $\varnothing$  3.5 × 8 inches)



Comparison of energy resolutions

| Detector Type          | Resolution @622 keV (%) | Density (g/cc) | Photoelectron Yield Relative to NaI | Primary Decay Time (usec) | W (eV/photon) |
|------------------------|-------------------------|----------------|-------------------------------------|---------------------------|---------------|
|                        | Resolution              | Efficiency     |                                     |                           |               |
| LaBr <sub>3</sub> (Ce) | 2.8 - 4.0               | 5.29           | 130                                 | 0.026                     | 16            |
| NaI(Tl)                | 7                       | 3.7            | 100                                 | 0.230                     | 25            |
| HPGe                   | 0.2 (1.3 keV)           | 5.35           | N/A                                 | N/A                       |               |

LaBr<sub>3</sub>(Ce) crystals is better than that of NaI(Tl) crystals in terms of "internal homogeneity". In other words, LaBr<sub>3</sub>(Ce) has much smaller variation in energy response across the detector than NaI(Tl).

This uniformity is crucial for a more accurate energy measurement and helps avoid broadening of the energy peaks

Crystal structure, losses due to quenching interactions

# Not Today 😊

- Scintillation
  - Organic scintillators
    - Anthracene
    - Stilbene
    - Plastic
    - Liquid
  - Inorganic scintillators
    - NaI(Tl)
    - CsI(Tl)
    - LaBr<sub>3</sub>(Ce)
    - BGO
- PMTs (Photomultiplier Tubes)
  - Mechanism
  - Photocathode
  - Quantum efficiency
- Time response
  - Organic
  - Inorganic
- Pulse shape discrimination
  - Organic
- Light output
  - Organic
  - Inorganic
- Energy resolution
  - Inorganic
- Detector efficiency
  - Heavy charged particle
  - Electrons
  - Gamma rays
  - Neutrons

## In-class activity

Figure out detection efficiency for different types of radiation (for scintillation detectors).

Heavy-ions

Electrons

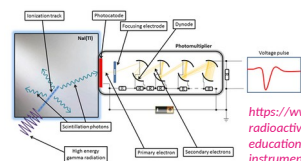
Gammas

Neutrons

## Questions to you

- How do scintillator detectors work? What is the mechanism of a scintillator detector independent from its type? What properties are important to look at when comparing various types of scintillator materials?
- Explain how scintillation light is produced in inorganic scintillator materials and why we dope inorganic scintillators.
- Explain how an organic scintillator produces light. What is the desired process?
- Compare organic and inorganic scintillators. List main differences.
- How can you estimate the energy resolution of an inorganic scintillator detector? Feel free to give numerical explanations.
- Which scintillator detector is optimum for:

- beta particles
- alpha particles
- gamma rays
- Neutrons



- What are the advantages of LaBr<sub>3</sub> detectors compared to NaI(Tl) detectors?
- Compare a typical gamma-ray pulse-height spectrum in organic and inorganic scintillator detector. Which one would you choose?
- Explain how a PMT works and what it is used for. Draw and explain.

## Pulse shape discrimination

**Slow light output component as a function of time** produces a long tail which depends on the nature of the exciting particle/radiation.

The slow component fraction should depend primarily on the rate of energy loss  $dE/dx$  of the exciting particle and should be greatest for particles with large  $dE/dx$ . ( $\alpha > \beta > \gamma$ )

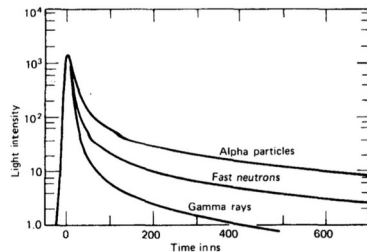


**Figure 8.5** The time dependence of scintillation pulses in stilbene (equal intensity at time zero) when excited by radiations of different types. (From Bollinger and Thomas.<sup>60</sup>)

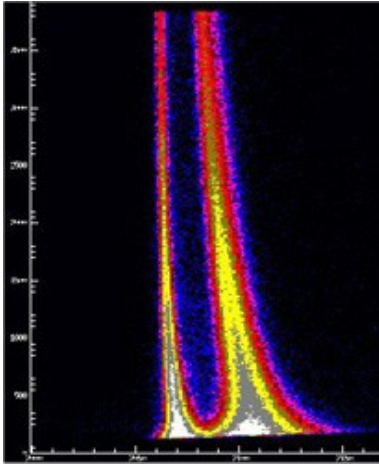
PSD is used to **eliminate gamma-ray-induced events when organic scintillators are used as neutron detectors.**

**stilbene and liquid scintillators**

One can therefore make use of this dependence to differentiate between particles of different kinds that deposit the same energy in the detector. This process is often called *pulse shape discrimination* and is widely applied to **eliminate gamma-ray-induced events when organic scintillators are used as neutron detectors.**

Mostly stilbene and liquid scintillators are used for pulse shape discrimination. These are the scintillation materials with large triplet concentration, i.e. high density of triplet states.

What about inorganic scintillators?



Otherway around:

LaBr<sub>3</sub>(Ce) detectors have fast timing, i.e. good time resolution, compared to NaI(Tl).

We can then use them to **eliminate neutron induced events as LaBr<sub>3</sub>(Ce) is used as gamma-ray detectors (OSCAR array at OCL).**

**Example:** Fission reaction produces a lot of neutrons in addition to gamma rays from the reaction products