Radiation Detection for the Beta-Delayed Alpha and Gamma Decay of ^{20}Na

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Review of the Basic Types of Radiation

Radiation Interactions

- The operation of any detector basically depends on the manner in which the radiation interacts with the material of the detector
  - To understand the output of a detector, one must understand the behavior of radiation in different materials and the energy loss incurred therein

Charged/Neutral Radiation

- Charged Particulate Radiation
  - Fast Electrons
    - **Beta Particles** (pos. or neg.) emitted in nuclear decay
    - Energetic electrons from any other process
  - Heavy Charged Particles
    - All energetic ions with one atomic mass (1u) or greater
      - Examples are **alpha particles**, protons, fission products
- Neutral Radiation
  - Electromagnetic Radiation
    - Includes X-rays emitted in the rearrangement of electron shells of atoms, and **gamma rays** that originate from transitions within the nucleus itself
  - Neutrons
    - Generated in various nuclear processes
    - Further divided into slow neutron and fast neutron subcategories

Categories of Radiation

- Soft Radiation (Alphas or Low Energy X-rays)
  - Penetrate only small thicknesses of material
  - Source must be deposited in very thin layers (μm)
    - Sources that are physically thicker are subject to "*self-absorption*"

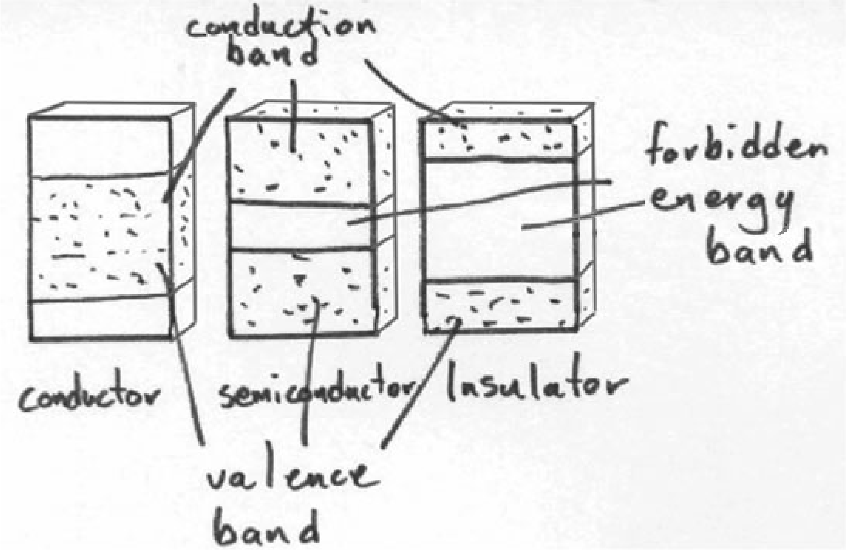
- "Medium" Radiation (Beta Particles)
  - Generally more penetrating
  - Sources can be up to a few tenths of a millimeter in thickness

- Hard Radiation (Gamma Rays or Neutrons)
  - Much less affected by self-absorption
  - Sources can be mm or cm in dimension

Charged Particle Radiation

Review of the Energy Band Structure

- Valance Band
    - Holes are created when electrons are 'excited' enough to cross the energy gap and into the conduction band
- Band Gap (Energy Gap)
    - No available energy levels
    - Width depends on temperature, pressure and the material
    - Large enough (in a semiconductor) that only a few electrons cross to the conduction band by thermal energy
- Conduction Band
    - Highest energy band
    - Region of free electrons



Charged Particle Radiation

- When a charged particle passes through a semiconductor many electron-hole pairs (information carriers) are produced along the tack of the particle

- When radiation interacts with the material of a semiconductor, the energy deposited always leads to the creation of equal numbers of holes and electrons

  - True regardless of whether the host semiconductor is pure, p-type or n-type.

- The quantity of practical interest for detector applications is the average energy expanded by the primary charged particle to produce one electron-hole pair.

  - This quantity is often loosely called the *ionization energy*
    - Experimentally observed to be independent of both the energy and type of the incident radiation

Charge Carriers

- When an electron is ‘excited’ from the valence band into the conduction band it leaves a ‘hole’ in the valance band
  - Referred to as ‘*electron-hole pairs*’
  - The motion of both of these charges contributes to the observed conductivity of the material
- With no E-field, thermally created electron-hole pairs eventually recombine, and an equilibrium is established
  - The concentration of electron-hole pairs is a strong function of temperature
    - Will decrease drastically if the material is cooled.

Motion of Charge Carriers

- The electrons in the conduction band can be made to move under the influence of an applied E-field. The hole, representing a net positive charge, will also tend to move in an applied field, but in a direction opposite that of the electron
        - Their motion in an applied E-field generates the basic electrical signal received from the detector
    - At higher E-field values, the drift velocity increases more slowly with the field. Eventually a saturation velocity is reached which becomes independent of further increases in the E-field
        - Many semiconductors are operated with electric fields sufficiently high to result in a saturated drift velocity for the charge carriers

Semiconductor Detectors

- To reduce statistical limits on energy resolution need to increase the number of information carriers per pulse

  - Semiconductor detectors offer more carriers per pulse than any other commonly used detector

- Main Advantage:
  - Smallness of the ionization energy required ~3 eV to create one carrier
    - As opposed to ~30 eV required in gas-filled detectors

- Main Disadvantage:
  - Limited to small sizes and are very susceptible to radiation-induced damage

n-type / p-type Semiconductors

- Pure Semiconductor
  - The number of holes equals the number of electrons in the conduction band
  - This balance can be changed by introducing a small amount of impurity atoms which have one more or one less valence electron in their outer atomic shell
    - Doped Semiconductors

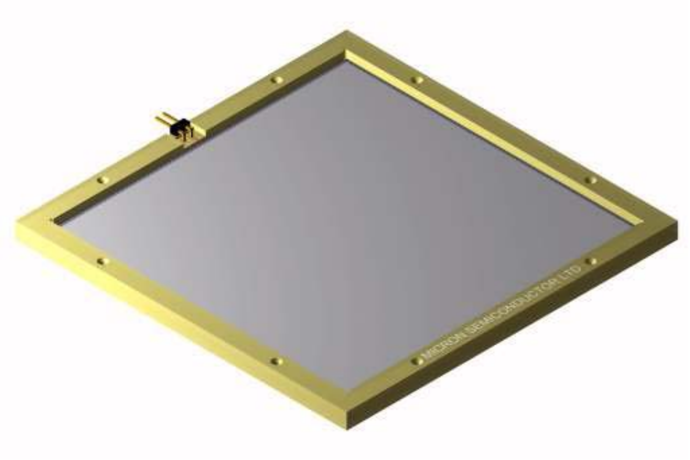
- The n-Type Semiconductor
  - More conduction electrons and fewer holes than in the pure material
    - Donor Impurities
  - Electrical conductivity is determined by the flow of electrons
    - Electrons are Majority Carriers, Holes are Minority Carriers.

- The p-type Semiconductor
  - More holes and fewer electrons than in the pure material
    - Accepter Impurities
  - Electrical conductivity is determined by the holes
    - Hole are Majority Carriers, Electrons are Minority Carriers

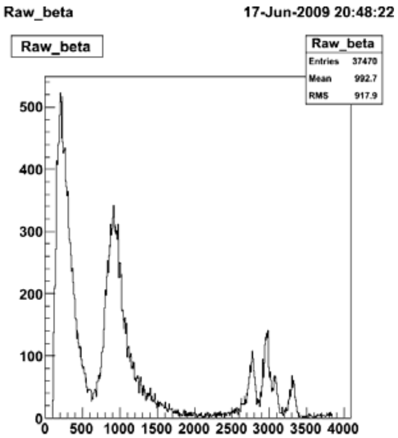
Silicon Detectors

- For charged particle detection, silicon is the most widely used semiconductor material
- Advantages
  - Room temperature operation
  - Wide Availability
- Disadvantage
  - Relatively Small Size
    - Most devices are limited to surface areas of a few ten’s of square cm

β Detector



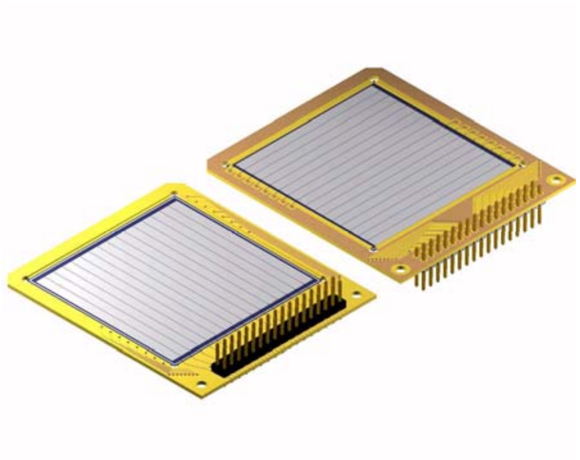
- Continuous detector
  - This is 1000 μm thick

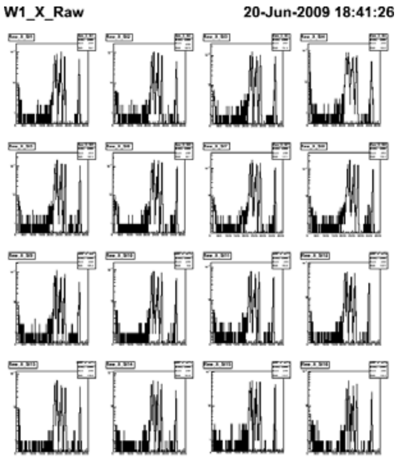


- Example spectrum
  - The ^{228}Th source
    - Alphas
    - Beta Continuum

Alpha Detector

- Two-side Silicon Strip Detector
  - Thickness: 65µm
- 16 Strips on each side
  - Strips are 3mm Wide
- Example of ^{228}Th





Neutral Radiation

Photon Properties

- Photons are invisible to our detectors
  - Unlike charged particles, photons can not undergo inelastic collisions with the atomic electrons of a material (absorber or detector).
- A beam of photons is not degraded in energy when it passes through matter, it only becomes attenuated in intensity

$$\boxed{I(x) = I_0 \exp(-\mu x)}$$

  - Only photons which have not interacted with the material will pass through.

Photon Interactions in Matter

- Three main photon interactions with matter:
  - Photoelectric Effect
  - Compton Scattering
  - Pair Production

Photoelectric Effect (1)

- Predominate for gamma-rays of relatively low energy
  - (up to several hundred keV).
- Involves the absorption of the gamma-ray photon by an atomic electron. There is then a subsequent ejection of an electron from the atom.
- Energy of the outgoing electron is then

$$\boxed{E = h\nu - B.E.}$$

.

Photoelectric Effect (2)

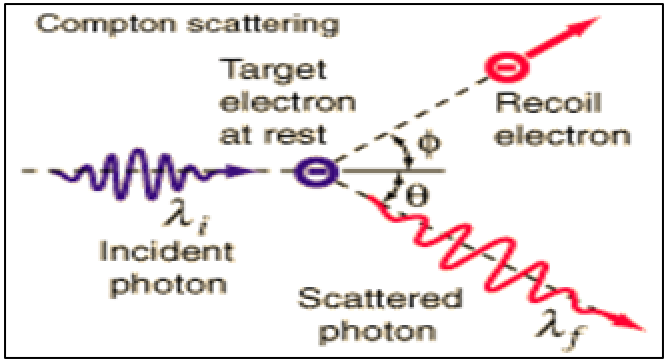
- If process is non-relativistic
  - Born approximation gives

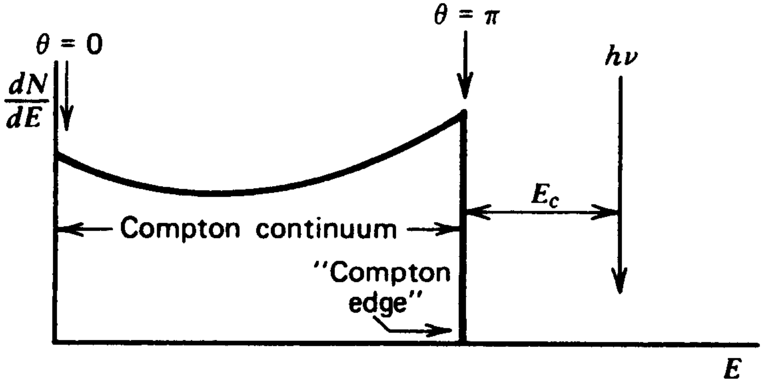
$$\boxed{\Phi_{photo} = 4\alpha^4\sqrt{2}Z^5\phi_0(m_ec^2/h\nu)^{7/2}}$$

- Cross-Section dependence
  - Proportional to Z to about 5th power
- Energy Dependence
  - To the power of (7/2)

- Higher Z materials are more favored for photoelectric absorption

Compton Scattering





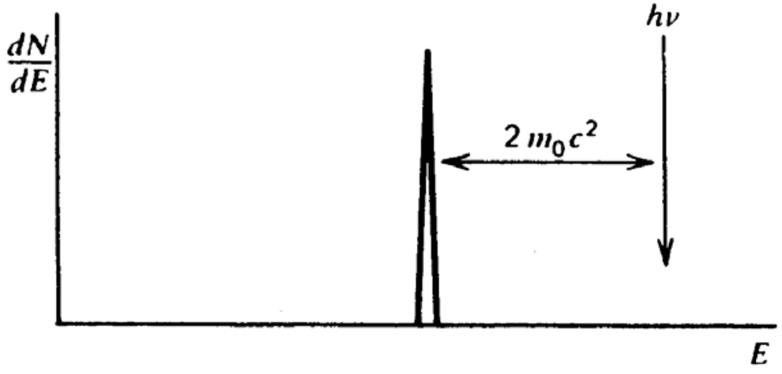
Cross-section is the Klein-Nishina formula:

$$\frac{d\sigma}{d\Omega} = zr_0^2\left(\frac{1}{1+\alpha(1-\cos\theta)}\right)^2\left(\frac{1+\cos^2\theta}{2}\right)\left(1+\frac{\alpha^2(1-\cos\theta)^2}{(1+\cos^2\theta)(1+\alpha(1-\cos\theta))}\right)$$

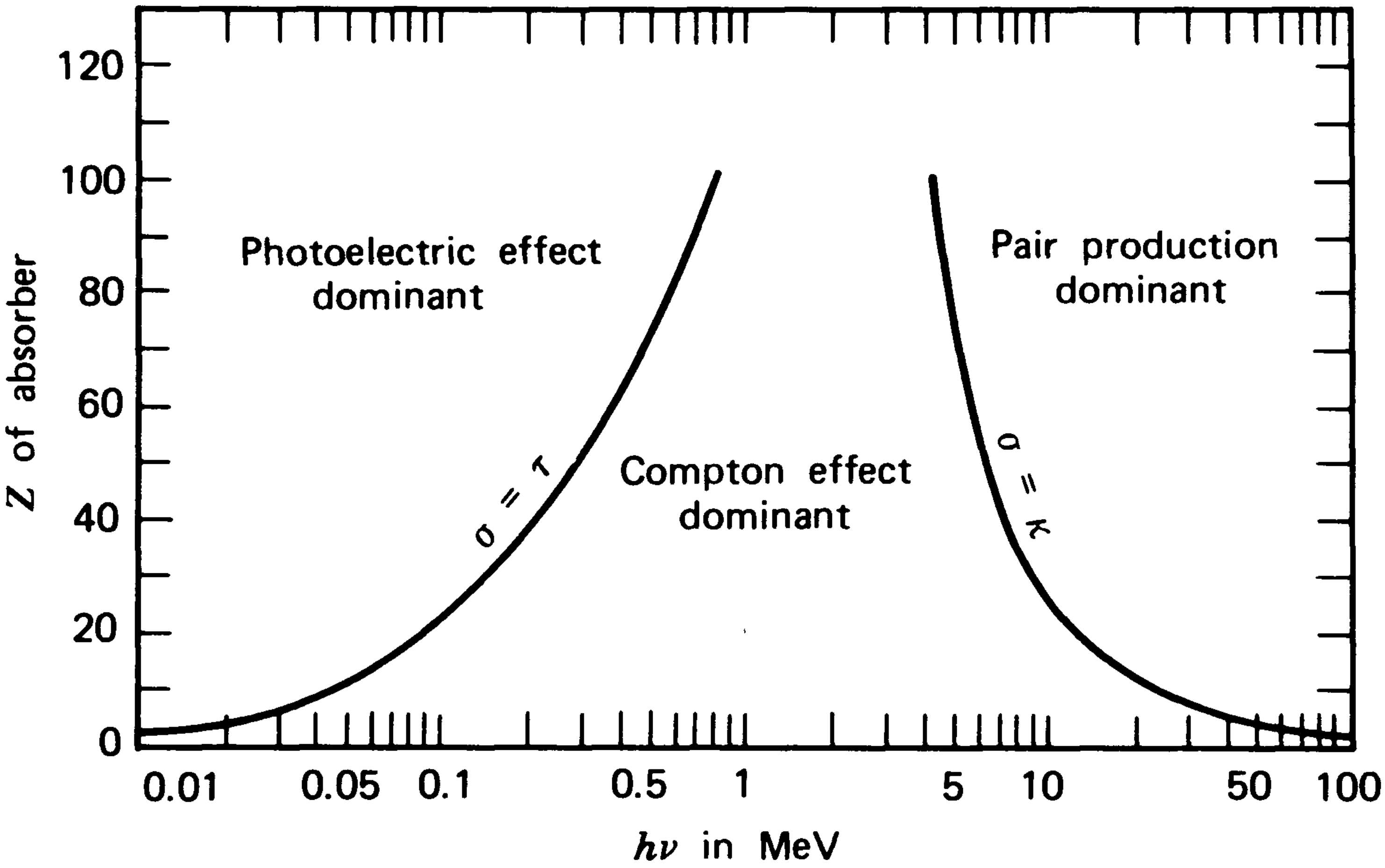
- Depends linearly on Z
- Predominate interaction in the energy range of about 1 to 5 MeV

Pair Production

- Predominate for high-energy gamma rays
  - (above 5-10 MeV)
- Photon is transformed into an electron-positron pair.
  - Minimum energy required is ~1.02 MeV
- The interaction must take place in the coulomb field of a nucleus
- Cross Section varies approximately as (Z^2)

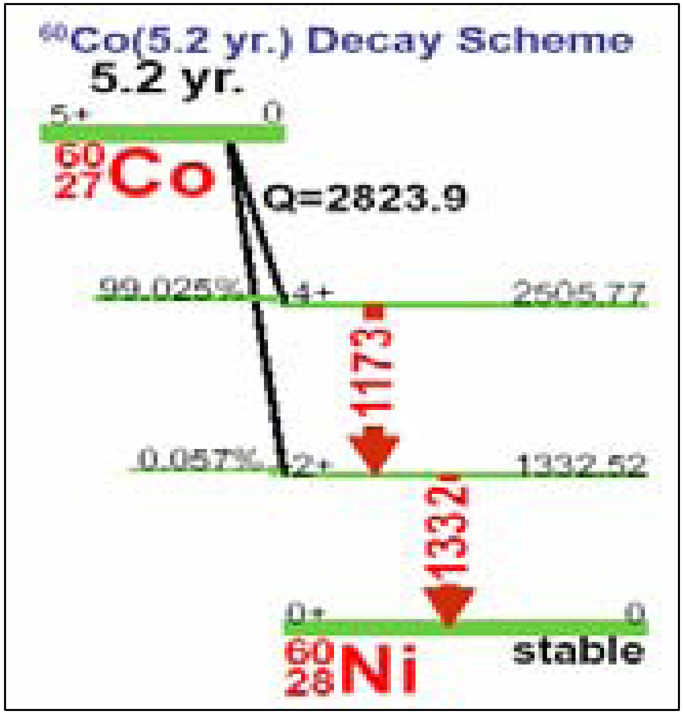


Interaction Summary



Gamma Rays

- Gamma radiation is emitted by excited nuclei when they transition to lower-lying nuclear levels.
    - Electromagnetic Radiation of the shortest wavelengths (below about 10 pm) and highest energy
- Consist of high energy photons with energies above 100 keV
- More penetrating then alpha or beta particles



What Gamma Rays Tell Us

- One of the primary ways to learn about the structure of excited nuclear states.
- Spectra give energies and intensities of the transitions.
- Coincidence measurements give info about how transitions might be arranged among the excited states.
- Internal conversion coefficients can give info on the character of the radiation and the relative spins and parities of the initial and final states.
  - Angular distribution and correlation measurements also help in this area
- Absolute transition probabilities can be found from the half-lives of the levels

Germanium Detectors

- Advantages
  - – Good energy resolution for gamma-rays above several hundred keV
    - Few tenths of a percent (compared to 5-10% of NaI)

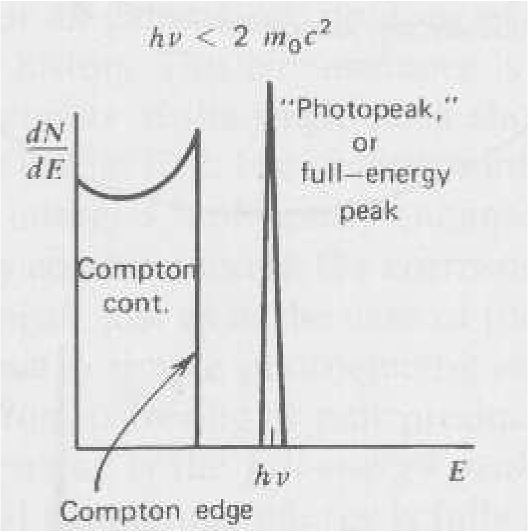
- Disadvantages
  - – Smaller size and lower Z give an order of magnitude less efficiency than NaI
  - – Need to be operated at LN_2 temperatures

Ideally Large Detector

- Detector is large enough that all secondary radiations interact within the detector active volume and none escape from its surface

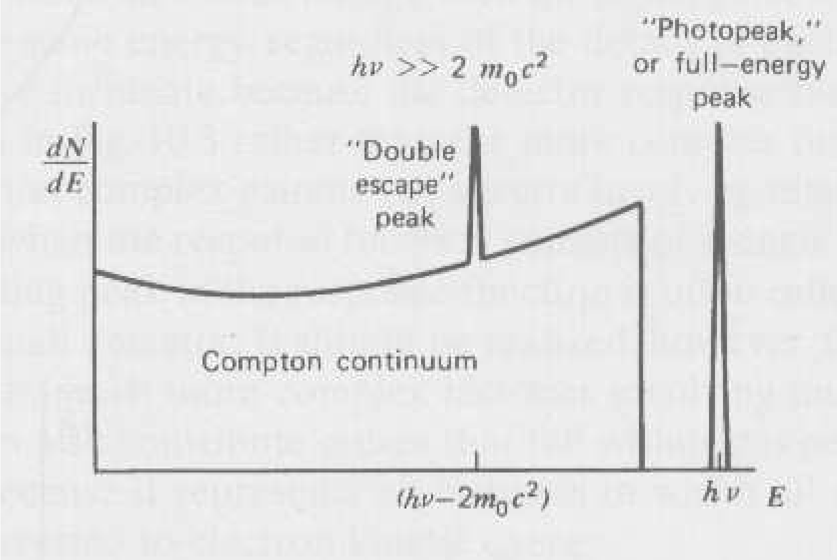
Ideally Small Detector (1)

- Small compared to the mean free path of the secondary gamma radiations (~1 to 2 cm).
  - Assuming incident gamma-ray energy is below the value at which pair production is significant



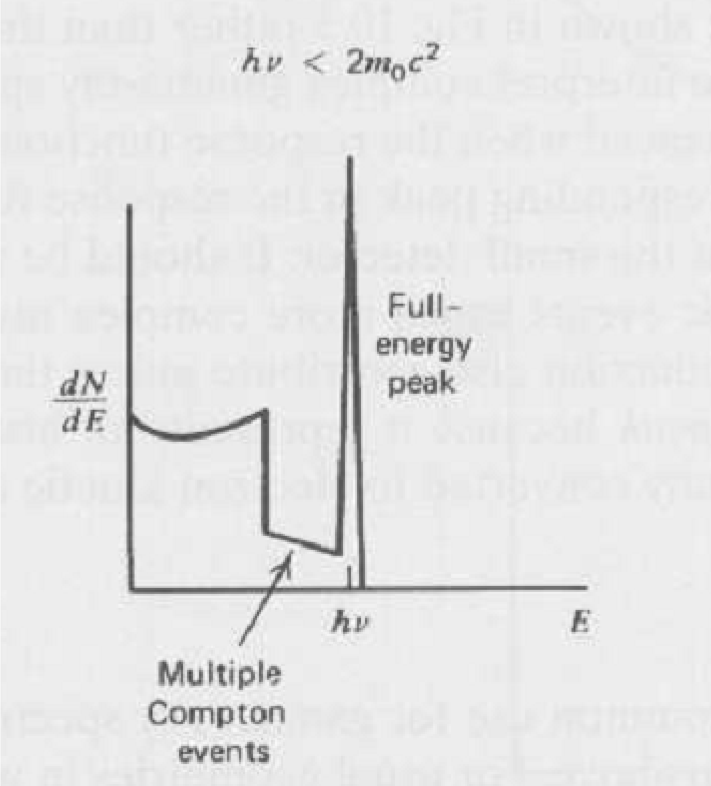
Ideally Small Detectors (2)

- Now, assuming incident gamma-ray energy is several MeV
  - Pair production results can be seen in the spectrum
- Both annihilation photons escape without further interaction and a double escape peak is seen ~1.02 MeV below the photopeak



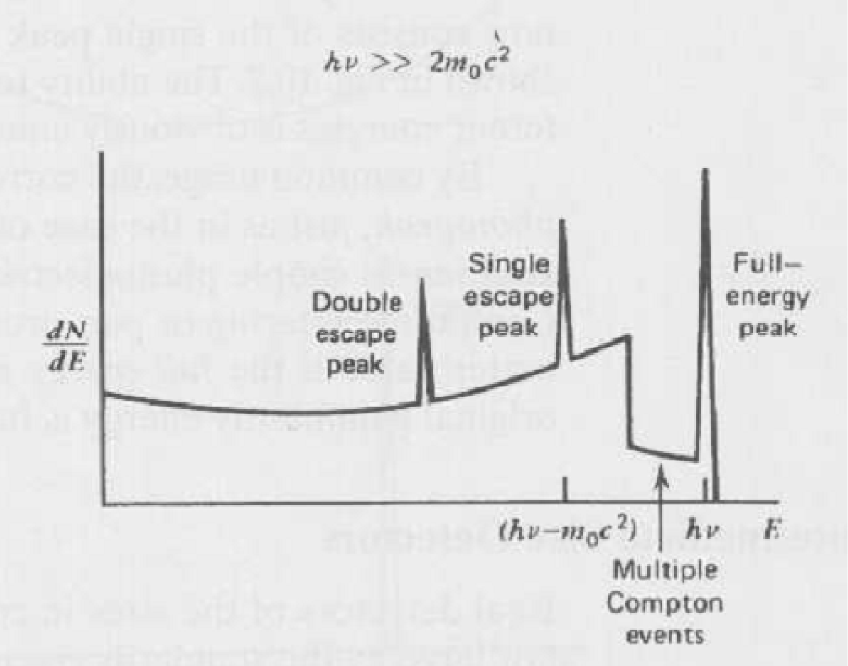
Normal Sized Detectors (1)

- When pair production is not significant
  - At energies less than ~100 keV, the Compton continuum may effectively disappear

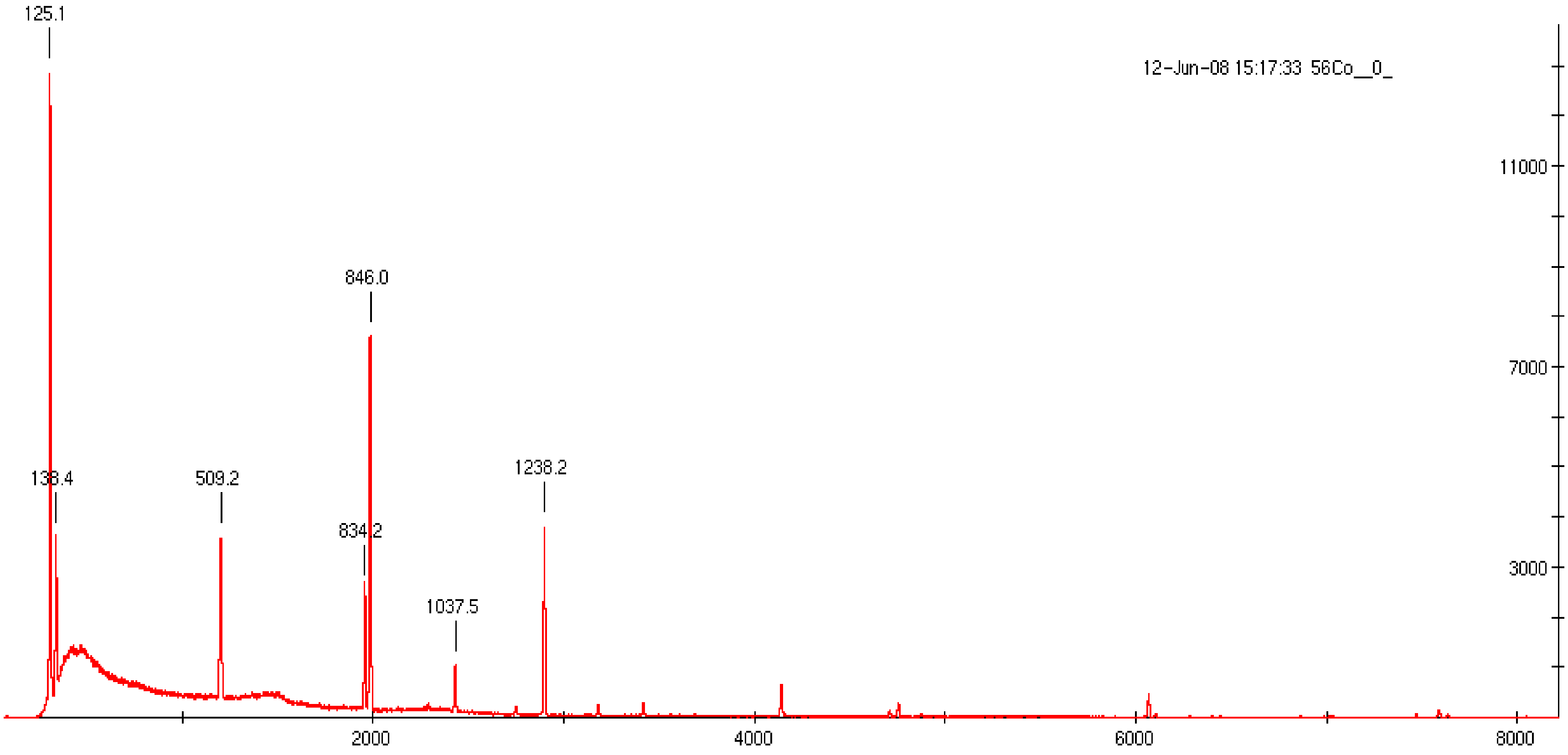


Normal Sized Detectors (2)

- When pair production becomes significant
- When both annihilation photons escape
  - Double escape peak.
- When one annihilation photon escapes (other is totally absorbed)
  - Single escape peak
    - appears ~0.511 MeV below the photopeak



Example Spectrum



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