Introduction

- Integrating dosimeters provide measurements of the full energy imparted to matter by radiation: TLD’s, film, chemical, and calorimetric dosimeters
- Pulse-mode detectors: gas proportional counters, Geiger-Muller counters, scintillators, and semiconductor detectors
- The objective is to discuss
  - the characteristics of these devices that make them useful for dosimetry
  - how their output signals can be interpreted in relation to the absorbed dose

Gas multiplication

- An ionization chamber operated at an applied potential great enough to cause gas multiplication
- Free electrons from ionizing events can derive enough kinetic energy from the applied electric field, within a distance equal to the electrons’ mean free path $\sigma$, to ionize other gas molecules with which they collide
- A single electron can give rise to an "avalanche"
- At atmospheric pressure the minimum field strength required is $\sim 10^3$ V/mm

Cylindrical counter

- Electrical field strength is not uniform:
  $X(r) = \frac{P}{r \ln(a/b)}$
- The maximum occurs at the surface of the inner electrode
  $X(b) = \frac{P}{b \ln(a/b)}$

Gas multiplication

- The central wire must serve as the anode, so that the free electrons produced by radiation in the counter gas travel toward the thin high-field sheath around the wire
- For gas multiplication to occur, at a pressure $p$ (atm), and applied potential $P$, the field strength $E(r)$ must satisfy
  $$pK \leq E(r) = \frac{P}{r \ln(a/b)}$$
- The radius $r_s$ of the outer boundary of the amplifying sheath region is
  $$r_s = \frac{P}{pK \ln(a/b)}$$
Gain factor

- The gain factor \( G \) is the number of electrons that arrive at the wire anode per electron released by ionizing radiation in the gas volume.
- For cylindrical geometry:
  \[
  G \approx \exp\left[\frac{0.693P}{\Delta V \ln(a/b)} - \ln\left(\frac{P}{Kp \ln(a/b)}\right)\right]
  \]
- \( \Delta V \) is the average potential difference (eV) through which an electron moves between successive ionizing events; \( K \) is the minimum value of the electric field strength per atmosphere of gas pressure; \( p \) is the gas pressure in atmospheres.

Gain factor

- For a chamber operating with a fixed gain \( G \), the total charge collected \( Q \) at the wire during a given exposure to ionizing radiation will be just \( G \times Q \) if the device had been operated as a saturated ion chamber.
- An ion chamber operating with \( G > 1 \) is called an amplifying ion chamber. Its advantages over a simple ion chamber are:
  - greater sensitivity, since the charge collected is \( G \)-fold larger
  - the gas-filled cavity comes closer to satisfying the B-G conditions if reduced pressure is employed.

Proportional counters

- All ionized particles are produced almost simultaneously and move “in unison”, giving rise to a sharply defined fast-rising electrical pulse.
- The height of the electrical pulse is proportional to the number of electrons in the associated avalanche, which in turn is proportional to the number of ion pairs created in the original ionizing event.
- Thus the size (i.e., height) of the electrical pulse is proportional to the energy imparted to the gas in the initial event, provided that \( W/e \) is constant (there is a small LET dependence).
- Free electrons reach the anode wire within \( \sim 1 \mu s \).
- Measured electrical pulse, however, is primarily due to the much slower motion of positive ions away from the central wire.
- If only gross pulse counting is required proportional counters can operate with pulse resolving times of about \( 1 \mu s \).
- If pulse heights are to be measured also, the average interval between pulses should be greater, approaching the transit times for the positive ions (\( \sim 100 \mu s \)) for greatest accuracy.

Gain factor

Characteristics of typical proportional-counting gases

<table>
<thead>
<tr>
<th>Gas</th>
<th>( K ) (V/cm atm)</th>
<th>( \Delta V ) (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90% Ar + 10% methane (&quot;P-10&quot;)</td>
<td>( 4.8 \times 10^8 )</td>
<td>23.6</td>
</tr>
<tr>
<td>Methane</td>
<td>( 6.9 \times 10^8 )</td>
<td>36.5</td>
</tr>
<tr>
<td>96% He + 4% isobutane</td>
<td>( 1.48 \times 10^8 )</td>
<td>27.6</td>
</tr>
</tbody>
</table>

- A cylindrical proportional counter with \( a = 1 \text{ cm}, b = 10^{-3} \text{ cm}, P=1000 \text{ V}, \) containing P-10 gas at 1 atm would have \( G \sim 100 \).
- Reducing the gas pressure to 0.5 atm would increase \( G \sim 2000 \).
- Substitution of the He-isobutane mixture at 1 atm would provide an even higher \( G \sim 4000 \).
- The upper \( G \) limit for proportional gas multiplication is \( \sim 10^4 \).
Pulse-height analysis

- Pulse height from a detector depends on the applied potential
- Two curves represent initial ionizing events releasing 10 and 10^3 electrons
- The ion-chamber region: almost complete collection of charge
- Proportional counting starts after the gas-multiplication threshold
- Limited proportionality region: space-charge effects limited
- G-M region: initiating events of different sizes produce equal pulses

Gain G changes from 1 to 10^4 through the proportional counting region

![Graph showing pulse-height analysis](image)

Pulse-height analysis

- Employ multi-channel analyzer to obtain a differential distribution of counts per channel vs. channel number
- To facilitate the calibration of the pulse height h in terms of absorbed dose to the counter gas, some proportional counters are equipped with a small α-particle source
- The expectation value of the dose contributed to the gas by each α-particle can be written as

\[
\bar{D}_a = \frac{1}{m} \left( \frac{dT}{d\rho x} \right) m - \text{mass of gas; } \rho - \text{gas density; } dT/dx - \text{mass collision stopping power of the gas for } \alpha\text{-particle}
\]

Pulse-height analysis

- The total dose in the gas can be found by summing all the counts, each weighted by its pulse height h expressed as

\[
D_g = \sum_{h=0}^{h_{\text{max}}} N'(h) \frac{h}{h_{\alpha}} \bar{D}_a = \sum_{h=0}^{h_{\text{max}}} N'(h) D(h)
\]

- Such a proportional counter can be used as an absolute dosimeter

Proportional counter: example

13-mm-I.D. tissue-equivalent proportional counter

- Rossi counters usually made with spherical walls of tissue-equivalent plastic, and are operated while flowing a tissue-equivalent counting gas through at reduced pressure, typically ~ 10^-2 atm
- Adjustment of the gas pressure allows simulation of biological target objects such as individual cells, in terms of the energy lost by a charged particle in crossing it

Proportional counters

- Proportional counters of various designs are also used for many applications in which pulse-height analysis is not used
- The main advantages of proportional counters over G-M counters in this connection are
  a) their short pulse length (~1 μs) with practically no additional dead time, accommodating high count rates, and
  b) the capability of discriminating by simple means against counting small pulses that might result, for example, from background noise, or γ-ray interactions in a mixed γ + neutron field
Geiger-Muller counters

- As the voltage applied to a gas counting tube is increased, the pulse height begins to saturate, gradually reaching the G-M region of operation
- For any voltage in that region all the gas-amplified pulses come out approximately the same, regardless of the size of the initiating event
- If the resulting pulse size is larger than the counter-circuit threshold \( h_t \), then the pulses will be counted. As a result, one would expect to see a step function in the count-rate-vs.-voltage curve where the pulse height begins to exceed \( h_t \)

Geiger-Muller counters

- Immediately after a discharge the positive space charge so weakens the electric field near the wire that gas multiplication cannot occur
- Thus the tube does not respond to radiation at all until the positive-ion cloud starts arriving at the cathode and the electric field strength gradually builds up again
- As that takes place, the tube becomes capable of responding to an ionizing event with a discharge of less than full size

Geiger-Muller counters: dead time

- If an ionizing event occurs during the true dead time, it causes no electron avalanche and hence has no effect on the tube
  - This is called nonparalyzable dead-time behavior
- If an ionizing event occurs after the end of the true dead time, but before the resulting pulse is large enough to be counted (i.e., > \( h_t \)), not only will that event go uncounted but a new dead-time period will begin
  - This is called paralyzable dead-time behavior

Geiger-Muller counters

- The counting plateau in a G-M tube. The solid curve is an “ideal” G-M plateau that would be seen for a narrow distribution of pulse heights. The dashed curve has a residual slope within the G-M region because of the presence of a low-amplitude “tail” on the pulse-height distribution (inset).

- The true dead time is the time from the start of the preceding pulse until the tube recovers starting to generate minimum-sized pulses
- The recovery time is the time until a full-sized pulse is possible
- The minimum time between detectable pulses will be less than the recovery time. This is the pulse resolving time, but is more commonly referred to as the “dead time”

Geiger-Muller counters: dead time

- Since G-M counters are only triggered by ionizing events, producing discharge pulses of more or less the same size regardless of the initiating event, the observed output has little information about the dose to the counter gas
- They are used in some dosimetry applications due to several advantages:
  - Require little if any further amplification, with pulses of 1-10V
  - Inexpensive and versatile in their construction and geometry
- They are often used in radiation survey meters to measure x- and \( \gamma \)-ray fields in radiation-protection applications
- When equipped with a thin (~1 mg/cm\(^2\)) window they can also be used to detect \( \beta \)-rays
Geiger-Muller counters

- Most G-M tubes are constructed of materials that are higher in atomic number than tissue or air, and exhibit strong photoelectric-effect response below ~ 100 keV.
- Enclosing the G-M tube in a suitable high-Z filter tends to flatten the overresponse at low energies; can be used as an approximate dose-rate or exposure-rate meter.

Scintillation dosimetry

- Many transparent substances, including certain solids, liquids, and gases, scintillate (emit visible light) in response to ionizing radiation.
- The light emitted can be converted into an electrical signal and amplified using photomultiplier (PM) tubes.
- Very fast decay times, down to ~ 10^-9 s, make organic liquid and plastic scintillators excellent choices for coincidence measurements with good time-resolution.
- Versatile in volume shape and size.
- Used in spectroscopic applications due to lower cost and the greater convenience of room temperature operation (compared to semiconductor detectors).

Scintillation dosimetry

- Only a very small part of the energy imparted to a scintillator appears as light; the rest is dissipated as heat. Typically ~ 1 keV of energy is spent in the scintillator for the release of one electron from the PM tube's photocathode.
- The light generated in a scintillator by a given imparted energy depends on the linear energy transfer (LET) of the charged particles delivering the energy.
- For dosimetry of γ-rays or electrons, either the PM-tube output should be measured as an electric current or the pulse-heights must be analyzed and calibrated in terms of dose. Simple counting of pulses without regard to their size is not a measure of the dose in a scintillator.

Scintillation dosimetry

- In typical organic scintillators increasing the particle LET decreases the light output for a given energy imparted.
- The light response from electrons that spend their full track length in the scintillator is proportional to their starting energy above ~125 keV.

Scintillation dosimetry

- For dosimetry applications where soft tissue is the dose-relevant material, organic plastics, liquids, and crystals are the most useful because they are made mostly of the low-Z elements C and H. Thus they do not overrespond to photons through the photoelectric effect.
- The hydrogen content makes the (n, p) elastic-scattering interaction the main process for fast-neutron dose deposition, as it is in tissue.
Scintillation dosimetry
Scintillators are often used as a more sensitive substitute for an ionization chamber in a γ-ray survey meters
• For plastic scintillators the average energy spent by an electron per light photon produced is ~ 60 eV; in a gases is ~30 eV
• For good optical coupling ~1/3 of the photons reach the PM-tube photocathode; typical photocathode efficiency is ~ 15%, and tube gain ~ 10^6. Thus for equal masses of chamber gas and plastic scintillator, the output current for the latter is 3x10^4 greater
• Assuming 1g/cm^3 for the scintillator and 0.001g/cm^3 for the gas in the ion chamber, equal volumes would favor the scintillator by a factor of 3x10^7 - comparable in sensitivity to a G-M tube of the same size
• However, the plastic scintillator has an output current for electrons (with E> 125 keV) that is proportional to the absorbed dose in the plastic medium, which approximates tissue

Semiconductor detectors
• Si and Ge detectors are used mainly for spectrometry in applications where highest energy resolution is required
• Semiconductor detectors have characteristics that make them attractive as dosimeters, for measuring either dose or dose rate, as a substitute for an ion chamber
• Can serve as a solid-state analogue of a proportional counter, since the ionization produced by a charged particle in traversing the detector sensitive volume is
  • proportional to the energy spent
  • independent of LET for particles lighter than α's
• Semiconductor detectors may be employed as neutron dosimeters by measuring the resulting radiation damage

Semiconductor detectors
• The mean energy spent per electron-hole pair
  • in Si at 300 K is 3.62 eV for α's and 3.68 for electrons
  • in Ge at 77 K it is 2.97 eV for both leading to ~ 10 times as much ionization is formed in semiconductor detectors as in ion chambers for the same energy expenditure
• Electrons have mobilities of 1350 cm/s per V/cm in Si and 3900 in Ge, at 300 K. Hole mobilities are 480 cm/s per V/cm in Si and 1900 in Ge, at 300 K, producing a voltage-pulse rise times ~ 10^7 - 10^8 s
Semiconductor detectors

- Si diode detectors with reverse bias applied offer great sensitivity and response time.
- There is an advantage in operating without external bias due to the DC leakage current decreasing more rapidly than the radiation-induced current with as the bias voltage is reduced to zero. Since this leakage current is strongly temperature-dependent, minimizing its magnitude is advantageous.
- The residual zero-bias radiation-induced current results from alteration of charge-carrier concentrations, giving rise to a potential difference between the electrodes.
- The measurement of the radiocurrent is done with a low-impedance circuit such as an operational amplifier.

- The ranges of dose rate measured in radiotherapy applications (0.03-3 Gy/min) produce adequate output currents from an unbiased silicon diode detector with a typical sensitivity of ~2x10^-11 A per R/min (a commercial device by Nuclear Associates, with volume of 0.2 mm^3).
- The Si detector has a strong energy-dependent response; a high-Z filter surrounding the detector helps flatten the energy dependence per roentgen or per tissue rad.
- Comparison of depth-dose measurements of linac x-ray beams taken with this detector and with a Farmer ion chamber demonstrated good agreement between the two, with a better signal-to-noise ratio in Si detector.

- The most common types of semiconductor detectors are the lithium-drifted type, prepared by diffusing Li^+ ions into high-purity Si or Ge crystals.
- Drifted regions up to ~ 2 cm in thickness can be achieved, and the entire intrinsic volume acts as the dosimeter’s sensitive volume. Changing the applied potential varies the electric field strength, but doesn’t change its depth.
- Ge(Li) detectors are preferred over Si(Li) for x- or γ-ray spectrometry >50 keV or energy-fluence measurements, because of the higher Z (32) and a greater photoelectric cross section.
- Si(Li) detectors are preferred for lower-energy x rays and for β-ray dosimetry due to their much lower backscattering. Detectors with areas ~ 15 cm^2 are available.

- The density of Si is ~ 2.3 g/cm^3, or about 1800 times that of air (Ge is 5.3 g/cm^3, 4100 times).
- Considering the ionization energy W difference, a Si(Li) detector will produce about 18,000 times as much charge as an ion chamber of the same volume, in the same x-ray field, at energies where the photoelectric effect is unimportant (> 100 keV).
- Disadvantage: Ge(Li) and Si(Li) detectors must be maintained at low (liquid nitrogen) temperature.

Summary

- Proportional counters: rely on gas multiplication; collected charge is proportional to the number of original electrons.
- Geiger-Muller counters: rely on gas multiplication; all pulses have the same amplitude.
- Scintillators: convert kinetic energy of charged particles into detectable light within a short time.
- Semiconductor detectors: electron-hole pairs are created along the path of charged particle (reverse biased, or with no external bias).