Physics Principles for Nuclear Cardiology

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Disclosures to Report: Honoraria--Corscan
Atomic and Nuclear Emissions

- Atomic and Nuclear Transitions
- Atomic Structure / Emissions
- Nuclear Structure / Emissions
- Radioactive Decay
- Interactions with Matter
Radioactive Decay Requires Special Units of Mass and Energy

- Mass Units
  - Universal Mass Unit (u) *
    - 1/12 mass of $^{12}$C
    - $u = 1.66043 \times 10^{-27}$Kg
  - Atomic Mass Unit (amu)
    - based on average mass all O isotopes
    - $u = 1.00083$ amu

* most commonly used
Basic Atomic and Nuclear Physics

Quantities and Units

• Mass and Energy Related by
  - \[ E = mc^2 \]
  
  • \( c = \text{Speed of Light} \ (3 \times 10^8 \text{ m/s}) \)
  
  - \[ 1\text{u} = (1.66 \times 10^{-27})(3 \times 10^8 \text{ m/s})^2 = 931.\text{MeV} \]

<table>
<thead>
<tr>
<th>Table 1-2</th>
<th>Mass and Energy Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiply ( \text{To Obtain} )</td>
<td>By</td>
</tr>
<tr>
<td>( \text{u} )</td>
<td>( 1.66043 \times 10^{-27} )</td>
</tr>
<tr>
<td>( \text{u} )</td>
<td>( 1.00083 )</td>
</tr>
<tr>
<td>( \text{eV} )</td>
<td>( 1.6021 \times 10^{-19} )</td>
</tr>
<tr>
<td>( \text{u} )</td>
<td>931.478</td>
</tr>
</tbody>
</table>
Basic Atomic and Nuclear Physics

Quantities and Units

• Electromagnetic Radiations are Referred to as Photons
  - Wavelength and Energy Related by
  - \( c = \lambda \nu \)
    - \( c \) = speed of light (3 X 10^8 m/sec)
    - \( \lambda \) = wavelength (cm or nm)
    - \( \nu \) = frequency

• \( E(\text{keV}) = \frac{12.4}{\lambda(nm)} \)
Atomic and Nuclear Emissions

➡ Atomic and Nuclear Transitions
➡ Atomic Structure / Emissions
➡ Nuclear Structure / Emissions
➡ Radioactive Decay
➡ Interactions with Matter
Basic Atomic and Nuclear Physics

Atomic

• Composition:
  • Electrons: Negatively Charged Particles with Very Small Mass
  • Protons: Positively Charged Particles with Very High Mass
  • Neutrons: No Electric Charge with Very High Mass
  - mass of proton ≅ mass of neutron
  - mass of electron ≅ \frac{1}{2000} \text{ mass of proton}
  - mass of atom ≅ 99\% P + N
Atomic and Nuclear Structure

Bohr Model of the Atom

- Nucleus (Protons & Neutrons)
- Orbiting Electrons
- Electron shells or energy levels (K, L, M shown)
- Outer Electron shell (N) is unoccupied
Atomic Energy Level Diagram

Atomic Structure... Electron Orbitals

Binding Energy Increases (eV or keV)
In shells close to the nucleus

Ground state

Free Electron

Low BE

High BE

K
L
M
N
Basic Atomic and Nuclear Physics

Atomic Structure... Electron Energy

- **Binding Energy**
  - Amount of Energy Required to Remove an Electron from a Shell
  - Specific to a Shell i.e. $K_B$, $L_{IB}$, $L_{IIB}$, $L_{IIIB}$
  - Increases with Z Number (# of protons)
  - Energy Required to Move an Electron from One Shell to Another = $K_B - L_B$
  - Moving from L → K Results in Emission
Atomic Emissions
- **Characteristic x-rays** occur when an inner shell electron is ejected, and it’s vacancy is filled by another electron
- $^{201}\text{TI}$ 69 - 80 KeV
Atomic Emissions
- Auger Effect is an alternative to Characteristic X-rays
  - occurs when the energy produced from filling vacancy is transferred to another electron
  - called an Auger Electron
Atomic and Nuclear Emissions

- Atomic and Nuclear Transitions
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Basic Atomic and Nuclear Physics

Nuclear Structure

- Nucleus composed of protons + neutrons
- Atomic Number (Z) = # of protons (determines element)
- Atomic Mass (A) = # of protons and neutrons
- Neutron Number (N) = A - Z
- Element ‘X’ represented as \( \frac{A}{Z} \), e.g. \( \frac{131}{53} \)
Basic Atomic and Nuclear Physics

Nuclear Families – Definitions

- Isotopes - nuclides composed of the same number of protons \((^{125}\text{I}, ^{131}\text{I}, ^{127}\text{I})\)

- Isotones - nuclides with the same number of neutrons \((^{131}\text{I}, ^{132}\text{Xe}, ^{133}\text{Cs})\)

- Isobars - nuclides with the same atomic mass \(A\) \((^{131}\text{I}, ^{131}\text{Xe}, ^{131}\text{Cs})\)

- Isomers - nuclides in different excited / metastable states \((^{99m}\text{Tc}, ^{99m}\text{Tc})\)
Basic Atomic and Nuclear Physics

Nuclear Structure

- comprised of protons and neutrons
- called nucleons
  - high density

<table>
<thead>
<tr>
<th>Particle</th>
<th>Charge</th>
<th>Mass(u)</th>
<th>Mass(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>+1</td>
<td>1.007277</td>
<td>938.211</td>
</tr>
<tr>
<td>Neutron</td>
<td>0</td>
<td>1.008665</td>
<td>939.505</td>
</tr>
<tr>
<td>Electron</td>
<td>-1</td>
<td>0.000549</td>
<td>0.511</td>
</tr>
</tbody>
</table>
Basic Atomic and Nuclear Physics

Nuclear Structure

• Nuclear Forces
  - Nucleons are Subject to Coulombic forces and Exchange Forces
  - When These Forces are Equal the Nuclide is Called Stable or Ground State
  - When these Forces are not Balanced, then
    • Exited State - very unstable and transient
    • Metastable State - unstable but longer lived also called Isomeric States
Basic Atomic and Nuclear Physics

Nuclear Structure

• Nuclear Energy States
  - any transition in which energy is carried off by a photon is a... γ-ray
  - if energy is imparted to an orbital electron, then particulate emission... internal conversion

Fig. 1-6. Partial nuclear energy level diagram for $^{131}$Xe nucleus. Vertical axis represents energy differences between nuclear states (or "arrangements"). Going up the scale requires energy input. Coming down the scale results in the emission of nuclear energy. Heavier lines indicate metastable states.
Characteristics of Stable Nuclei

- Light Elements
  - $N = Z$
- Heavy Elements
  - $Z = 1.5N$

P:N ratio determines stability/instability

Line of Stability
Atomic and Nuclear Emissions

- Atomic and Nuclear Transitions
  - Atomic Structure / Emissions
  - Nuclear Structure / Emissions
- Radioactive Decay
- Interactions with Matter
Basic Atomic and Nuclear Physics
Radioactive Decay

• General Concepts
  - unstable nucleus is called the parent
  - the product, usually more stable, daughter
  - radioactive decay is spontaneous and therefore random
  - the energy released is called the transition energy (Q)
    • carried off by particles, photons, and nucleus
Basic Atomic and Nuclear Physics
Radioactive Decay

Nuclear Emissions

- Decay by $\beta$-emission with / without $\gamma$-emission ($\beta^-, \gamma$)
  - $^{99}\text{Mo} \rightarrow ^{99}\text{mTc}$
- Isomeric Transition (IT) or Internal Conversion (IC)
  - $^{99}\text{mTc} \rightarrow ^{99}\text{Tc}$
- Electron Capture and $\gamma$ emission (EC, $\gamma$)
  - $^{201}\text{Tl} \rightarrow ^{201}\text{Hg}$ (characteristic x-rays)
- Positron decay and $\gamma$ emission ($\beta^+, \gamma$)
Decay Modes

• $(\beta^-, \gamma)$ Decay
  - If the $\beta^-$ results in an unstable daughter, the daughter will likely decay by emitting a $\gamma$-ray
    
    $^{\text{AX}}_Z \rightarrow ^{\text{AY}^*}_{Z+1} \rightarrow ^{\text{AY}}_{Z+1}$

    - Occurs in Neutron Rich Nuclei
Decay by $\beta^-$ Emission

Decay Scheme for $^{14}\text{C}$

Transition energy, $Q = 0.156$ Mev

Increasing Atomic Number, $Z$
Basic Atomic and Nuclear Physics

Decay Modes

$^{99}\text{Mo}$ (65.94 h)

\[ \beta^- \text{ decay} \quad 100.00 \]

\[ Q_{\beta^-} = 1.3572 \]

$^{99m}\text{Tc}$

$^{99}\text{Tc}$ (2.111E+5 y)
Basic Atomic and Nuclear Physics
Decay Modes

- **Isomeric Transition (IT) and Internal Conversion (IC)**
  - if daughter is long lived a metastable state occurs called **Isomeric Transition**
    - gamma ray emission occurs
  - if nucleus transfers energy to an electron, then **Internal Conversion** occurs
    - conversion electron is emitted
Decay by Isomeric Transition

Transition energy, $Q = 0.140$ MeV

Decay scheme for $^{99m}\text{Tc}$
Decay by Internal Conversion

Internal Conversion
Transition energy transferred to an orbiting electron (usually K-shell)

Conversion electron emitted with energy equal to \( \gamma \)-ray energy minus binding energy of K-shell.

\[ E_e = E_\gamma - E_K \]
Basic Atomic and Nuclear Physics

Decay Modes

TECHNETIUM-99M
ISOMERIC LEVEL DECAY

\[ 99m^{43} \text{Tc} \rightarrow \gamma_1 \quad 0.1405 \]

\[ \gamma_1 \quad 0.1405 \]

\[ \gamma_3 \quad \gamma_2 \]

\[ 2.12 \times 10^5 \gamma \]

\[ 99^{43} \text{Tc} \]


DECAY MODE - ISOMERIC LEVEL

<table>
<thead>
<tr>
<th>MEAN NUMBER</th>
<th>MEAN ENERGY</th>
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<tbody>
<tr>
<td>( \gamma_1 )</td>
<td>( 0.0000 )</td>
</tr>
<tr>
<td>( \gamma_2 )</td>
<td>( 0.0011 )</td>
</tr>
<tr>
<td>( \gamma_3 )</td>
<td>( 0.0039 )</td>
</tr>
<tr>
<td>( \gamma_4 )</td>
<td>( 0.0068 )</td>
</tr>
<tr>
<td>( \gamma_5 )</td>
<td>( 0.0035 )</td>
</tr>
<tr>
<td>( \gamma_6 )</td>
<td>( 0.0011 )</td>
</tr>
<tr>
<td>( \gamma_7 )</td>
<td>( 0.0041 )</td>
</tr>
<tr>
<td>( \gamma_8 )</td>
<td>( 0.0221 )</td>
</tr>
<tr>
<td>( \gamma_9 )</td>
<td>( 0.0105 )</td>
</tr>
<tr>
<td>( \gamma_{10} )</td>
<td>( 0.0152 )</td>
</tr>
<tr>
<td>( \gamma_{11} )</td>
<td>( 0.0055 )</td>
</tr>
<tr>
<td>( \gamma_{12} )</td>
<td>( 0.1093 )</td>
</tr>
<tr>
<td>( \gamma_{13} )</td>
<td>( 1.2359 )</td>
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</tbody>
</table>
Electron Capture
- orbital electron captured by nucleus, combines with proton to form a neutron
  - $p^+ + e^- \rightarrow n + \nu + \text{energy}$
  - $^{A}_{Z} X \rightarrow ^{A}_{Z-1} Y$
- Occurs in Proton Rich Nucleii
Decay by Electron Capture

Decay Scheme for $^{125}$I

Transition energy, $Q = 0.177$ MeV

Decreasing Atomic Number, $Z$
Decay by Electron Capture

\[ e + p \rightarrow n + \nu + \text{energy (EC)} \]

\[ e + p \rightarrow n + \nu + \gamma + \text{energy (EC,}\ \gamma) \]
Basic Atomic and Nuclear Physics
Decay Modes

\[ ^{201}\text{Tl} \rightarrow ^{201}\text{Hg} \]
Basic Atomic and Nuclear Physics

Decay Modes

- **Positron (β⁺) and (β+, γ)**
  - a proton in the nucleus is transformed into a neutron and a positively charged electron \( β^+ \)
  - \( p^+ \rightarrow n + e^+ \nu + \text{energy} \)
  - \( ^AX \rightarrow ^AY \)
  - occurs in Proton Rich Nuclei
Decay by Positron ($\beta^+$) Emission

$\nu$  

$\beta^+$

$\rho \rightarrow n + e \ (\beta^+) + \nu + \text{energy}$
Annihilation Reaction

*Positron ($\beta^+$) and an Electron ($\beta^-$)*

- Positron collides with an electron.
- Both are converted to energy.
- Results in the emission
  - 2 gamma rays, each of energy 511 keV
  - emitted in opposing directions ($\sim 180^\circ$)
Decay by Positron ($\beta^+$) Emission

Decay Scheme for $^{18}\text{F}$

Note: $^{18}\text{F}$ can also decay by Electron Capture

$E_{\beta}^{\text{max}} = 0.633$ MeV

Transition energy, $Q = 1.655$ Mev

Decreasing Atomic Number, Z
Radioactive Decay

Definitions

**Definition of Decay**

A process by which an unstable nucleus transforms into a more stable one by emitting particles and / or photons and releasing energy.

**Terminology**

- Parent nucleus = the unstable nucleus
- Daughter nucleus = the more stable product
- Transition energy $Q =$ energy released
Radioactive Decay

Definitions

• Half-life
  - Sometimes called Physical Half-life.
  - Time required for activity to decay to 50% of its initial value.
Radioactive Decay

Physical Half-Life

Decay curve with $T_{1/2} = 4$ hours
Radioactive Decay

Definitions... Activity

Curie (Ci) 1 Ci = $3.7 \times 10^{10}$ disintegrations / sec
1 mCi = $3.7 \times 10^7$ disintegrations / sec

Becquerel (Bq) 1 Bq = 1 disintegration / sec
= $2.7 \times 10^{-11}$ Ci

Conversion Factors
1 mCi = 37 megaBecquerels (MBq)
1 MBq = 27 μCi
Decay Constant \( (\lambda) \)

Fraction of the atoms undergoing radioactive decay per unit time (during a time period that is so short, only a small fraction decay during that interval)

For a sample of \( N \) radioactive atoms, the average decay rate \( \frac{dN}{dt} \) is given by

\[
\frac{dN}{dt} = -\lambda N
\]
Decay is an exponential function of time

\[ N_t = N_0 \, e^{-\lambda t} \]

where \( N_t \) = number of atoms at time \( t \)
and \( N_0 \) = number of atoms at time \( 0 \)
\( \lambda \) = decay constant
Radioactive Decay
Definitions... Decay Factor

Decay Factor \( (e^{-\lambda t}) \)

Fraction of the atoms remaining after time \( t \)

For a sample of \( N \) radioactive atoms, the remaining atoms left after .25 hours is

\[
e^{-0.1151 \times 0.25} = 0.972
\]

\[
N_{(15')} = N_{(0)} e^{-\lambda t} = 30 \times 0.972 = 29.16
\]
Radioactive Decay
Definitions...Half-Life

The Physical Half-Life ($T_{1/2}$ or $T$) is the time required for the number of atoms to decrease by half. The relationship between the Decay Constant $\lambda$, and Half-Life $T_{1/2}$ is given below:

At $t = T_{1/2}$, Activity = 0.5 $\times$ Initial Activity

i.e. $\frac{N}{N_0} = 0.5$, or

$0.5 = e^{-\lambda T_{1/2}}$

$\therefore \log_e(0.5) = -\lambda T_{1/2}$, or

$-0.693 = -\lambda T_{1/2}$

$\therefore \lambda = \frac{0.693}{T_{1/2}}$

or $T_{1/2} = \frac{0.693}{\lambda}$
Radioactive Decay
Definitions...Half-Life

\[ \frac{dN(t)}{N} = -\lambda t \]

\[ \lambda = \text{decay constant} \]

\[ N(t) = N_o e^{-0.693t/T_h} \]

\[ N_o = \text{original number of atoms} \]

\[ T_h = \text{Half-Life} = \ln 2/\lambda = 0.693/\lambda \]
Atomic and Nuclear Emissions

- Atomic and Nuclear Transitions
- Atomic Structure / Emissions
- Nuclear Structure / Emissions
- Radioactive Decay
- Interactions with Matter
Interactions of Radiation with Matter

• Particulate
  - Mass
  - Momentum
  - Kinetic Energy

• Photon
  - Pure Energy in Motion
  - No Mass
  - Frequency and Wavelength Determines Energy
Charged Particles in Matter

Collisions

- $\alpha$ and $\beta$ particles
  loose energy through Collisions
  - Interactions with charge fields... not mechanical
    - Excitation
    - Ionization
    - Bremsstrahlung
Charged Particles in Matter
Interactions

• **Excitation** occurs when the incident particle interacts with an outer shell electron
  - Energy carried off by molecular vibrations, infrared, visible or UV radiation

• **Ionization** occurs when an outer shell electron is ejected
  - Secondary electron (δ ray) may cause ionizations

• **Bremsstrahlung** occurs when the particle penetrates the electron cloud
Charged Particles in Matter

LET

- Particles with high mass, lose energy over a short path length and low mass over a longer path length.
- The relative amount of energy loss as a function of path length is defined as, LINEAR ENERGY TRANSFER (LET).

\[ \alpha (\text{LET}) \]
\[ \beta (\text{LET}) \]
Photon Interactions with Matter

- **100% Energy Conversion**
  - EM to Kinetic Energy
- **Spatially Discrete**
- **<100% Energy Conversion**
  - Energy Degraded Photon
  - High Energy
  - $> 1.022$ MeV
- **Altered Pathway**
**Photoelectric Absorption**

- Photon is absorbed by atom; energy goes to free an electron:

\[ E_e = E_\gamma - \Phi \]

- \( E_\gamma \) is incoming photon’s energy.
- \( E_e \) is freed electron’s \( E_k \).
- \( \Phi \) is binding energy of electron.
Compton Scattering

- Incident $\gamma$ scatters with free electron
  - $\gamma$ energy is reduced.
  - $\gamma$ direction is changed.
  - $\gamma$’s lost energy is gained by electron

$E_{\gamma_1} = E_{\gamma_0} - E_{e^-}$
Compton Scattering - E loss vs. angle

- The energy lost by an incidence photon is:

\[ E_1 = \frac{E_0}{1 + \frac{E_0}{m_e c^2 (1 - \cos \theta)}} \]

- \( E_0 \) is original photon energy
- \( E_1 \) is scattered photon’s energy
- \( m_e \) is the electron mass (\( m_e c^2 = 511 \text{ keV} \))
- \( \theta \) is the scattering angle (\( \theta = 0 \) is no scatter)
Photon Interactions with Matter

Multiple Interactions
### Photon Interactions with Matter

#### Secondary Radiations

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Secondary Photon(s)</th>
<th>High-Energy Secondary Electron(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photoelectric</td>
<td>Characteristic x rays</td>
<td>Photoelectrons Auger electrons</td>
</tr>
<tr>
<td>Compton</td>
<td>Scattered photon</td>
<td>Recoil electron</td>
</tr>
<tr>
<td>Pair production</td>
<td>Annihilation photons</td>
<td>Positive-negative electron pair</td>
</tr>
</tbody>
</table>
Photon Interactions with Matter
Probability Distribution
Photon Interactions with Matter
Probability Distribution

$^{82}\text{Pb}$

$^{99m}\text{Tc} - 140\text{ keV}$
Photon Interactions with Matter

Probability Distribution

- $^{99m}$Tc - 140 keV
- $^{201}$Tl - 72 keV

$H_2O$
Photon Interactions with Matter

Attenuation

- Attenuation depends on the thickness and $Z$ of the absorber
  - Greater thickness leads to greater absorption
  - Energy and $Z$ relationship is more complicated
  - Linear attenuation coefficient ($\mu_l$)... cm$^{-1}$

\[
I(x) = I(0) e^{-\mu x}
\]
Transmission through an absorber is described by:

\[ I(x) = I(0) e^{-\mu x} \]

HVT (aka HVL) is the thickness required to absorb 50% of the beam

\[ HVT = \frac{0.693}{\mu_l} \]
Physics Principles for Nuclear Cardiology

Summary

• Relationship of atomic structure to
  – Mode of decay
  – Emissions

• Understand and explain radioactive decay

• Interactions of photons with matter
  – Tissue
  – Image quality
Basic Principles of Radiation Detection
Radiation Detectors

Gas-filled Detectors
- Ionization chambers
- Geiger-Mueller counters

Scintillation Detectors
- Inorganic scintillators (NaI)
- Organic liquid scintillators

Semiconductor Detectors
- Ge(Li) and Si(Li) detectors
- CZT detector
Gas-Filled Detectors

Radiation

+ (Anode)

- (Cathode)

Current Amplifier
Effect of Voltage on Detector Performance

- Recombination Zone
- Ionization Plateau
- Proportional Counter
- GM Counter
- Continuous Discharge Zone
- GM Plateau
Gas-Filled Radiation Detectors

• Ion Chamber
  Used for dose calibrators, pocket dosimeters

• Geiger-Mueller Counter
  Output independent of absorbed energy
  Used for survey meters
  10 times more sensitive than ion chamber
Radiation Detectors

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Solid Scintillation Materials

- Sodium Iodide doped with Thallium (NaI) used extensively in Nuclear Medicine
- Bismuth Germanium Oxide (BGO) widely used in PET systems
- Barium Fluoride (BaF$_2$) / Cesium Fluoride (CsF$_2$) used in PET systems
- Lutheum Orthosilicate (LSO) used in hybrid PET/SPECT systems
- Plastic inexpensive bulk scintillator
Principle of $\gamma$-ray Detection

Radioactive sources $\rightarrow$ Nal (TI) crystal $\rightarrow$ Photomultiplier tube $\rightarrow$ Voltage output

Gamma rays $\rightarrow$ Photons of light $\rightarrow$ Voltage pulses

300 keV $\rightarrow$ Voltage

200 keV $\rightarrow$ Time
**Voltage (Energy) Discriminator**

- **BASIC PRINCIPLES OF PULSE HEIGHT ANALYSIS**
  - Requires a proportional detector...

![Diagram](image)

- Consists of discriminators
  - ULD
  - LLD

Examination of signal amplitudes to determine energy
Voltage Pulse to $\gamma$-ray Energy
Energy Spectrum Components

- Photopeak
- Compton Edge
- Backscatter Peak
- Lead x-ray Peaks
Energy Spectrum Components

PP = Photopeak
BP = Backscatter Peak
CE = Compton Edge
C1 = 1st Order Compton
C2 = 2nd Order Compton
Pb = Lead X-ray
γ-ray Energy Spectrum

Energy Windows

Counts or No. of Events

γ-ray Energy
Energy Resolution

- **FWHM**
  - Full Width Half Maximum
- **%FWHM**
  - Expressed as a % of photopeak energy

\[
\text{FWHM (%)} = \frac{\Delta E}{E_p} \times 100% = \frac{46}{662} \times 100% = 7% 
\]
Energy Resolution of NaI

Energy Resolution

Emry Resolution of NaI

Energy Resolution

Measured FWHM

Calculated : FWHM

Energy Resolution

FWHM (%)

Energy (keV)

0 100 200 300

5 10 15 20

Measured FWHM

Calculated : FWHM
Pulse-Height Analysis

• What are the various peaks and valleys in the energy spectrum?

• What parts of the spectrum contain useful information?

• Where should we place the energy window?

• Why are the peaks so broad?
Scintillation Detectors

Summary

• Voltage pulse $\propto$ energy deposited in crystal
• Measure voltage = measure energy
• Low voltage gives error in energy measurement
  Hence energy resolution $\sim 1/\sqrt{E}$

• Scatter in source $\Rightarrow$ range of detected energies
• Energy window selects events / energies we want

• $\gamma$-ray detection efficiency depends on thickness of NaI crystal and energy of $\gamma$-ray.
Radiation Detectors

Gas-filled Detectors
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Semiconductor Detectors
- Ge(Li) and Si(Li) detectors
- CZT detector
Radiation Detectors

Semiconductor Detectors

- Ge(Li) and Si(Li) detectors
- CZT detector
Semiconductor Properties
How an Electrical Charge is Generated

Note: Some of the positive charge is lost due to hole charge carrier trapping losses. Leads to tailing effects in energy spectrum!
Tc-99m Energy Resolution
Semiconductor vs Scintillation Technology

![Graph showing Tc-99m energy resolution for CZT and NaI technologies. The graph compares the energy resolution of CZT and NaI detectors for Tc-99m emissions.]