Nuclear Medicine Physics

Lecture 3
Radiation Detectors

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References :
- RSNA/AAPM Physics Modules
  http://www.rsna.org/RSNA/AAPM_Online_Physics_Modules_.aspx
- Physics in Nuclear medicine, 4th ed. by Cherry et al.
- Essentials of Nuclear Medicine Physics and Instrumentation, 3rd ed. by Powsner

Radiation detection

- Nature of radiation detection in NM imaging /therapy → we know the kind of radiation
- in contamination, may be faced with the task of identifying the type of the radiation.

➢ Simple detection : Is radiation present?
contamination of surrounding or personnel

➢ Quantity of radiation
- How much radiation or radioactivity is present?
- Or in relative terms (i.e., with respect to a standard)
- Requires measurement of radioactivity or counting rate as a functional time → dynamic imaging

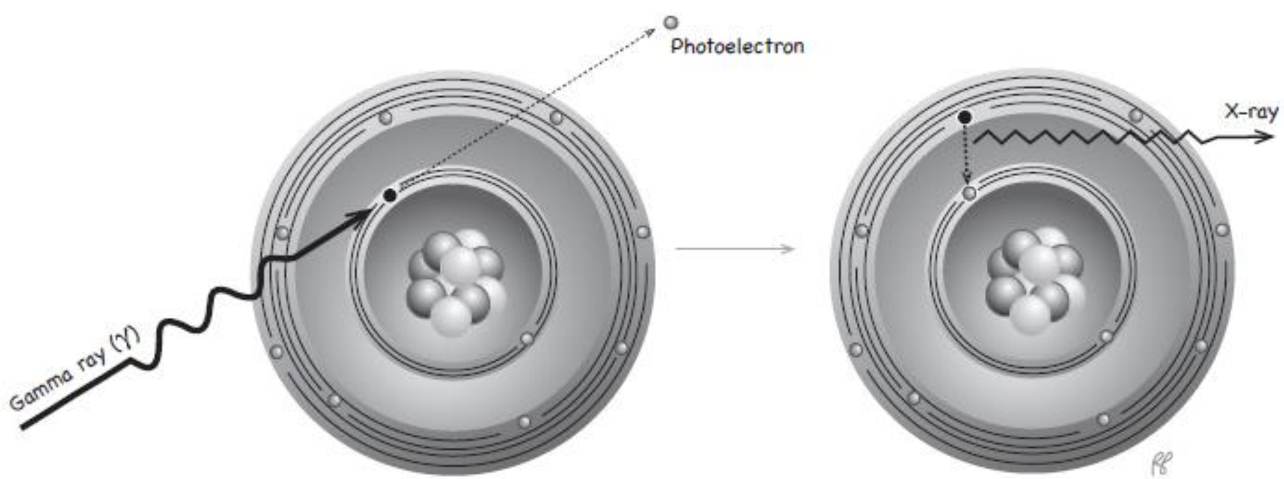
➢ Energy of radiation?
- In NM imaging, discriminate true signal against undesired events such as scattered gamma rays → may be identifies by energy measurement
- to identify two radionuclides that may be used simultaneously

Interaction of Radiation with matter (review)

- **<u>Charged particle (α,β)</u>** : interact with negatively charged electrons and positively charged nuclei of the target atoms or molecules
  → loses its energy
  → target atoms in ionization or excitation
  → non-penetrating radiation → stopping power or range

- **<u>Photons (x-ray, γ-ray) interacts through three processes</u>**

1. Photoelectric effect : <u>transfer all energy</u> to one of atomic electrons
→ leads to ionization by the emission of an electron (photoelectron)

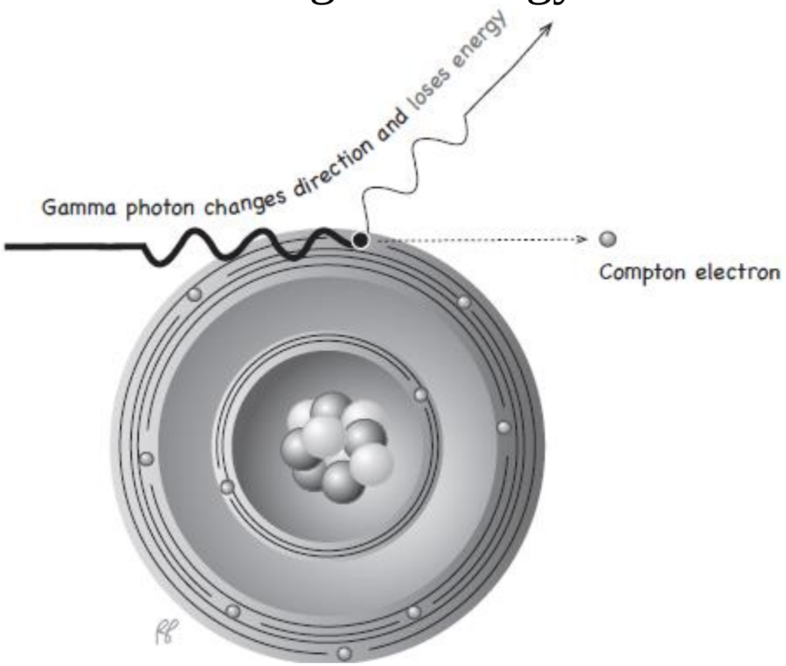


Powsner Fig. 2.4

Interaction of Radiation with matter (review)

2. Compton effect :
individual photons collide with single electrons that are free or quite loosely bound in the atoms of matter

→ incident photon loses energy and the scattered electron gains energy
→ ionization



Powsner Fig. 2.2

3. Pair production:
for photons with E >1.02MeV, interact with nucleus and create a election and a positron

For gamma rays used in NM, photoelectric and Compton effects are dominant.

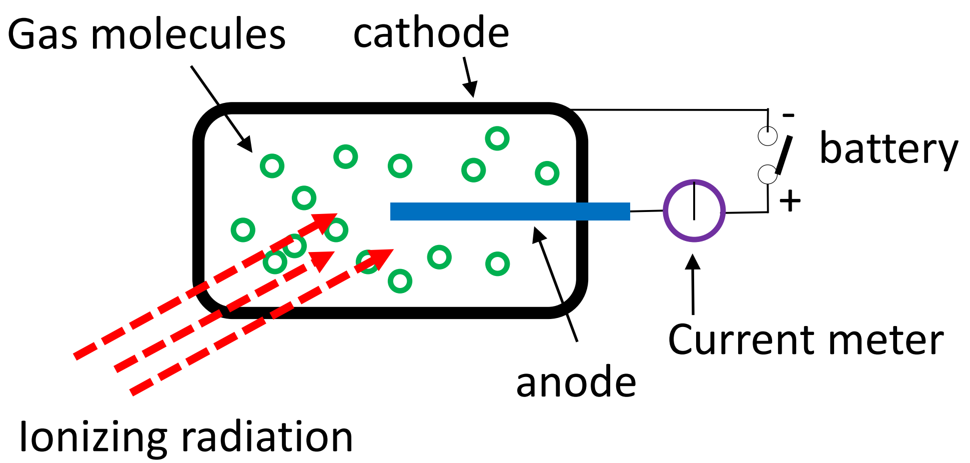
Detectors in Nuclear Medicine

- **Gas-filled detectors**
  - Gas trapped in a container.
  - Radiation interacts within the gas → and ionize gas atoms → resulting positive gas ion and free electrons (ion pair)

- **Solid detectors (crystals)**
  - scintillation detector : gamma ray into light photons
  - semiconductor detectors : radiation creates electron-hole pair

Gas-Filled Detectors

Ionization of gas molecules by radiation, followed by collection of the ion pairs as charge or current with the application of a voltage between two electrodes

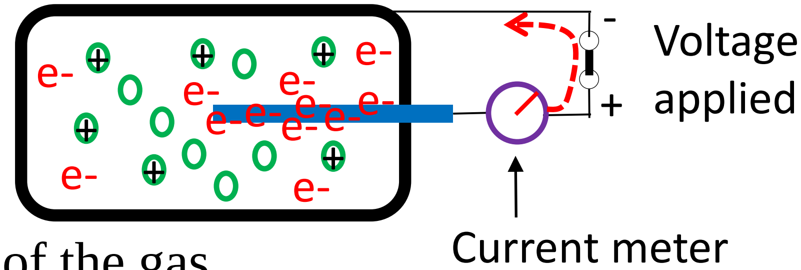


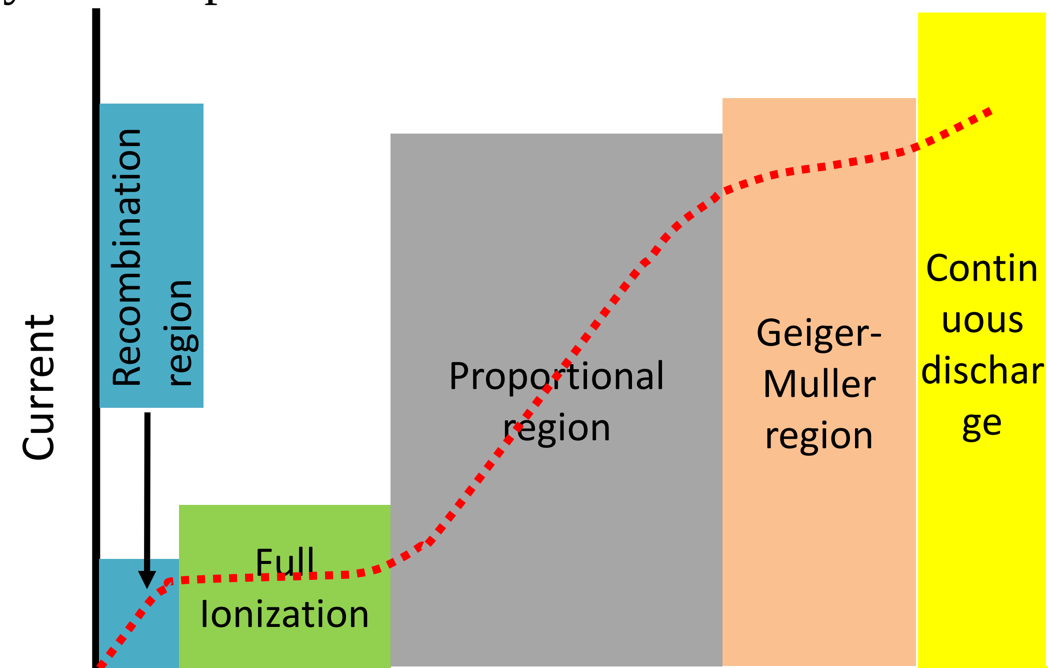
- ✓ The average energy required to produce an ion pair in **gases** is ~33 eV, the energy from a 140 keV gamma ray can create 4,200 ion pair if the energy is completely deposited in the air. (15,500 for a 511keV photon)
- ✓ Usually pressurized for a greater chance of integrations, e.g, argon
- ✓ Detection efficiency is low, radiation travel through the low-density gas

Gas-Filled Detectors

The amount of current depend on

- Radiation type
- Applied voltage (most important)
- Distance between two electrodes,
- type of gas, volume, pressure, temperature of the gas,
- geometry and shape of electrodes.





- Low voltage
- Too weak to efficiently
- Some will recombine
- Full signal is not measured

High eno
the ions p

Elect
high
→ Ca
→ increase the measured current
→ Current increases with the applied voltage

Reached at which m
detector is massively
successive ionization → no amplification is possible

Voltage is too high, no
radiation is required

Gas-Filled Detectors

Mostly used in Current mode (integration)

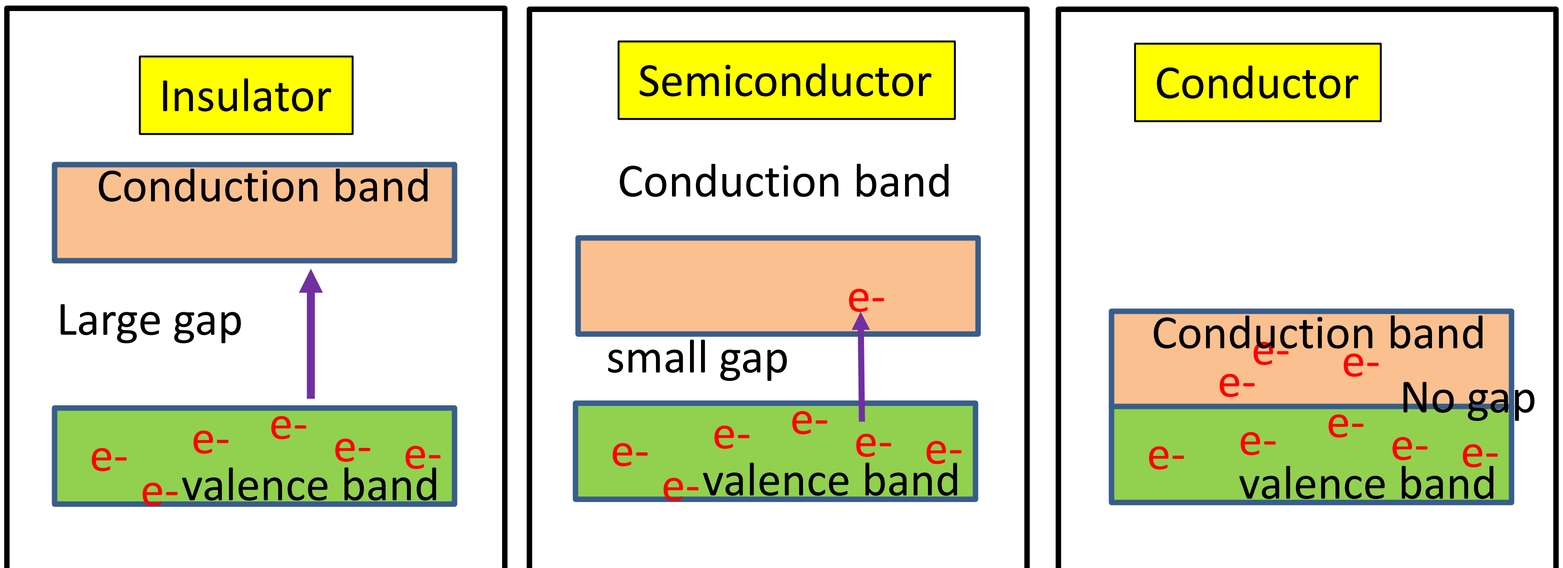
- continuous charge collection, which results in the loss of information for individually events
- Amplitude of the signal generated is proportional to the rate of energy deposition or dose rate → represents the total energy being detected in the given interval.
- Because individual events are not being processed, the energy of individual radiation being detected cannot be measured

Nuclear Medicine Equipment (More discussion in Lecture 5)

- Ionization chambers : operating voltages : 50-300V
  - cutie-pie meters
  - Dose calibrators
  - Pocket dosimeters
- Geiger-Muller Counters : 400 -900V
  - Convert a 9V battery voltage to higher voltage by the GM tube

Solid detectors

- There are only certain allowed energy states for electrons in solids (election energy levels in atoms, nuclear energy levels in nucleus)
- There are two energy band states for elections in solids
  - Valence band (bound electrons)
  - Conduction band (range of energies for unbound/free electrons)



Insulators have no free charge carriers and thus are non-conductive (wood, glass, rubber)

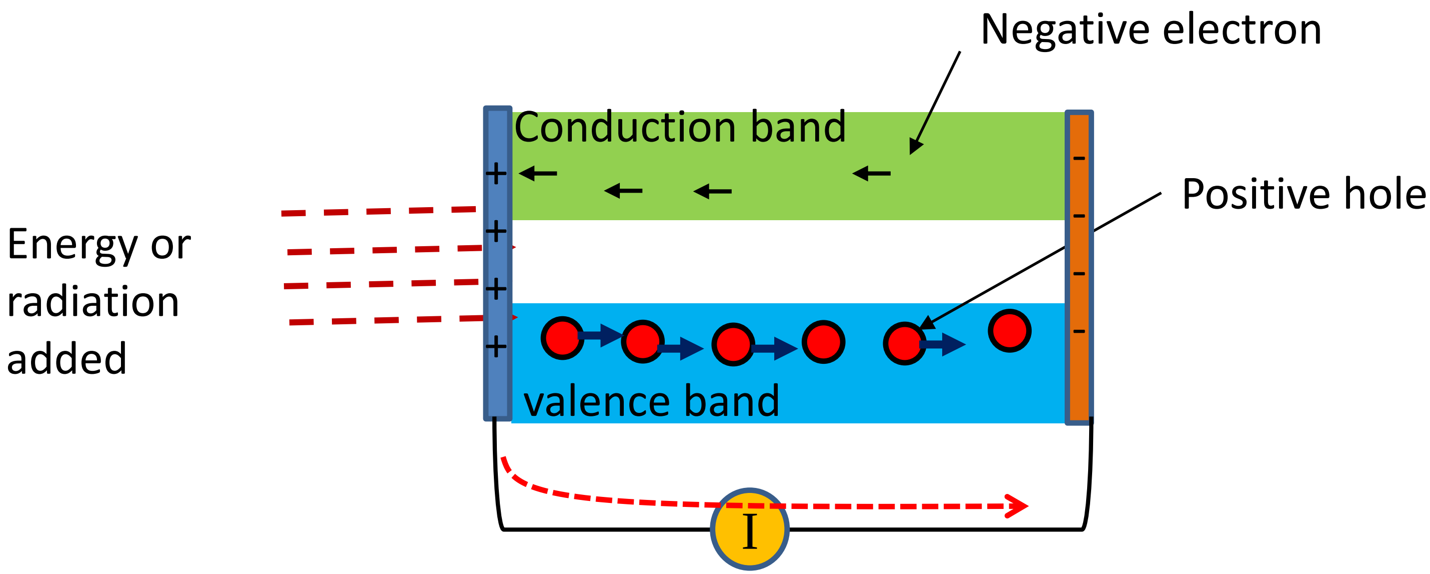
Small energy is required to move electrons from valence to conduction (Ge, Si)

electrons can move easily (Copper, iron, aluminum)

Semiconductor detector

Functionally equivalent to gas detectors :

- ion pair vs electron-hole pair
- radiation interacts with electrons of gas molecules vs the atomic electrons in the solids



When an external voltage is applied,

→ the negatively charged electrons in the conduction band will move towards the positive terminal and

→ the positively charge holes in the valence band will move towards the negative terminal.

→ current flow can be measured

Semiconductor detector

- For each interaction, the amount of electron-hole pairs can be estimated
- Energy of each radiation can be estimated

- Primary advantage of using solid
  - much higher density → more interaction → more signals
- Elections in semiconductor are less tightly bound to their atoms than electron in the atoms in gas molecules

  2-3 eV vs 33 eV

  → For any incoming radiation, much greater yield of charges in semiconductor

  → Better energy resolution

- small volume of solid material is needed→ can produce smaller device

Semiconductor detectors in NM

Dedicated cardiac scanner

Dedicated breast imaging system

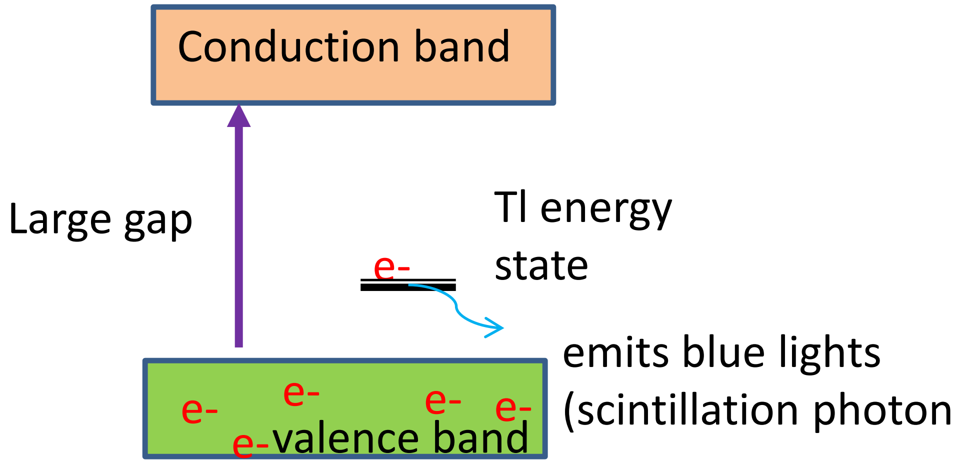
Handheld gamma camera

Scintillation detector

Gamma ray loses its energy in a detector through Compton or photoelectric interaction

→ Produce electrons in the crystal in an excited state
→ Electrons return to their original state
→ Some of their energy is released as light photons
→ e.g. a **1 keV gamma** can create **40 light photons**.

- NaI(Tl) - Typical NM detector :
  Sodium Iodide (NaI) crystals are doped with small amount of thallium (Tl)



The amount of light produced determines the energy of the radiation

Scintillation detector

Gamma Camera, SPECT : for detection of various gamma rays (~70 – 350keV)

- NaI (Tl) : Thallium doped Sodium Iodide
- CsI(Tl) : Thallium doped Cesium Iodide

PET scanner: for detection of 511 keV photons require a higher density, higher attenuation coefficient

- BGO (Bismuth Germanate, $Bi_4Ge_3O_{12}$)
- LSO (Lutetium Oxyorthosilicate, Lu_2SiO_5:Ce)
- LYSO (Lutetium Yttirium Oxyorthosilicate, $LuYSiO_5$:Ce)
- $LaBr_3$:Ce (Lanthanum Bromide)

Scintillation detectors in NM

Gamma Camera (SPECT)

PET

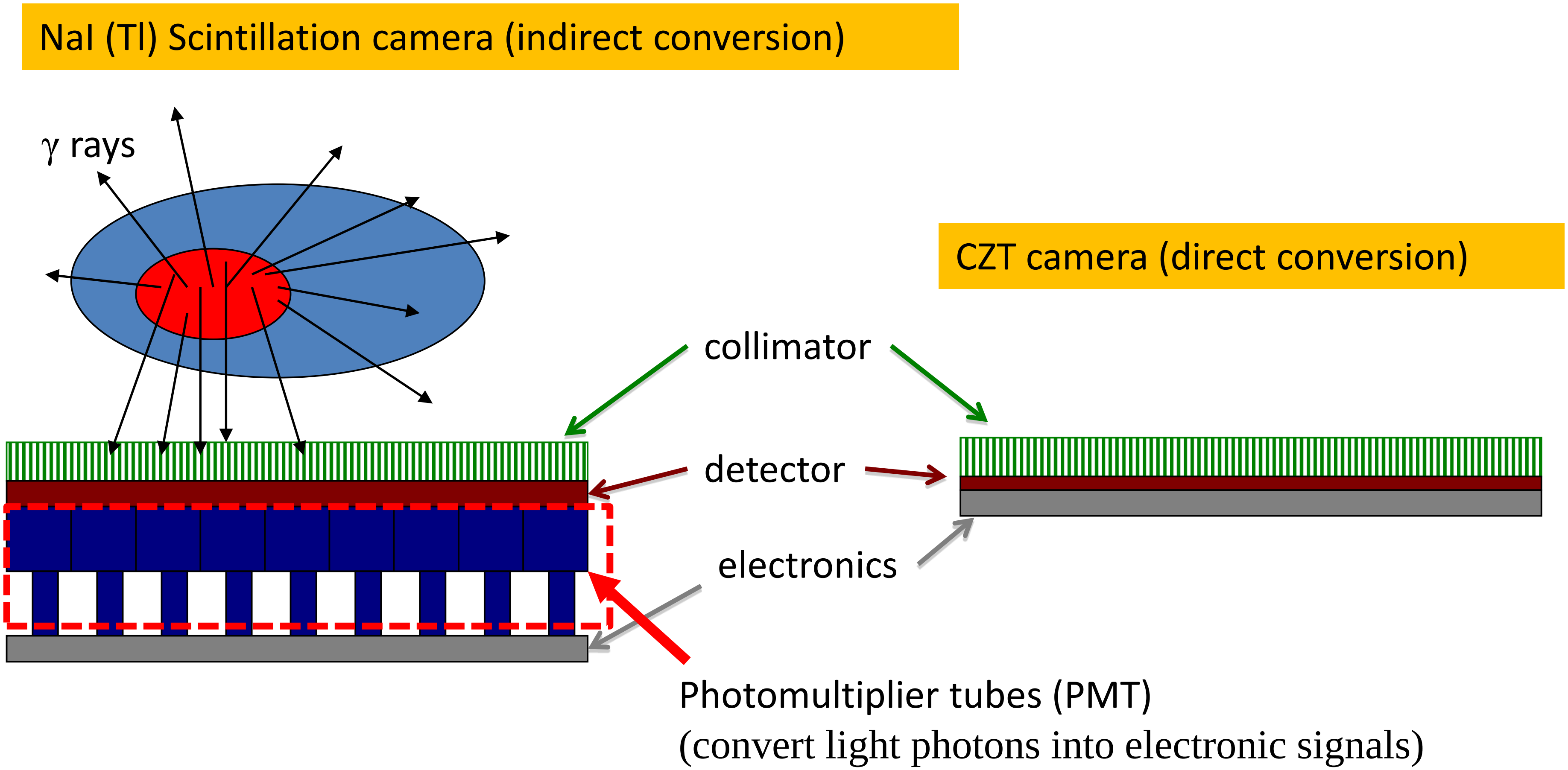
Handheld intraoperative probe

well-counter

Survey meter

Thyroid probe

Major Difference, scintillator vs. semiconductor



- CZT : Convert gamma-ray energy directly into electronic signal
- No need of the PMTs
- Compact design

Detection parameters

What makes one detector better than another?

Important properties of a detector in NM

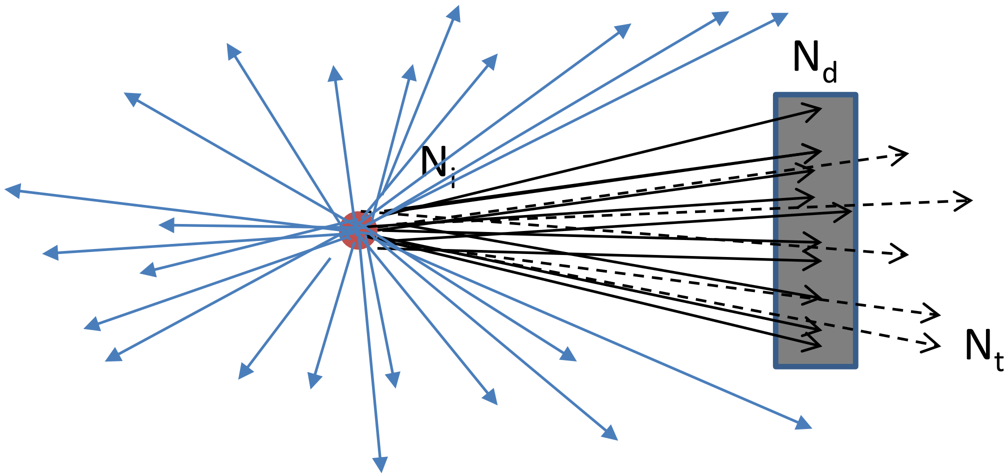
- Intrinsic efficiency (or sensitivity)
- Dead time or resolving time
- Energy discrimination capability or energy resolution
- Spatial resolution

- Not susceptible to change with fluctuation in voltage and with environment (temperature, humidity)
- Simple to operate and inexpensive.

Detector performance : strongly influenced by the details of the electronics

Intrinsic Efficiency

A number of event detected in a given interval divided by the number of radiation incident on the detector in the same interval



$$\text{Efficiency} = \frac{N_d}{N_i} = 1 - \frac{N_t}{N_i}$$

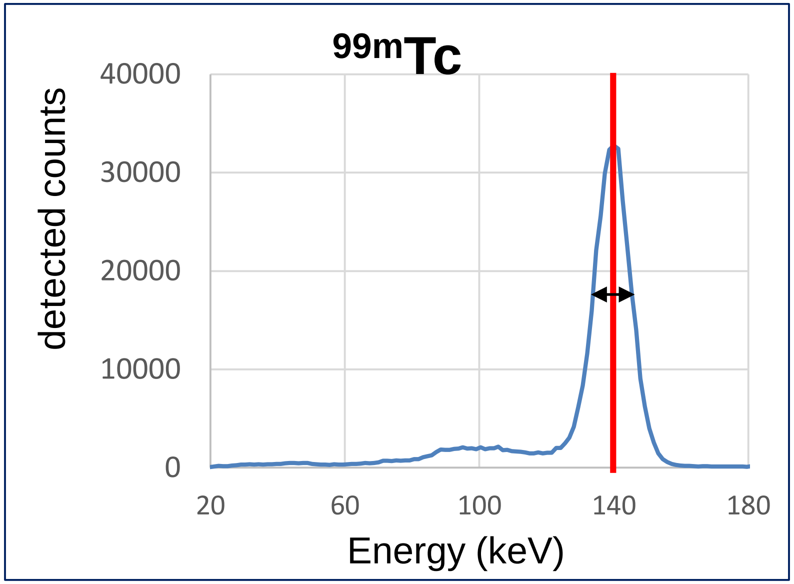
- Intrinsic efficient is determined by stopping power of the detector for the radiation of interest (α, β, γ)
- Stopping powers depends on Thickness, Density, Atomic number of the detector
- Interaction probability, p= $1 - e^{-\mu x}$, where μ is linear attenuation coefficient
- μ is function of density, atomic number and photon energy

The intrinsic efficiency for CZT is slight higher than NaI(Tl) at similar thickness

Energy Resolution

- The ability to accurately represent the energy of the detected radiation

The energy resolution of the detector is determined by measuring the width of the photopeak at exactly one-half of the height (full width at half maximum, FWHM)



$$\textbf{Energy Resolution (\%)} = \frac{\textbf{FWHM}}{\mathbf{E}\boldsymbol{\gamma}} \times \mathbf{100}$$

Example : ^{99m}Tc with a 3/8 inch thick NaI(Tl)
E.Res = (13 keV /140 keV)*100 = 9.3%

Factor affecting energy resolution

- thickness
- photon energy
- Detector material
- characteristic of the electronics.

NaI(Tl) : 9-10% at 140 keV with 3/8 inch (9.5mm) thick detector
CZT : 6-7% at 140 keV with 5mm thick detector

Efficiency & Energy Resolution

Increasing energy of photon
→ increase in the number of photons emitted in the scintillation process
→ Reducing statistical variation on measured photon energy
→ Better energy resolution

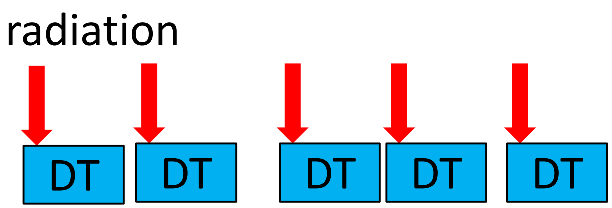
Increasing energy of photon
→ decreases in stopping power (higher changes for not being detected)
→ decreases in detection efficiency

Dead time (resolving time)

- Pulse mode : each individual event is processed separately
    - process lights from scintillator for the energy and position information.
    - measure the collected charges

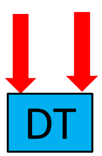
- a small but finite interval between the time when a ray interact with a detector and the time when the detector responds and the event is recorded

  → **“dead time” or “resolving time”**

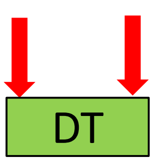


DT < event interval → all events are recorded

What happen if a second radiation arrives and starts interacting with the detector while it is still processing the first ray?

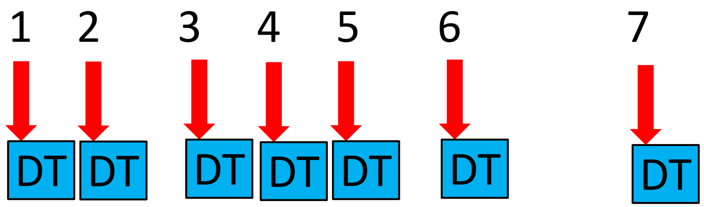


Event interval is short, e.g., high count rates

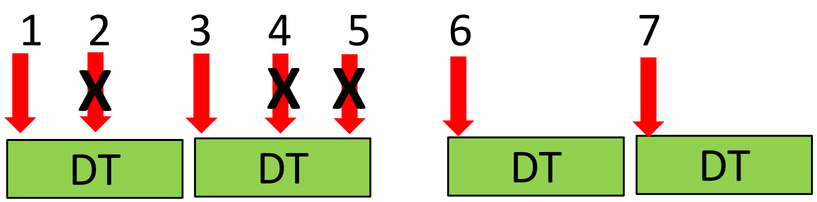


Detector with a long deadtime?

Dead time (resolving time)

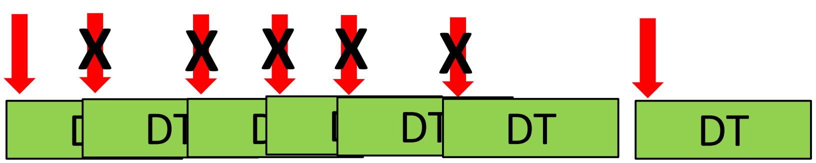


DT < event interval
→ all 7 events are recorded



DT > event interval
→ 4 events are recorded

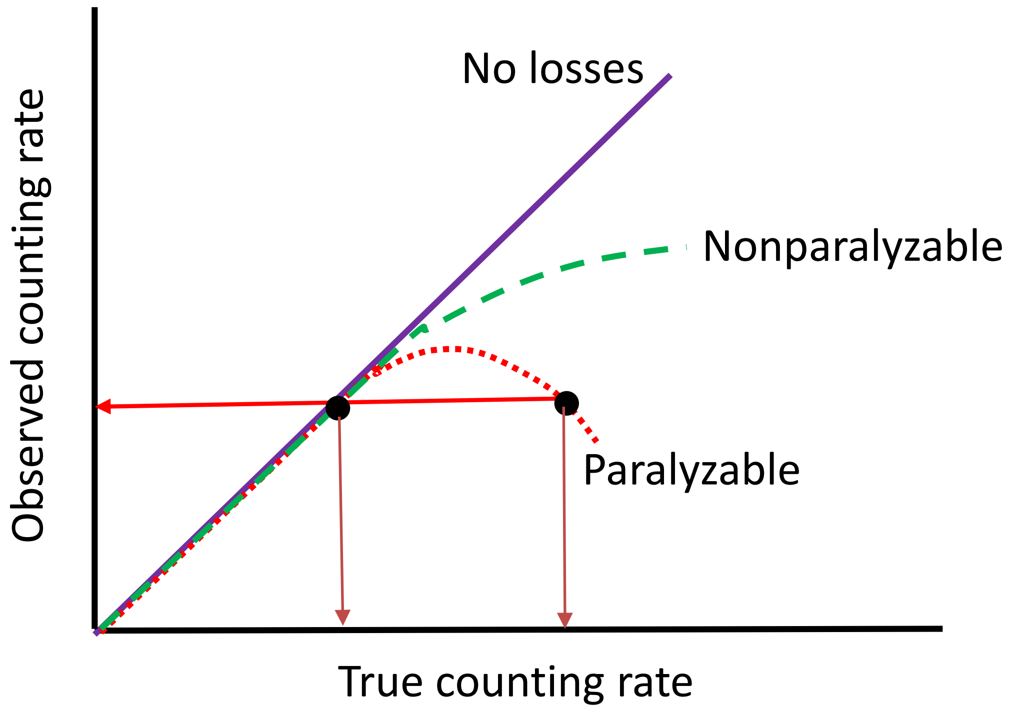
Nonparalyzable detector : signals arriving during deadtime are lost.



DT > event interval
→ **2 events are recorded**

Paralyzable detector : if signals arrive during deadtime, the detector becomes insensitive for another time interval equal to the time of arrival of the second ray

Dead time effect and count rate



Count rate is important! → injected dose and scan mode

Dead time (resolving time)

- Detectors in NM scanners are "paralyzable"
- Ideally, the detector should have a short dead time because it will detect very high count rates without significant loss

  - For typical count rates in NM, e.g., static imaging, ~ 10 μsec deadtime is acceptable → ~100,000 counts processed in1 sec without deadtime effect

  - For fast dynamic imaging, e.g., myocardial perfusion imaging, higher count rates are desirable, shorter deadtime is essential; 2-3 μsec.

Deadtime comparison
CZT (nano sec) vs NaI (micro sec)

1. What part of an imaging system emits light photons when it has absorbed a gamma ray?

   a. photomultiplier tube

   b. pulse height analyzer

   c. scintillation crystal

   d. collimator

2. Which of the following is correct about CZT semiconductor detector?

   a. Has a relatively longer deadtime compared to NaI (Tl) detector
   b. Offers better energy resolution compared with NaI (Tl) detector
   c. Photomultiplier is required to process the electronic signals
   d. Does not require collimator