Radiation Detection Principles and Instruments

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Keywords

Excitation, ionization, interactions with matter, gas-filled, six ranges, Geiger-Mueller, Scintillation, six steps of scintillation detection, semiconductor detectors, detection systems, nuclear instrumentation systems, detector ranges, fission chamber detectors, nuclear instrumentation circuitry, thermoluminescent dosimeter, personnel monitoring, portable survey instruments, radiation detection principles.

Description

This document provides an outline and notes for providing a lecture on the principles of radiation detection and the instruments used in radiation detection.

Supporting Material

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NET 130: Radiological Protection

Module 5: Radiation Detection Principles and Instruments

Overview

- Many instruments have been developed to detect radiation
- Based on knowledge of how radiation interacts with matter
  - Excitation
  - Ionization
    - Charged particles cause ionization directly through Coulombic interactions
    - EM radiation produces ion pairs in matter
      - Photoelectric effect
      - Compton scattering
      - Pair production
    - Neutrons produce ions through secondary mechanisms
- Four methods for detecting ionizing radiation:
  - Ions collected to produce signal
  - Amplification of ionization to produce stronger signal
  - Fluorescence of a substance that has absorbed energy from radiation
  - Radiation-induced chemical reactions

- Three major types of detection instruments:
  - Nuclear instrumentation
  - Portable survey instruments and area monitors
  - Personnel monitoring devices

Gas-Filled Detectors

- Detect incident radiation by measurement of two ionization processes
  - Primary process: ions produced directly by radiation effects
  - Secondary process: additional ions produced from or by effects of primary ions
    - Townsend Avalanche

- Primary and secondary ions produced within the gas are separated by Coulombic effects and collected by charged electrodes in the detector
  - Anode (positively charged electrode)
    - Collects the negative ions
  - Cathode (negatively charged electrode)
    - Collects the positive ions

Gas-Filled Detector: Components

- Cylindrical gas chamber
  - Air
  - P-10 gas mixture (10% methane, 90% argon)
  - Helium
  - Neon
- Anode (+): Wire at center of chamber
- Cathode (-): Chamber walls
- Operating Principles
  - Voltage applied across electrodes
  - Incident radiation (α, β, or γ) enters chamber and ionizes the fill-gas
  - Ions (+/-) separate and migrate to respective electrodes
  - Current output is generated and scaled to radiation level

- Voltage too low
  - Ions may recombine and neutralize each other prior to reaching electrodes
- Proper operating voltage
  - All primary ion pairs are collected
- Voltage too high
  - Chamber becomes flooded with ions due to secondary ionizations caused by high-energy primary ions
  - Output current is no longer proportional to number of primary ionizations
  - Radiation events no longer measured
    - Ionization “avalanche” propagated by input voltage itself

- Recombination Region
  - Applied voltage too low
  - Recombination occurs
  - Low electric field strength

- Ionization Chamber Region
  (aka Saturation Region)
  - Voltage high enough to prevent recombination
    - All primary ion pairs collected on electrodes
  - Voltage low enough to prevent secondary ionizations
  - Voltage in this range called saturation voltage
  - As voltage increases while incident radiation level remains constant, output current remains constant (saturation current)

- Proportional Region
  - Gas amplification (or multiplication) occurs
    - Increased voltage increases primary ion energy levels
    - Secondary ionizations occur
    - Add to total collected charge on electrodes
  - Increased output current is related to # of primary ionizations via the proportionality constant
    (aka gas multiplication factor)
    - Function of detector geometry, fill-gas properties, and radiation properties

- Limited Proportional Region
- Collected charge becomes independent of # of primary ionizations
- Secondary ionization progresses to photoionization (photoelectric effect)
- Proportionality constant no longer accurate
- Not very useful range for radiation detection

- Geiger-Mueller (GM) Region
  - Any radiation event strong enough to produce primary ions results in complete ionization of gas
  - After an initial ionizing event, detector is left insensitive for a period of time (dead time)
    - Freed primary negative ions (mostly electrons) reach anode faster than heavy positive ions can reach cathode

    - Photoionization causes the anode to be completely surrounded by cloud of secondary positive ions
    - Cloud “shields” anode so that no secondary negative ions can be collected
    - Detector is effectively "shut off"
    - Detector recovers after positive ions migrate to cathode
  - Dead time limits the number of radiation events that can be detected
    - Usually 100 to 500 μs

- Continuous Discharge Region
  - Electric field strength so intense that no initial radiation event is required to completely ionize the gas
  - Electric field itself propagates secondary ionization
  - Complete avalanching occurs
  - No practical detection of radiation is possible.

Gas-Filled Detectors

- Most commonly used detection instrument due to versatility
  - Can detect and discern between all types of radiation over entire energy spectrum
  - Cylindrical shape provides the strongest electric field and output current for a given operating voltage
- Most common detectors operate in the ionization chamber, proportional, and Geiger-Mueller regions
- No detectors operate solely in the recombination, limited proportional, or continuous discharge regions.

- Can discriminate between α, β, and γ radiation
  - Pulse height discrimination: electronically filter out pulses below or above expected height for radiation type of interest
- Less sensitive over long range than GM
- Include:
  - Portable neutron radiation survey meters
  - Personnel contamination monitoring

- Include:
  - Area radiation monitors
  - Portable high-range radiation survey meters (Teletector)

Advantages

- highly sensitive: capable of detecting low intensity radiation fields
- Only simple electronic amplification of the detector signal is required
- less insulation required to decrease “noise” interference

- Some GM detectors detect γ only
  - Solid casing
- Some detect α, β, and γ
  - α, β radiation: short travel range
    - Cannot penetrate detector casing
  - Mylar window to allow α and β radiation to enter

  - α and β can be separately detected by using different window types and thicknesses to filter incident radiation
  - Shield must be placed over window to detect γ
    - Blocks α and β

Scintillation Detectors

- Detect radiation by induction of luminescence
  - Absorption of energy by a substance with the subsequent emission of visible radiation (photons)

- Incident radiation interacts with the scintillator material
- Excites electrons in material
- Electromagnetic radiation emitted in the visible light range

- Common scintillator materials
  - Anthracene crystals
  - Sodium iodide crystals
  - Lithium iodide crystals
  - Zinc sulfide powder
  - Lithium iodide, boron, and cadmium can be used to detect neutrons

6 Steps of Scintillation Detection

- Inside scintillator:
  - Excitation due to absorption of radiation
  - Emission of light photons from de-excitation
  - Transit of light to photocathode inside photomultiplier tube
- Inside photomultiplier tube:
  - Production of photoelectrons in photocathode
  - Multiplication of photoelectrons
- Outside scintillator and photomultiplier tube:
  - Conversion of electronic detector output to useful information

Common Scintillator Materials

- Anthracene crystals
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Photocathode

- Light-sensitive material that absorbs photons and emits photoelectrons
- Common material: Antimony-Cesium
- Emits about one electron for every 10 photons absorbed

Photomultiplier Tube: Dynodes

- Photoelectrons strike successive dynodes and are multiplied (secondary electron production)
- Amplifies the output signal
- If tube has 10 dynodes, total gain would be around 10^6

- Typical tubes made with 6 to 14 dynodes

Semiconductor Detectors

- Operation similar to gas-filled detectors, but chamber filled with solid semiconductor material
- Crystalline material whose electrical conductivity is intermediate between that of a good conductor and a good insulator
- Benefits compared to other types
  - Very little fluctuation in output for a given energy of radiation
  - Fast
- Energy transfer from radiation to semiconductor target produces a freed electron and an electron vacancy, or hole
- Electrons travel to the anode
- Hole “travels” toward the negative electrode
  - Not physically
  - Successive exchanges of electrons between neighboring molecules in the crystalline lattice

Semiconductor Detectors: Pros/Cons

- Pros
  - Fast response time
    - Due to high mobility of electrons and holes
    - Takes longer for ions to physically travel through space in a gas-filled detector
  - Less statistical fluctuations for any given radiation energy
    - A smaller amount of energy required to produce electron-hole pair in a semiconductor than an ion pair in a gas
    - For a given energy, 8 to 10 times as many charge-carrying pairs are produced in semiconductors as in gases
  - Total charge collected varies linearly with radiation energy

- Cons
  - Very sensitive to heat: must be cooled to eliminate error
  - Photomultiplier output very weak
    - Powerful amplifiers needed in the external circuit

Detection Systems

- Two main components:
  - Detector
    - Gas-filled, scintillation, or semiconductor
  - Measuring apparatus
    - Converts signal output from detector to usable information for the operator
- Detection system categories, by output type:
  - Pulse-type output
  - Mean-level output
- Detection system categories, by application:
  - Nuclear instrumentation
  - Portable survey instruments and area monitors
  - Personal dosimetry

- Pulse-Type Output:

  - records a series of individual signals (pulses) separated or “resolved” over time
  - each pulse represents a separate radiation event within the detector
  - “Frisker”-type survey instruments found near any contaminated area access point

Nuclear Instrumentation (NI)

- NI detectors are used to measure/record neutron (η) flux as a measure of reactor power level
- Range of η flux is wide, spanning from:
  - Shutdown
  - Reactor start-up
  - 100% power
- To accurately monitor η population at all power levels, there are three overlapping detector ranges
  - Source range: ($10^0 – 10^6$)
  - Intermediate range: ($10^1 – 10^{10}$)
  - Power range: ($10^{10} – 10^{12}$)

NI Detector Ranges

Neutron Energy Ranges

- Fast neutrons have an energy > 1 eV
- Slow neutrons have an energy less than or equal 0.4 eV.
- Hot neutrons have an energy of about 0.2 eV.
- Thermal neutrons have an energy of about 0.025 eV.
- Cold neutrons have an energy from 5x10−5 eV to 0.025 eV.

NI: Fission-Chamber Detectors

- Neutron detection in source and intermediate ranges
- Gas-filled ionization-type detector
- Inner “cans” coated with U-235 lining
- Fast neutrons exiting the core are thermalized by the time they make their way inside the F-C detector
  - Interact with materials outside the core
  - Interact with the plastic covering of the detector
- Thermal neutrons lead to fission of the U-235 lining inside the detector
- Reactor core neutron flux is then measured as a product of the fission of U-235 in the F-C detector

Fission-Chamber Output Signal

- Pulse height discrimination implemented in order to pass only the signal portion due to neutron effects
- Pulse discriminator bias: the selective value for pulses
- Products of incident thermal neutrons: fission fragments with average energy of 165 MeV
- Energy of alphas from uranium isotope decay: 4 MeV
- Fission gammas: no more than 7 MeV
- The fission fragment energy due to neutron entering the detector is clearly distinct
  - Pulse is much larger than those for non-fission reactions within detector

Pulse Height Discrimination

NI: Power vs. Intermediate Range

- Any power level: reactor produces both neutron and gamma fluxes
- In intermediate range, exact correlation between gamma and neutron flux is not easily predictable
- For an ion chamber to read power in the intermediate range, it must be compensated
  - Electronically cancel out gamma effects

- In power range, gamma flux becomes insignificant compared to neutron flux
- Gamma compensation no longer necessary

NI: Uncompensated Ion Chambers

- Monitor reactor power in the power range
  - Single boron-lined cylindrical chamber operating in the ionization chamber region
  - Mean-level output
  - Gamma-induced current typically represents only 1% of total output signal

NI: Incore Instrumentation

- Monitor power production at select locations within the core
- Verify reactor core design parameters: flux mapping
- Data only– no operational plant control
- Simpler version of fission chamber
  - Approx 0.2” diameter, 2.1” length
  - Uses uranium oxide clad in stainless steel, with helium fill gas

NI Detector Circuitry

- A channel consists of a detector, its measuring apparatus (transducer), and a display
  - Sends signals to the reactor control and protective systems
- At main control panel, reactor core is monitored by
  - Two source range channels
  - Two intermediate range channels
  - Four power range channels (0 to 120% power)
- Third source range channel with dual displays
  - Nuclear instrument cabinet
  - Control room evacuation panel

- Main control panel: U-235-based FC detector
- Instrument cabinet: Boron Triflouride (BF_3) FC detector
- Both are dual-element (dual-can) detectors
  - Provides increased sensitivity in the low η fluxes of the source range
- Pulse height discriminators “screen out” γ flux from η

- Each FC is powered by a high voltage power supply
- Each FC output is amplified and filtered by a separate preamplifier
  - Filter electronic noise due to cable lengths
- Preamplifier outputs from 2 FCs are summed at the channel’s discriminator
  - Non-neutron pulses are filtered out
  - Signal is further processed and amplified for use as indication of power level

Nuclear Instrumentation: Intermediate Range

- Spans the source ($10^0 – 10^6$) and power ($10^{10} – 10^{12}$) ranges
- One U-235 fission chamber (can) per detector
- Output signal
  - Pulse-type in the source range
  - Mean-level in the power range

Nuclear Instrumentation: Intermediate Range

- "Pulse pile-up"
  - When passing source and power ranges in either direction, neutron events occur and change so rapidly that less overall sensitivity is needed
  - Gamma flux is not predictably related to neutron flux
  - Cannot be "filtered" by pulse height discrimination
  - Intermediate range neutron flux levels are several orders of magnitude higher than source
  - Pile-up occurs at upper end of detector range due to high magnitude of combined γ and η flux
  - The predictable pulses from the lower end effectively change from an AC signal to a fluctuating DC signal

- Campbell Theorem
  - "With a random occurrence, the variations in the occurrence is proportional to the square root of the random rate."
  - Simply put: by taking the mean value of the oscillations in detector output appearing at the upper-end of the detector scale, a meaningful detector signal is obtained

- Monitored by four independent channels
- Each channel uses a long, boron-lined uncompensated ion chamber
- Each chamber includes two separate neutron detecting sections
- Gammas are so out-numbered by the neutrons that gamma-compensation is not necessary

- One high voltage supply (0-1500 VDC per channel) powers both sections of detector
- Output current from each section is fed to an amplifier
- Amplifier output sent to
  - Protection and control systems
  - Control panel readouts
  - Summing amplifier
    - Add signals from separate detector sections and amplify to make combined signal proportional to total core power (0 to 120%)
- Summing amplifier output sent to
  - Protection and control systems
  - Control panel readouts
- Gammas are so out-numbered by the neutrons that gamma-compensation is not necessary

Power Range Detector Channel Portable Survey Instruments and Area Monitors

- Survey meters

  - Compact detector systems used to monitor an area for neutrons, beta, alpha, or gamma radiation

- Portable Instruments
  - Survey meter, powered by batteries
  - Can be carried to any remote location

- Area Monitors
  - Survey instruments in permanent installation

Portable Survey Instruments and Area Monitors

Considerations:

- Reduction of size and weight
  - Gas-filled detector produces the most intense output for the lowest applied voltage
  - To reduce the size and weight
    - Reduce battery size: balance between weight and battery life
    - Reducing chamber size: erratic readings, useless
  - A bulky, reliable instrument is preferred to a small one that yields erratic results
- Type, energy, and intensity of the radiation field
  - Low range beta and gamma survey meters
  - High range beta and gamma survey meters
  - Alpha survey meters
  - Neutron survey meters

Low Range β and γ Survey Meters

- Low range: fields ranging from background level to levels of a few hundred milliroentgens per hour
- Most used: Geiger-Mueller tube
- Also used: Scintillation detectors

Low Range β and γ Survey Meters

- G-M tube: Advantages
  - Variety of sizes and shapes
  - Inexpensive
  - The slightest radiation event strong enough to cause primary ionization results in ionization of the entire gas volume
  - Thus detector is highly sensitive, even in lowest intensity radiation fields
  - Only simple electronic amplification of the detector signal is required
    - Hardware lasts longer
    - Requires less power
  - Strong output signal means G-M needs less electrical noise insulation than other detectors

Low Range β and γ Survey Meters

- G-M tube: Disadvantages
  - Incapable of discerning between type and energy of the radiation event
  - Only counts events and yields output in events per unit time or dose rate
  - A beta particle or gamma ray, high or low energy, represents one event counted
  - Only capable of detecting fields to some upper limit of intensity
    - Limited to lower intensity fields due to detector dead time

- Most common G-M gases: noble gases
  - Helium
  - Argon
  - Neon
  - Sometimes hydrogen and nitrogen
  - Characteristics of gas affect dead time

- After primary ionization, avalanche, and output pulse, G-M detector enters phase called tube recovery
  - Positive ions slowly migrate to cathode
  - Neutralized upon arrival
  - Neutralization may result in production of additional electrons and/or photoelectrons
  - Can result in another discharge of the tube, effectively lengthening dead time

- Quenching
  - Process used to prevent multiple G-M tube discharges
  - Methods
  - Electronic circuitry external to detector (inefficient)
  - Quench gases added to the gas volume
    - Self-quenching, efficient
    - Common type: ethyl alcohol, bromine or chlorine
    - Quench gas molecules neutralize positive ions in fill-gas before they can reach cathode
    - Charged quench gas molecules are then neutralized by cathode
    - Dampens potential for secondary discharge

- G-M tube requires high input voltage
  - Permits strong signal from ion collection
  - Frequent replacement of high voltage batteries

- Detecting beta particles with G-M
  - Particles have short range: window required
  - Mica, mylar, or thin stainless steel
  - Based on window material and thickness, correction factors can be determined to help narrow output to reflect beta activity alone

High Range β and γ Survey Meters

- Most: Uncompensated ion chambers
  - Very simple compared to G-M
  - Pulse or mean-level output
  - Strength of output signal is directly proportional to the # of ion pairs collected
  - Correlates in turn to a function of radiation energy
  - Signal converted to dose rate
- Can detect wide range of field intensities, but…
- Disadvantages of Ion Chambers
  - Output signal weak
  - Must be amplified considerably

  - Battery power limitations
  - Electronic noise-- frequent zeroing (taring) might be required
  - Signal-to-noise ratio renders ion chamber inefficient at low range compared to G-M
- Ion chambers
  - Insulation must be very good
  - Fill gas
    - Air at atmospheric pressure
    - Noble gases
  - For beta, ion chamber must be equipped with a thin wall or window

Alpha Survey Instruments

- A 1.0 MeV alpha particle has a range in air of only ~0.6 cm compared to 330 cm range of beta particles of the same energy in air
- Alpha particle ranges are considerably shorter in denser materials
- Detectors commonly used:
  - Ion chambers
    - Small field intensities
    - Very thin window must be incorporated
  - Scintillation detectors
    - Very effective
- Scintillation detectors (continued)
  - Commonly sodium iodide (NaI), cesium iodide (CsI), or silver-activated zinc sulfide also
  - Activator materials
    - Desirable "impurities" in scintillator material
    - Capture electrons and holes created through ionization of the scintillator and to emit the light photons upon returning to ground state
    - Examples
      - Silver in zinc sulfide
      - Thallium in sodium and cesium iodides

Neutron Survey Instruments

- Neutrons alone do not produce ionization (a detectable signal)
- The detector must contain a material with which the neutron interacts to produce ions
- Most common target material: Boron
  - Either as a fill gas or a coating on the inner wall
- Survey meters used for neutron detectors
  - Gas-filled
  - Semiconductor
  - Scintillation
- Common setup for gas-filled portable neutron survey meter
  - BF_3 proportional counter surrounded by a cadmium loaded, polyethylene sphere
    - Sphere thermalizes incoming fast neutrons so they can be detected
  - Meter output can read directly in millirem or rem per hour

- Ion chambers as neutron survey instruments
  - As with NI, commonly use boron-10 coating

  - Must be compensated for gamma
- Scintillation detectors as neutron survey instruments
  - Common material: lithium iodide
  - Thermal neutrons interact with lithium to form tritium and an alpha particle
  - Alpha particle causes measurable ionization

Portable Radiation Survey Instruments

- Pre-operational checks:
  - Battery-check: battery strength should be well within the acceptance range
  - Calibration check: a sticker affixed to the side of the instrument notes the “calibration due date”
  - Visual inspection: inspect for no visible signs of damage (i.e. loose, or missing parts; damaged detector; cracked meter face, etc.)
  - Source check: expose the detector to the “check source” [either internal or external] and note the meter response. It shall respond within the set “acceptance range”

- Pre-operational checks:
  - Zero-check: adjust so that the meter reads zero (0) when unexposed to a source
  - Light-check: applicable to a scintillation detector, the meter should read zero (0) when no source is present. Spurious counts are indicative of a damaged detector (i.e. light is leaking into the detector)

Pocket Ion-Chamber Dosimeter

- Self-reading
- Records dose in either milliroentgen (mR) or Roentgen (R)
- Sensitive to gamma only
- DC voltage applied to quartz fibers inside the chamber
- As gamma interactions/ionizations occur within the chamber, and the ions are collected, the coulombic repulsion is decreased, and the fibers move closer together
- Extremely sensitive to shock
- Located in Emergency Kits

Electronic Dosimeter

- Activated using the Electronic Dosimeter reader
- Self-reading, digital display of accumulated dose and dose rate
- Records accumulated dose and “highest dose rate field” in milliroentgen (mR) and milliroentgen per hour (mR/hr), respectively (can be set to record in units of Roentgen)
- Visual and audible alarms for accumulated dose and dose rate
- Silicon diode detector to detect gamma radiation (sensitive to gamma only)
- Resistant to shock
- Downloads dose and dose rate data to Radiation Exposure Control database when deactivated by the ED reader

Thermoluminescent Dosimeter

- Scintillation-type device
  - Lithium Flouride (LiF) or Calcium Flouride (CaF)
- CaF: high efficiency for detecting gamma and “X” radiation – poor at detecting neutrons
- LiF: capable of detecting alpha (α), beta (β), gamma (γ),“X” and neutron (η) radiation – typically used at nuclear power plants

- As incident radiation interacts with the crystal, the resultant ionization/excitation energy is stored.

- Crystal retains this energy until heat is applied.
- The “trapped” energy is then released in the form of light, as the atoms of the crystal return to their “ground state”
- The light emitted is then correlated to dose received
- Once the TLD has been “read”, memory is cleared
- TLD is then available for re-use