Detection of Radiation

Basic Principles

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Types of radiation

- Charged particles
  - alpha radiation: charge +2
  - protons: charge +1
  - beta radiation
    - electron: charge -1
    - positron: charge +1
- Electromagnetic radiation
  - x-rays
  - gamma rays
  - can be viewed as wave or particle
  - at high energies, particle view is more appropriate
  - photons (packets of energy) travel in straight lines

Use of radiation in medicine

- Imaging
  - x-rays and gamma rays
    - energy range: 20-400 keV (green light ~ 3.3 eV)
    - positrons (511 keV gamma rays)
- Therapy
  - photons
    - x-rays (4-25 MeV)
    - gamma sources (e.g., cobalt, ~ 1 MeV)
  - charged particles

Interaction of radiation with matter

- Detection is based on interaction of radiation with detector material.
- Energy is deposited by either:
  - Ionization: removal of electron from atom or molecule, yielding ion pair (cation + anion or free electron)
  - Excitation: electron in excited state, may result in emission of visible or UV light
- Most energy from radiation interactions is converted to heat

Detectors: basic principles (I)

classification by mechanism

- gas-filled (ionization) detectors
  - gas volume, two electrodes
  - ions collected, electrical signal
- scintillation detectors
  - excitation followed by emission of visible or UV light
  - light converted to electrical signal
- semiconductor detectors
  - pure crystals + trace impurities (diodes)
  - excitation leads directly to pulse of current

Detectors: basic principles (II)

classification by measurement mode

- counters (number of interactions)
- spectrometers (energy distribution)
- dosimeters (total energy due to multiple interactions)

Detectors: basic principles (III)

- signal produced by detector passes through series of electronic circuits, each of which performs a function, such as amplification, processing, or storage
- pulse mode (separate processing of each signal)
  - disadvantage: dead time
- current mode (total signal)
  - no information on interaction rate
  - no information on energies deposited in individual events
  - not affected by dead time
- spectroscopy (pulse mode)
  - amplitude of each pulse proportional to energy deposited by an event
  - not always energy of incident photon because sometimes only part of the photon energy is absorbed by detector

AJR study guide 17.e.i.c

Dead time

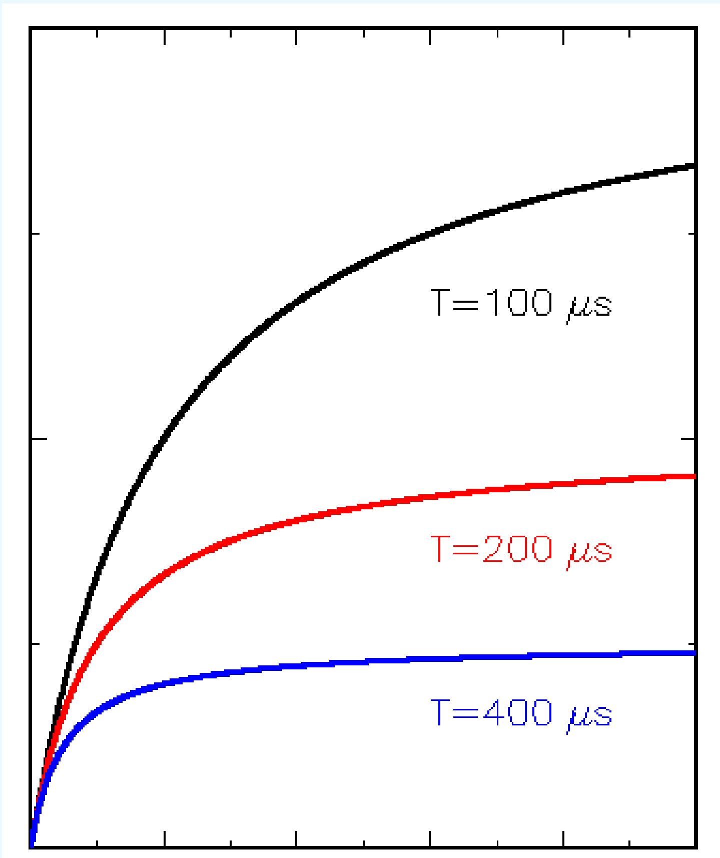
- μsecs to hundreds of μsecs
- leads to lost or distorted signals
- determined by component with longest dead time
- effects depend on count rate
- two types of dead time
    - paralyzable: interaction within the dead time extends the dead time
    - nonparalyzable

(AJR study guide 17.e.i.c)

Physics

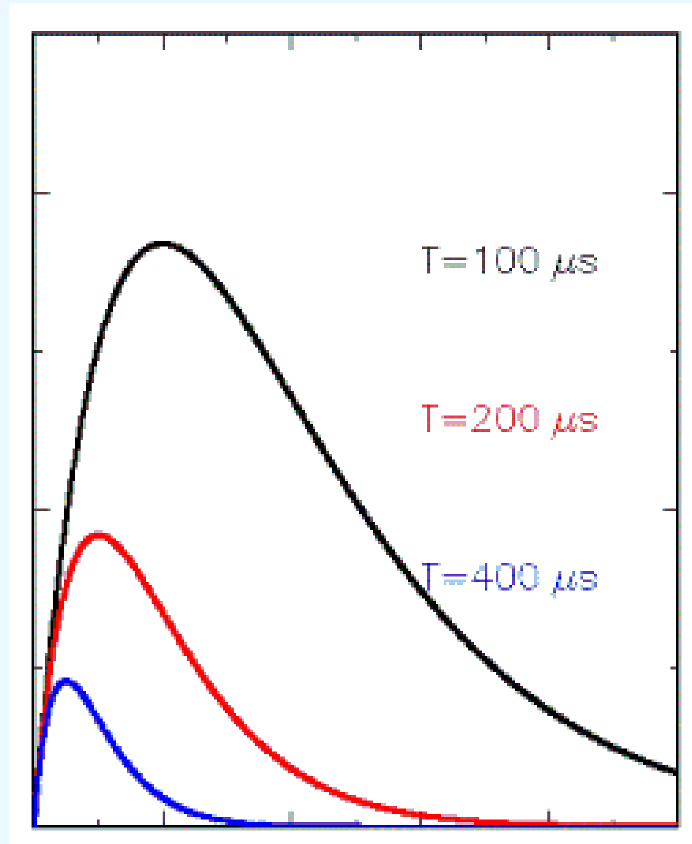
Effects of dead time on detected count rate

nonparalyzable system



interaction rate

paralyzable system



interaction rate

figures adapted from http://www.hzdr.de/db/Cms?pOid=14474&pNid=69

(AJR study guide 17.e.i.c)

Radiation detectors (IV)
efficiency

- efficiency: number detected/number emitted
- efficiency = geometric efficiency x intrinsic efficiency
- geometric efficiency: number reaching detector/number emitted
    - depends on distance between source and detector
    - for detectors surrounding source, depends on solid angle of coverage
    - approaches 1 for well counters
- intrinsic efficiency: number detected/number reaching detector
    - depends on photon energy and atomic number, density, thickness of detector
    - for a parallel beam of monoenergetic photons, given by:

$$1 - e^{-\left[\left(\mu/\rho\right)\rho\, x\right]}$$

(AJR study guide17.e.i.a & 17.e.h.ii)

Detectors

- gas-filled detectors
- scintillation detectors
- semiconductor detectors

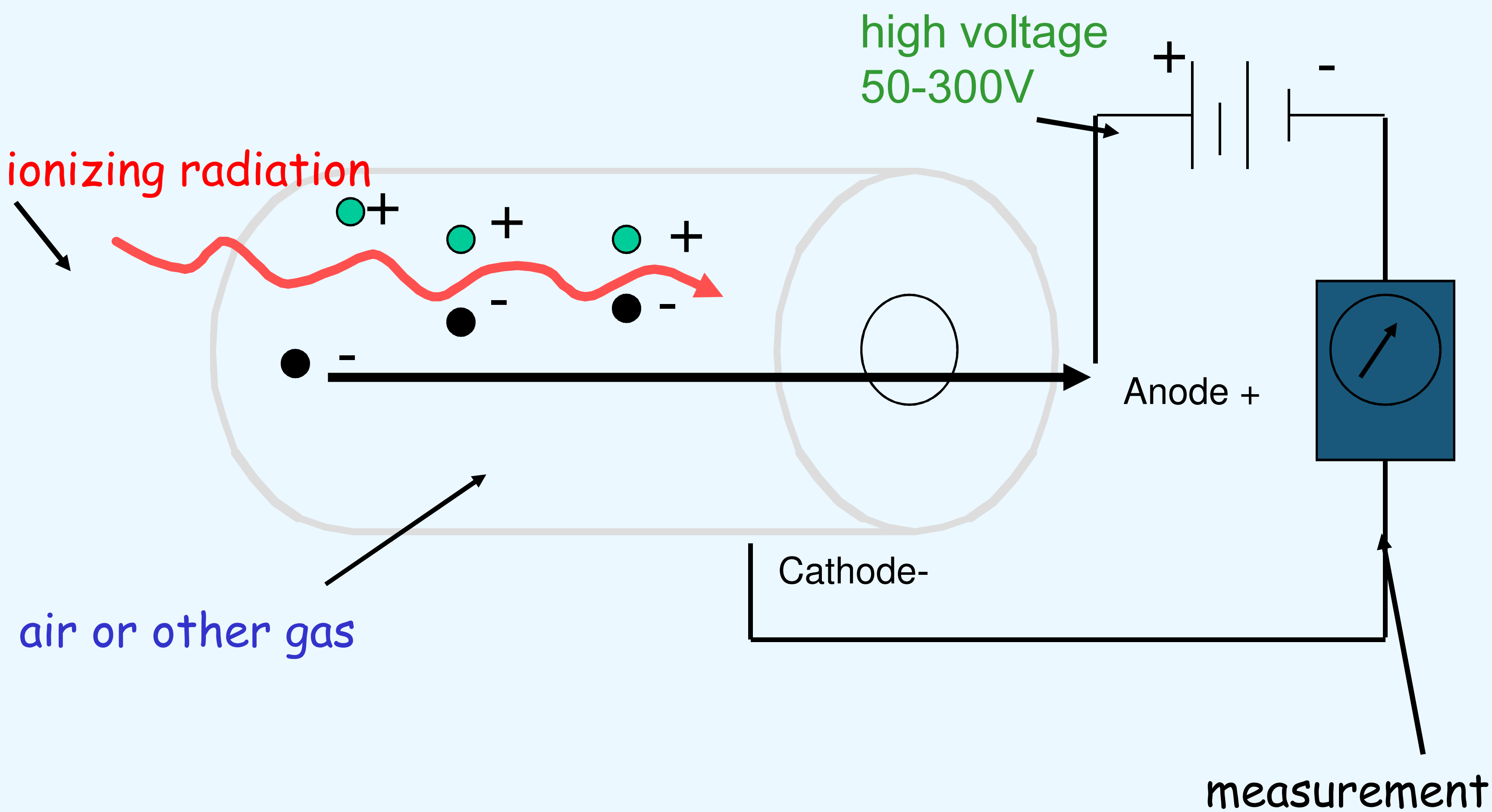
Detectors

Gas-filled detectors

Gas-filled detectors
basic principles

- chamber is filled with gas (sometimes at high pressure)
- a high voltage is applied
  - anode and cathode can be two plates
  - chamber wall can be the cathode and a wire the anode
- radiation passing through the chamber produces ion pairs
- ions travel towards anode and cathode
- electric current is measured

Gas-filled detector



Gas-filled detectors

- three types, determined by voltage
  - ionization chambers
  - proportional counters
  - Geiger-Mueller counters
- anode must be a wire for proportional counters and GM counters
- low sensitivity to x- and gamma radiation; can be increased by:
  - using high-Z gas, e.g., argon (18), xenon (54)
  - pressurizing gas

Physics

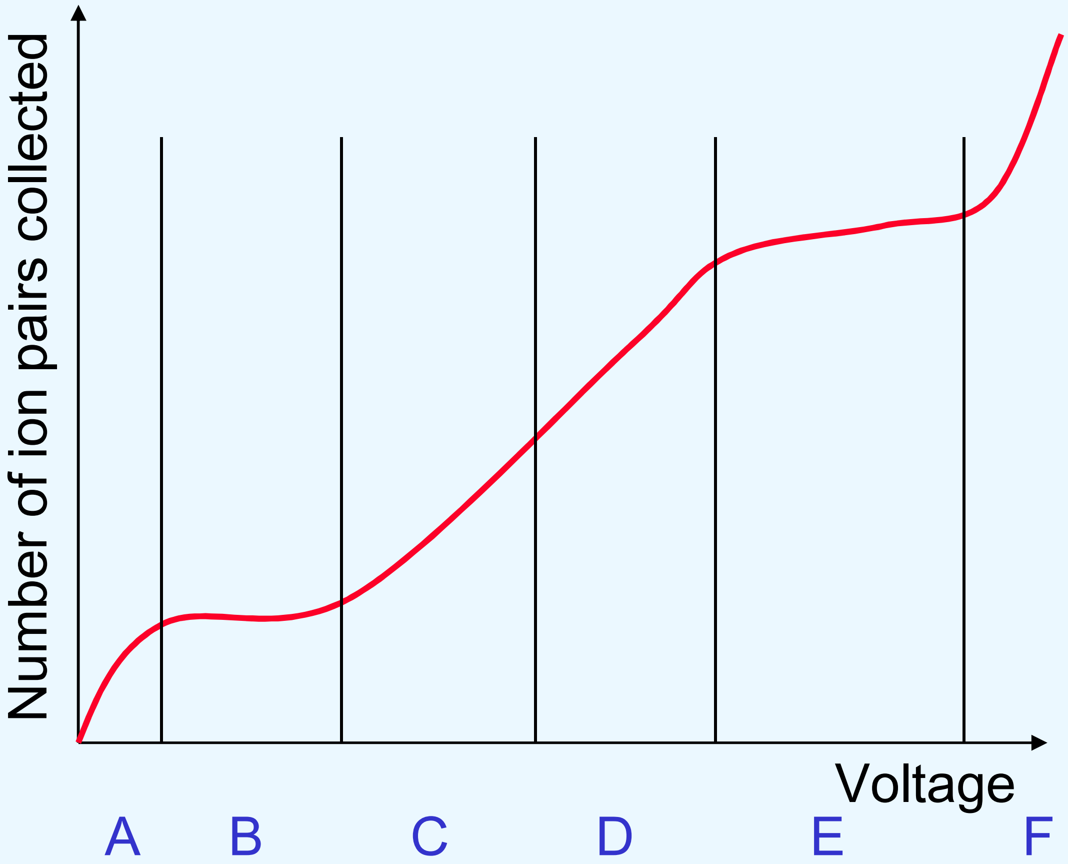
Output vs Voltage

(refer to figure on next slide)

- As voltage increases:
  - No voltage → no current, ion pairs recombine
  - Small voltage → some cations attracted to cathode, some electrons or anions attracted to anode, before they can recombine
  - Increasing voltage → more attracted, fewer combine
  - Saturation → all ion pairs are attracted, no recombination (ion chambers)
  - Proportional region → when voltage is high enough, ions are energetic enough to create other ion pairs; gas multiplication, amplification
  - Beyond proportional region → GM region where all current is the same no matter how much energy is deposited by the interaction
  - Too high voltage → continuous discharge

(AJR study guide 17.f.i)

Output vs Voltage



A - recombination region

B - saturation region (ion chamber)

C - proportional region (prop counter)

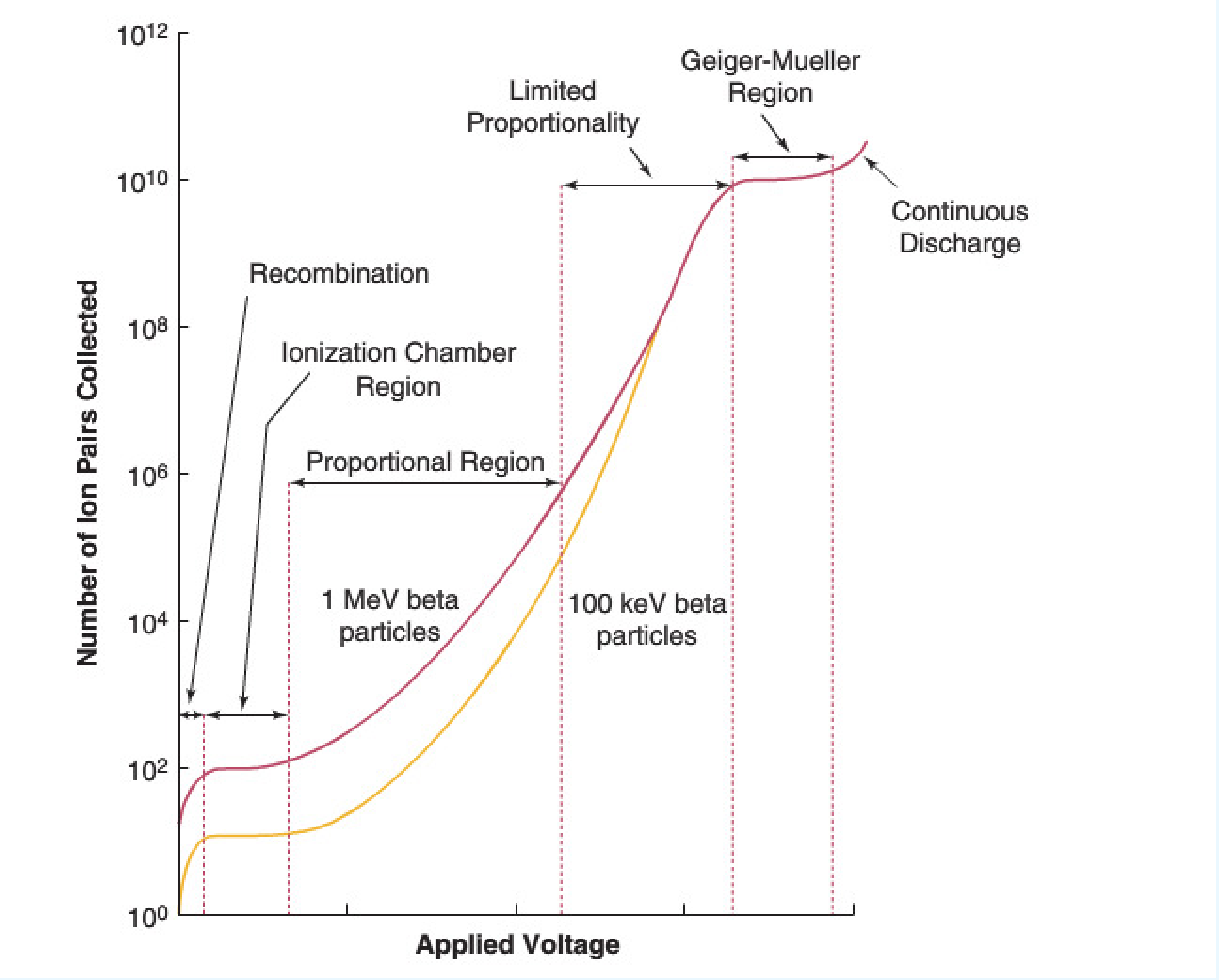
D - region of limited proportionality

E - Geiger-Muller region

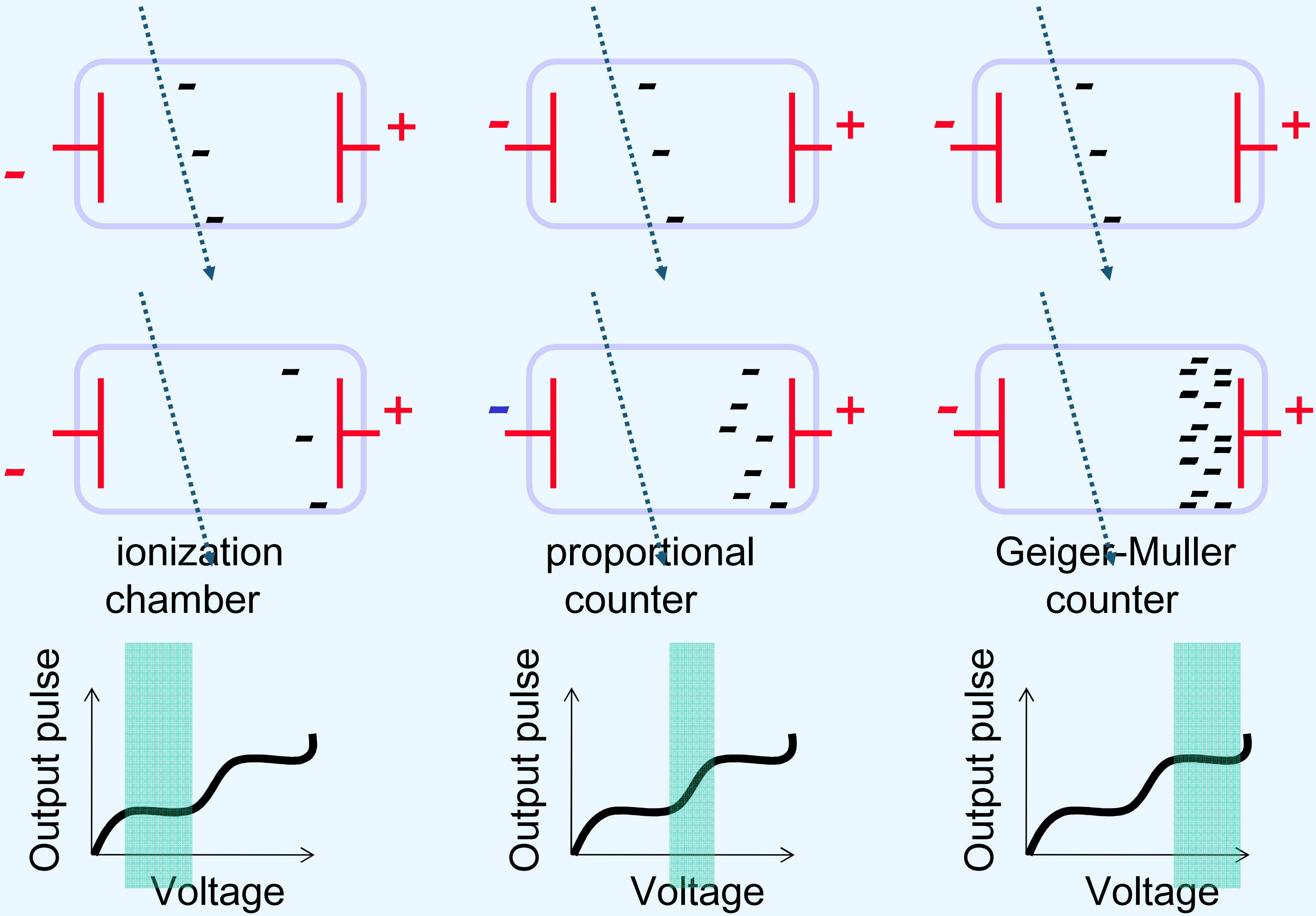
F - continuous discharge

(AJR study guide 17.f.i)

Output vs Voltage



Three types of gas-filled detectors



Ionization chambers

- operate at voltages 50-300 V
- filled with air or gas (may be at high pressure)
- very small current is produced by each event
- not used to discriminate events --> measure total current
- very poor (< 1%) intrinsic efficiency for γ and x-rays (<1%)
- used to measure high intensity radiation

(AJR study guide 17.f)

Dose calibrators

- ionization chambers (usually filled with pressurized argon, Z=18)
- used to calibrate radioisotope injection doses
- capable of measuring very high intensity radiation

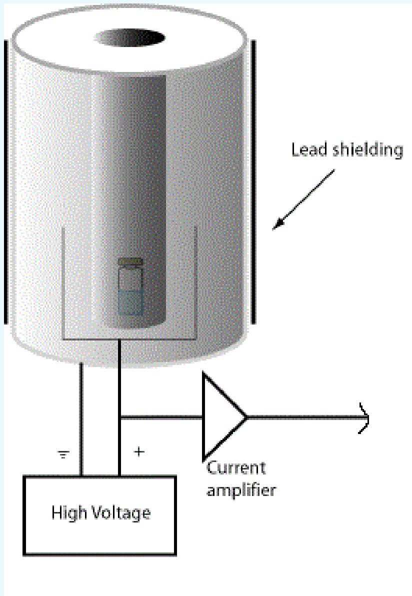


figure on left from http://www.phoenixphysics.com/products-equipment/hot-lab-equipment/dose-calibrators/

figure on right adapted from http://nucleus.iaea.org

(AJR study guide 17.f.ii)

Proportional counters

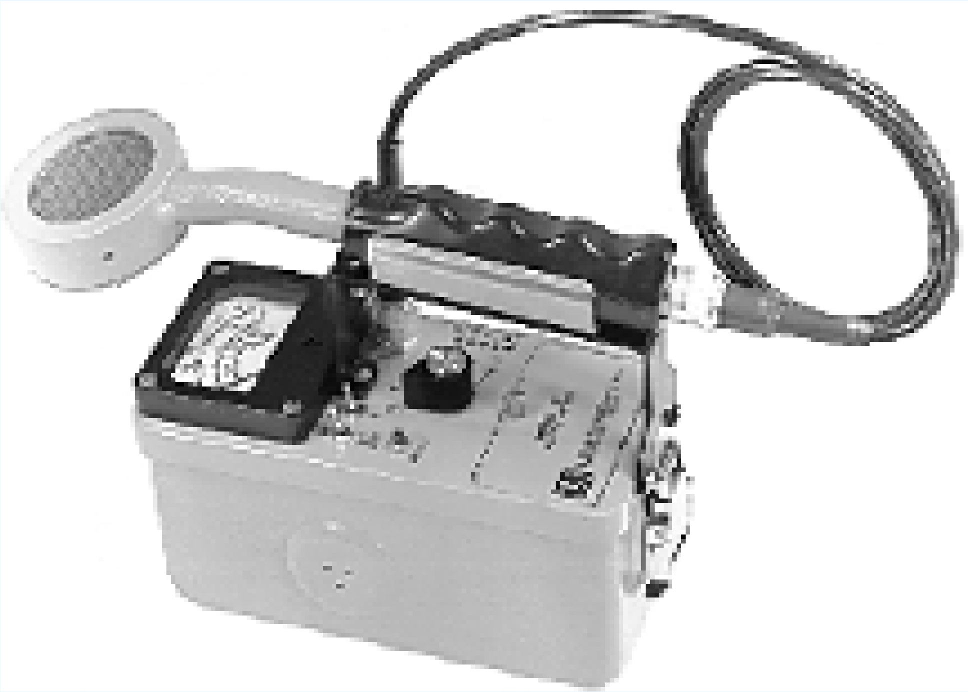
- usually filled with mixture of 90% argon/10% methane
- signal amplification is up to 10^3 (gas multiplication)
- larger signal allows for counting individual events (pulse mode)
- pulse size proportional to energy
- not used in nuclear medicine
- used in standards labs, research
- most commonly used for measuring alpha or beta activity
- can be used for x-ray spectroscopy

Geiger-Muller Counters

- operate at voltages 500-900 V
- amplification may be as high as 10^{10}
- high efficiency for charged particles/low efficiency for photons
- current does not depend on energy (always the same)
- approximately measures exposure rate
- may have a thin front-window for β detection
- very long dead times
- use in medicine: G-M counters are used to detect radioactive contamination

(AJR study guide: 17.f.ii)

Geiger-Muller Counters



Detectors

Scintillation Detectors

Scintillation detectors

• convert high-energy photons to low-energy photons

• consist of scintillators, which emit visible or UV light, and photomultiplier tubes (PMT) or photodiodes, which convert light to electrical signals

Scintillation detectors (I)

- ionizing radiation excites electrons in the scintillating material
- the scintillator material "glows" as electrons return to their ground state emitting light photons (luminescence)
    - prompt emission (fluorescence)
    - delayed emission (phosphorescence)
- amount of emitted light increases with energy deposited
- in current mode, prompt and delayed signals cannot be separated; in pulse mode, prompt and delayed signals can be separated electronically
- in pulse mode, may be used for spectroscopy
- “dead time” depends on light emission timing (and electronics)

Scintillation detectors (II)

- desirable properties of scintillators:
  - high detection efficiency for photons (high Z and density)
  - high conversion efficiency (fraction of deposited energy converted into light or UV; leads to good energy resolution)
  - short decay times
  - transparency to emitted light
  - frequency spectrum matched to sensitivity of PMT or photodiode
  - robust, inexpensive, not affected by moisture
- scintillating materials
  - organic (not used for medical imaging; low Z)
  - inorganic (must be in crystal form; grown with trace impurities)

Scintillators in nuclear medicine

- **NaI (Tl)** - the most widely used, most SPECT cameras, gamma well counters, very efficient, cheap but fragile and hydroscopic, may be grown into large blocks
- **BGO ($Bi_4Ge_3O_{12}$)** - used for positron emission cameras, has high density and atomic number, poor light output (and energy resolution), slow
- **LSO (Lu_2SiO_5)** - new detector material, faster than BGO (40ns), better energy resolution, high efficiency, used for PET
- **LYSO ($Lu_{1.8}Y_{0.2}SiO_5$):** – similar to LSO

(AJR study guide 17.h.i)

Scintillators used in NM

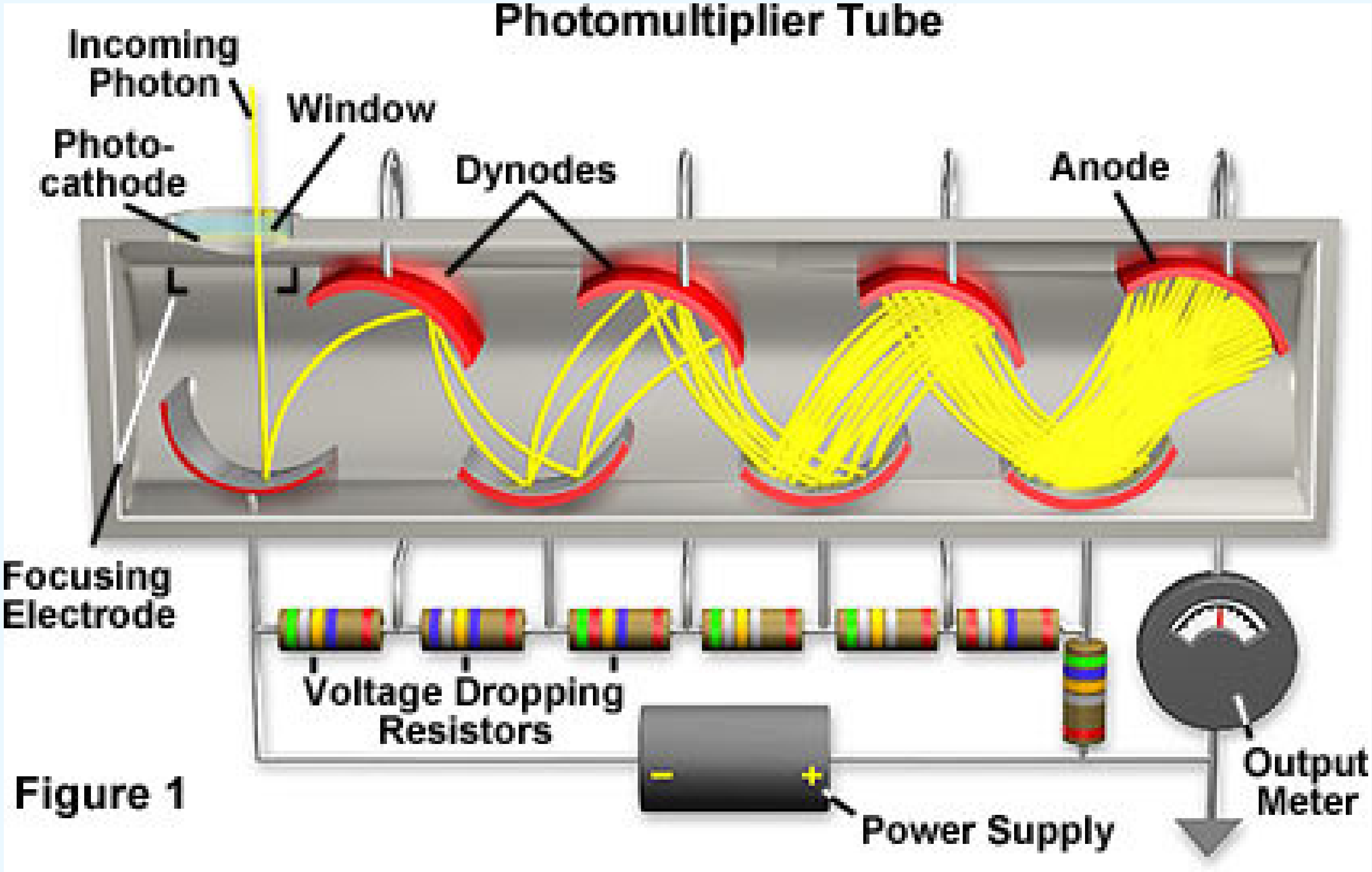
scintillator:	NaI	BGO	LSO	LYSO
density (g/cc)	3.7	7.1	7.4	7.1
effective atomic number	51	74	66	60
scintillation time (ns)	230	300	40	41

(AJR study guide 17.h.i)

Photomultiplier tube (PMT)

- PMT has thin clear window at the entrance and vacuum inside
- next to the window is a photocathode producing about 1 electron per ~5 incident light photons
- PMT usually contains 10 dynodes
- voltage applied is ~ 100 V per dynode (total ~ 1000 V)
- at each dynode ~ 5 electrons are produced per incident electron
- PMT multiplies the signal about $5^{10} = 10^7$
- electric pulse at the exit anode is measured
- photodiodes have smaller size, but low amplification and require low-noise electronics

Photomultiplier tube (PMT)



(figure from http://learn.hamamatsu.com/articles/photomultipliers.html)

Personnel monitoring

- Film Badge - radiation sensitive film with filters for γ and β radiation, after development this film is compared with another, calibrated film to determine dose. Not accurate, cannot be stored for long time.

- TLD (thermoluminescent dosimeter) - inorganic chip; when crystals are exposed to radiation their valence electrons are excited and trapped in the forbidden band. When heated, the crystal releases these electrons emitting light. Amount of light is proportional to the dose. Quite accurate, can be reused.

- OSL (optically stimulated luminescence) - similar to TLD but stimulated by light. Released photons are measured by PMT.

Detectors

Semiconductor Detectors

Semiconductor detectors

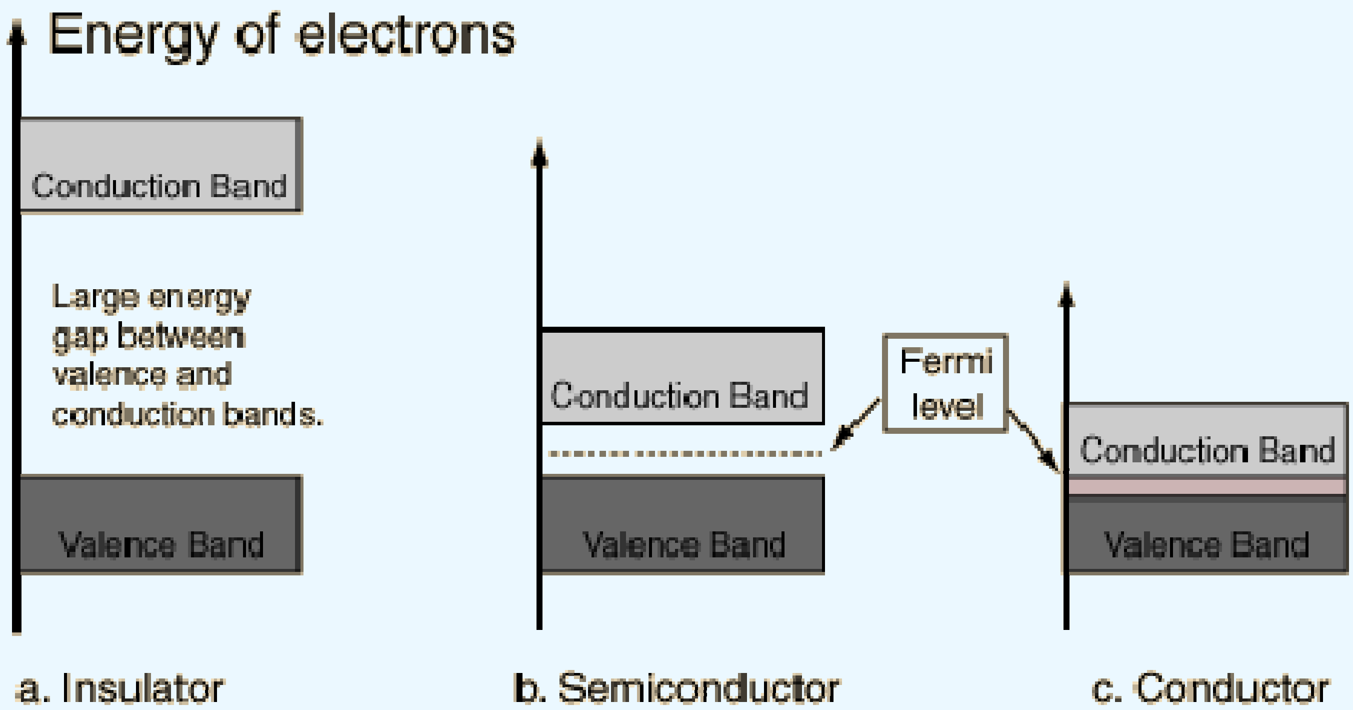


figure from http://jntu-ece.blogspot.com/p/blog-page_13.html

(AJR study guide 17.g.i)

Semiconductor detectors

- Semiconductor detectors can be viewed as "solid state" ion chambers
- radiation produces electron-hole pairs instead of ion pairs
- impurities: ***p-type***: electron acceptor, ***n-type***: electron donor
- in response to radiation, electrons are bumped up to conduction band and move to p-type region --> electron holes drift to n-type region
- applied voltage directs e-h pairs to electrodes where electric signal is acquired
- solid state material is more dense than gas
- have much higher efficiency than gas detectors
- high electron-hole pairs yield per keV

(AJR study guide 17.g.i)

Semiconductor materials

- **Ge(Li)** - small size (< 10cm), due to high thermal noise require liquid nitrogen temperatures to operate, produce about 3.5 e-h pairs per keV, have very good energy resolution
- **Si(Li)** - mainly used for α, β and very low energy γ, operates in low temperatures, has very good energy resolution
- **CdZnTe (CZT)** - new detector, doesn't require cooling, has very high efficiency so can be made into arrays of very small detectors for excellent spatial resolution, good energy resolution

material:	Si(Li)	Ge(Li)	CdZnTe	Air
density (g/cc)	2.3	5.3	5.8	0.0013
atomic number (Z)	14	32	48	7, 16, …

(AJR study guide 17.g.ii)

Scintillators vs semiconductors for nuclear medicine imaging

- scintillators
  - advantages: high sensitivity to γ-rays, low cost
  - disadvantages: need to convert light to electrons with loss of signal, worse spatial and energy resolution, large size
- semiconductors
  - advantages: direct conversion to electrons, compact, excellent spatial and energy resolution, operates at lower voltage
  - disadvantages: limited thickness, lower sensitivity

Dedicated Cardiac SPECT Cameras

- D-SPECT - CZT detectors
- GE Discovery NM 530c - CZT detectors
- Digirad Cardius 3 XPO –
  - CsI(Tl) detectors
  - individual silicon photodiodes/electronics

D-SPECT