Radiation Detection --- Some Basics

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http://www.lbl.gov/abc/cosmic/
Except neutrons, these particles interact *primarily* with electrons … thus, the term ionizing radiation. The coulomb interaction is long-ranged so the slowing down of charged particles is most effective and is a continuous process. On the other hand, electromagnetic interactions can be viewed as “collisions” of a photon and electron and lead to discrete stopping processes for photons. Neutrons are detected through the secondary products of nuclear reactions.

The observation of this ionization is the fundamental basis for radiation detectors.

The amount of ionization is sometimes strongly, other times weakly related to the incident kinetic energy of the particle and depends critically on the stopping medium.

E.g, solid Silicon: $^{14}\text{Si}$ atom, $r \sim 120 \text{ pm}$, nucleus $r \sim 3.6 \text{ fm}$

$$\sigma_{\text{Geo}} = \pi r^2 \sim 4.5 \times 10^{-20} \text{ m}^2 \sim 4.1 \times 10^{-29} \text{ m}^2$$

(and there are 14 electrons in that space)

Energy Scales: atomic eV, nuclear MeV
Object: Cosmic Rays

Cartoon of a “shower” event

Calculation of a “shower” event

~$10^9$ to $10^{20}$ eV

UPPER ATMOSPHERE

SECONDARIES

(heavy charged particles and ions)

~$10^9$ to $10^{20}$ eV

(heavy mesons, pions, muons, electrons, positrons, ...)

~2 particles cm$^{-2}$ min.

dE/dx $\sim 1.5$ keV / mg/cm$^2$

$\sim \cos^2 \Theta$ angular distribution

R. Chartrand, et al. LANL
Interaction of massive C.P. with Matter

Massive charged particles interact with the electrons in the bulk material but the very large ratio of masses (e.g., the smallest ratio is $m_p/m_e \sim 1800$) means that the ions will travel on straight lines, continuously slow down, and finally stop at some point after a huge number of interactions.

We expect that the ion intensity remains essentially constant with depth until the end of the range when the ions come to rest. On the other hand the kinetic energy of the ion will drop continuously in tiny increments until rest. In a single collision the energy change is small.

Cloud Chamber Images of $^{252}$Cf

From: http://www.lateralscience.co.uk/cloud/diff.html

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Primary Ionization is created by the interaction of the radiation in the bulk material of the ‘detector’ – then what?

<table>
<thead>
<tr>
<th>Rate</th>
<th>Technique</th>
<th>Device</th>
<th>Energy Proportionality?</th>
<th>Temporal Information?</th>
<th>Position Information?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Collect ions</td>
<td>Ion Chamber</td>
<td>Excellent</td>
<td>Poor</td>
<td>Average</td>
</tr>
<tr>
<td></td>
<td>Multiply &amp; Collect ions</td>
<td>Proportional counter</td>
<td>Very good</td>
<td>Average</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Convert into photons</td>
<td>Scintillation counter</td>
<td>Acceptable</td>
<td>Good</td>
<td>Varies</td>
</tr>
<tr>
<td></td>
<td>Create discharge</td>
<td>Geiger-Mueller Ctr. Spark chamber</td>
<td>No</td>
<td>Good</td>
<td>Varies</td>
</tr>
<tr>
<td>High</td>
<td>Collect current</td>
<td>Ion Chamber</td>
<td>Radiation Field</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

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Scintillation Counters

A few photons are produced in de-excitation of primary ionization, scintillation devices rely on enhancing and detecting these photons. The primary ion pairs are essentially ignored and these materials are generally insulators.

**General requirements:**
- Linear conversion of $\Delta E$ into photons
- Efficient conversion into (near) visible light  
  (e.g., Plastics: 20k/MeV or NaI: 38k/MeV)
- Transparent to scintillation photons, good optical medium
- Short decay time for fluorescence (ns OK, ps good)
- Good mechanical properties (n~1.5 for glass)

**Scintillator classes:**

Organic molecules – molecular transitions in fluor  
Inorganic materials – transitions in atomic dopants
Photomultiplier Devices: Light to Current

The scintillation process produces photons in proportion to the primary ionization ... we need to count the number of photons to obtain the energy deposited by the primary radiation in the detector.

- Photocathode / photoelectric effect
- Various coatings, low w & high quantum efficiency
- Electrons avalanche down a string of “dynodes” (8-14)
- Dynodes are also coated to enhance cascades
- HV can be positive or negative
- Vacuum tube – internal getter to maintain vacuum
- Low potassium glass (\(^{40}\)K)
- KE of electrons start out very low – some electron optics and external magnetic shields
PMTs – Other Resolution Issues

Stray magnetic fields – use so-called mu-metal or iron shields

Differential sensitivity of photocathode surface – diffuse light over surface

Dark current – thermal photoelectrons, electronic noise, cosmic rays!

High voltage stability … \( Q \sim V^n \) where \( n \sim \) (number of stages minus a few)

Photocathode glass … transparent to uv or not?

http://www.scionixusa.com/
The Berkeley Cosmic Ray Detector

Plastic scintillator, active material, creates ~ 30k photons, must be polished so that light is internally reflected to one end

PMT converts photons to electrical pulse, good optical connection, wrapped to keep stray light (photons) out

Circuit board, supplies voltages to PMT’s, records pulses and coincidence pulses

Two paddles – coincidences are sensitive to direction
Supplementary Material

Radiation Sources .. Charged Particles –1–
Radiation Sources .. Electrons –2–
Radiation Sources .. γ Rays – 3 –
Alpha Decay: $^{A}Z \rightarrow ^{A-4}(Z-2)^{2-} + ^{4}\text{He}^{2+} + Q_{\alpha}$  

E.g., $^{238}\text{U} \rightarrow ^{234}\text{Th}^{2-} + ^{4}\text{He}^{2+} + Q_{\alpha}$  

$Q_{\alpha} = M[^{A-4}(Z-2)^{0}] + M[^{4}\text{He}^{0}] - M[^{A}\text{Z}]$

Nuclei heavier than $A \sim 150$ are theoretically unstable against alpha decay but because it is a quantum mechanical tunneling process that is extremely sensitive to the Q-value of the process. Thus, alpha decay is only important for the heaviest nuclei and it rarely feeds excited states.

The particles are quite energetic 4 - 9 MeV but interact very efficiently with electrons in materials and stop within ~100 microns in solids.

Two-body final state gives a discrete energy distribution – must subtract recoil energy.

E.g., the “A=4N” natural decay chain:

$^{232}\text{Th} \rightarrow ^{228}\text{Ra} \rightarrow ^{228}\text{Ac} \rightarrow ^{228}\text{Th}$

$^{228}\text{Th} \rightarrow ^{224}\text{Ra} \rightarrow ^{220}\text{Rn} \rightarrow ^{216}\text{Po} \rightarrow ^{212}\text{Pb}$

$^{212}\text{Pb} \rightarrow ^{212}\text{Bi} \rightarrow ^{212}\text{Po} \rightarrow ^{208}\text{Pb}$

$E_{\alpha} = 8.78$ MeV

$E_{\alpha} = 6.05, 6.09$ MeV

$E_{\gamma} = 2.61$ MeV

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Beta Decay: \( n \rightarrow p^+ + e^- + \nu + Q \) e.g., \( ^{14}\text{C} \rightarrow ^{14}\text{N}^+ + e^- + \nu + Q \)

\[ Q = M(^{14}\text{N}^0) - M(^{14}\text{C}) \]

and \( (p^+ \rightarrow n + e^+ + \nu + Q') \) e.g., \( ^{13}\text{N} \rightarrow ^{13}\text{C}^- + e^+ + \nu + Q' \)

\[ 13\text{N} \rightarrow ^{13}\text{C}^0 + e^- + e^+ + \nu + Q' \]

\[ Q' = M(^{13}\text{C}^0) + 2m_e c^2 - M(^{14}\text{C}) \]

Three-bodies in final state gives continuous energy distribution but there are thousands of radioactivities to choose from. Note limits: \( 0 < \text{Kinetic Energy} < Q \)

Phase space or Fermi Functions have Coulomb shifts … Interesting example of a radioactivity that can “decay two ways”

\( ^{64}\text{Cu} \rightarrow ^{64}\text{Ni}^- + e^+ + \nu + Q_{\beta^+} = 0.6529 \ \text{MeV} \)

\( ^{64}\text{Cu} \rightarrow ^{64}\text{Zn}^+ + e^- + \nu + Q_{\beta^-} = 0.5782 \ \text{MeV} \)
Gamma rays are emitted by nuclear excited states, their lifetimes are generally too short to provide useful sources (except for some special cases called "isomeric" states).

**Beta-delayed:** $^A(Z+/1) \rightarrow ^A Z^* \rightarrow ^A Z + \gamma$  the gamma decay is for many purposes prompt, but often the lifetimes of the excited states can be significant and their exponential decay can be measured.

Two-bodies in final state gives a discrete energy distribution …

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Decay Mode</th>
<th>Energy (MeV)</th>
<th>Lifetime (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{60}\text{Co}$</td>
<td>$^\beta^-$</td>
<td>2.506</td>
<td>1.1</td>
</tr>
<tr>
<td>$^{60}\text{Ni}$</td>
<td>$^\beta^+$</td>
<td>1.3325</td>
<td>0.71</td>
</tr>
</tbody>
</table>

There will be an angular correlation among the beta and two gammas ..

**Annihilation Radiation:**

$e^+ + e^- \rightarrow \gamma + \gamma$

**Bremsstrahlung:** from electron beams, continuous energy spectrum primarily used for irradiations