PART IV

Detection and Measurement of Radiation

Outline

I. Gas Filled Detectors; Theory of Operation
   - A. Ionization Chambers
   - B. Proportional Counter
   - C. Geiger-Muller Counters

II. Scintillation Counter; Theory of Operation
   - A. Organic Phosphors
   - B. Inorganic Phosphors
   - C. Types of Scintillation Counters

III. Solid State Detectors

IV. Comparison of Radiation Detection Devices

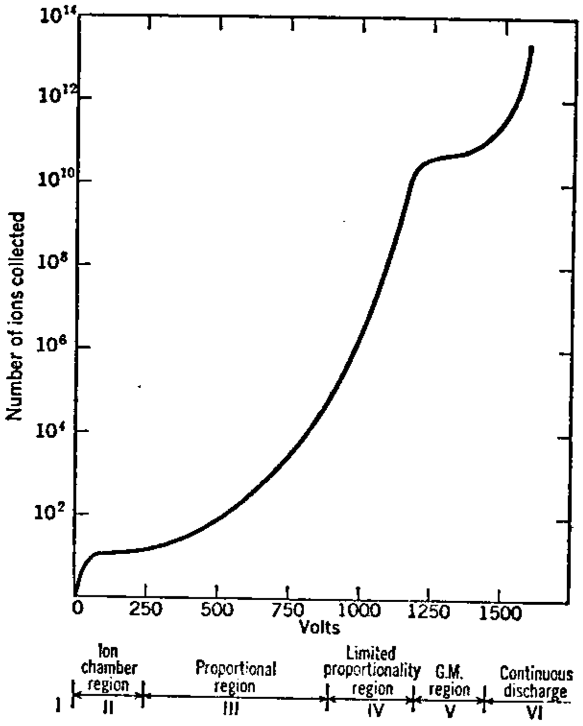
V. Problems

SECTION I

Gas Filled Detectors: Theory of Operation

Depends on interaction of electric field of moving particle with detector material (gas) to produce ionization.

Recall: ∿ 34 eV/ion pair



IG. 1. The number of ion-pairs formed, as a function of tector voltage.

A. Ionization Chambers

1. Small pulse requires external amplification

2. Usually cheap and rugged

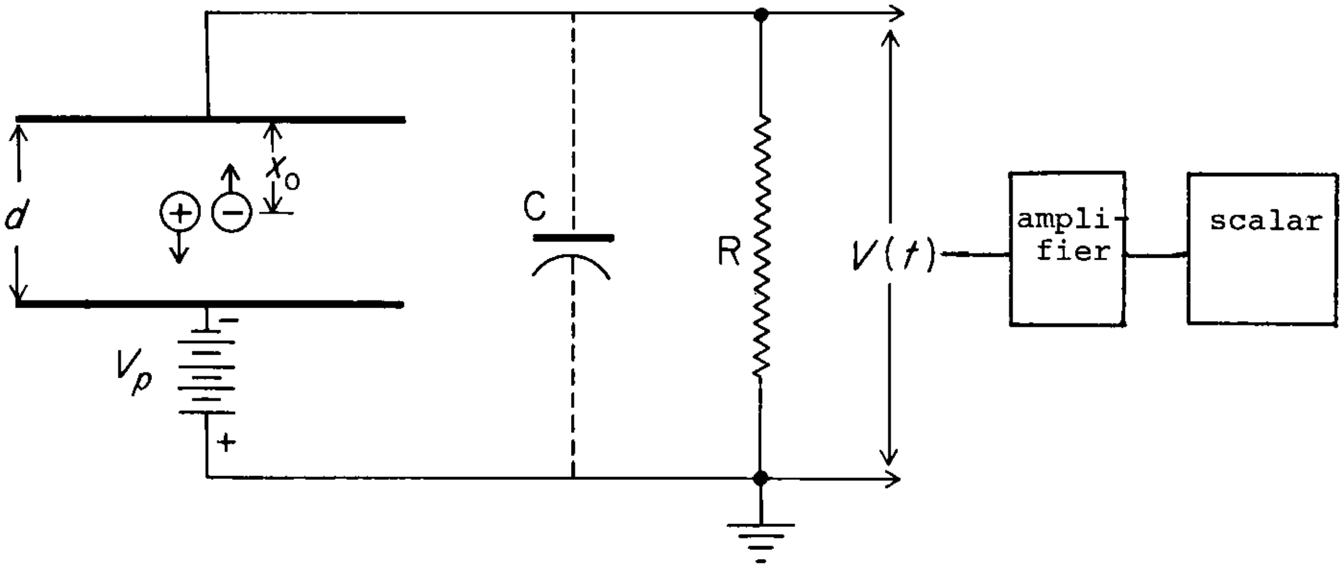


FIG. 2. Pulse-type ionization chamber.

EX: If a 4.2 MeV alpha particle dissipates all its energy ionizing the gas, how many ion pairs are formed?

No. ion pairs = 4.2×10^6 eV/34 eV

Collected charge = $(1.2 \times 10^5)(1.6 \times 10^{-19}) \simeq 2 \times 10^{-14}$ coulomb

If time of collection = 10^{-5} sec

$$\text{The average current} = \frac{2 \times 10^{-14}\ \text{coulomb}}{10^{-5}\ \text{sec}} = 2 \times 10^{-9}\ \text{amp}$$

Important: The size of current pulse is proportional to the charge liberated and hence the amount of energy lost by particle in the gas.

B. Proportional Counters

Electric field strength at distance r from electrode is inversely related to r.

Ex: If applied voltage to cylindrical chamber of radius 1 cm is 1000 volts, the potential in vicinity of a center wire 0.001 inches in diameter $\sim 7 \times 10^4$ volts/cm. Causes acceleration of e's leading to secondary ionization.

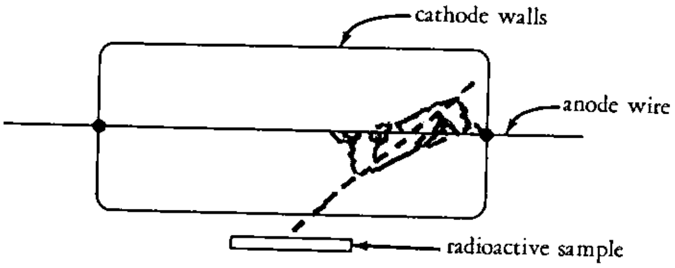


FIG. 3. Localization electron multiplication at the center anode wire in a proportional counter.

M = gas multiplication factor

$$= \frac{\text{number of electrons collected}}{\text{number of electrons in primary ionization}} \sim 10^3 - 10^5$$

Proportional counters can be constructed with or witho "window". Source of radiation - outside for window, inside for windowless detectors.

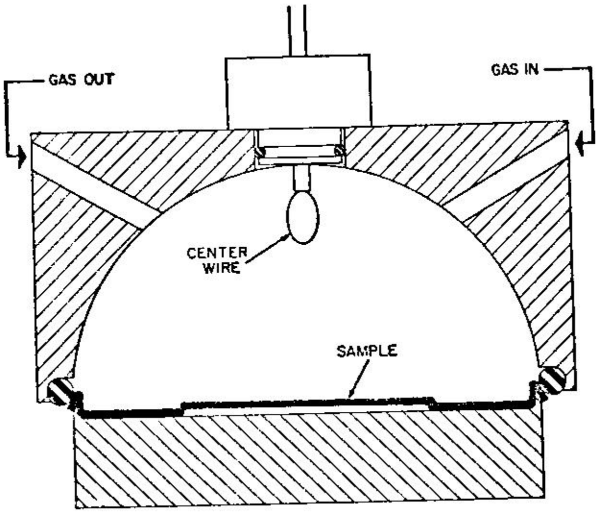


FIG. 4. Windowless flow chamber

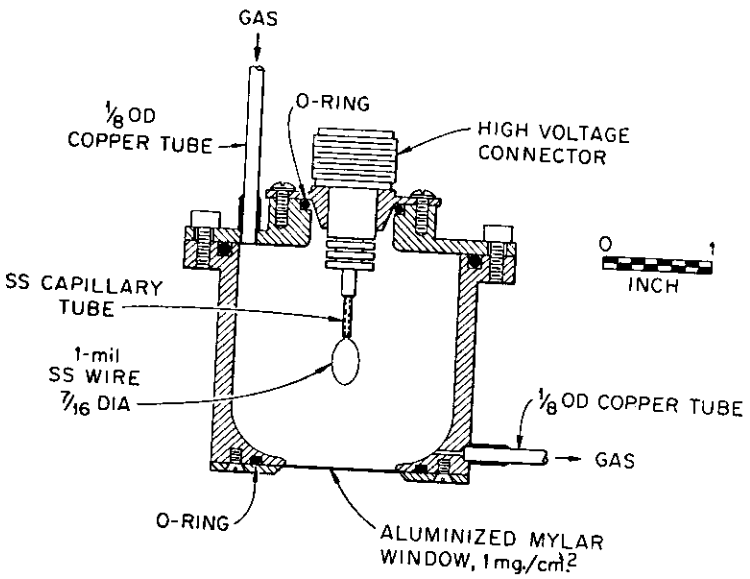


FIG. 5. End-window proportional counter for routine beta-ray counting.

Characteristics of Proportional Counters

1. Can distinguish between alpha and beta particles

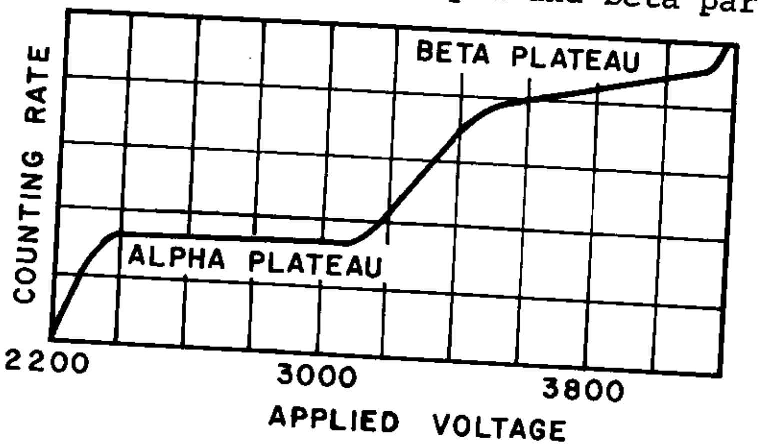


FIG. 6. A counting rate-voltage curve obtained with an end-window proportional counter and a source containing both an alpha and a beta emitter.

2. Can detect extremely high count rates

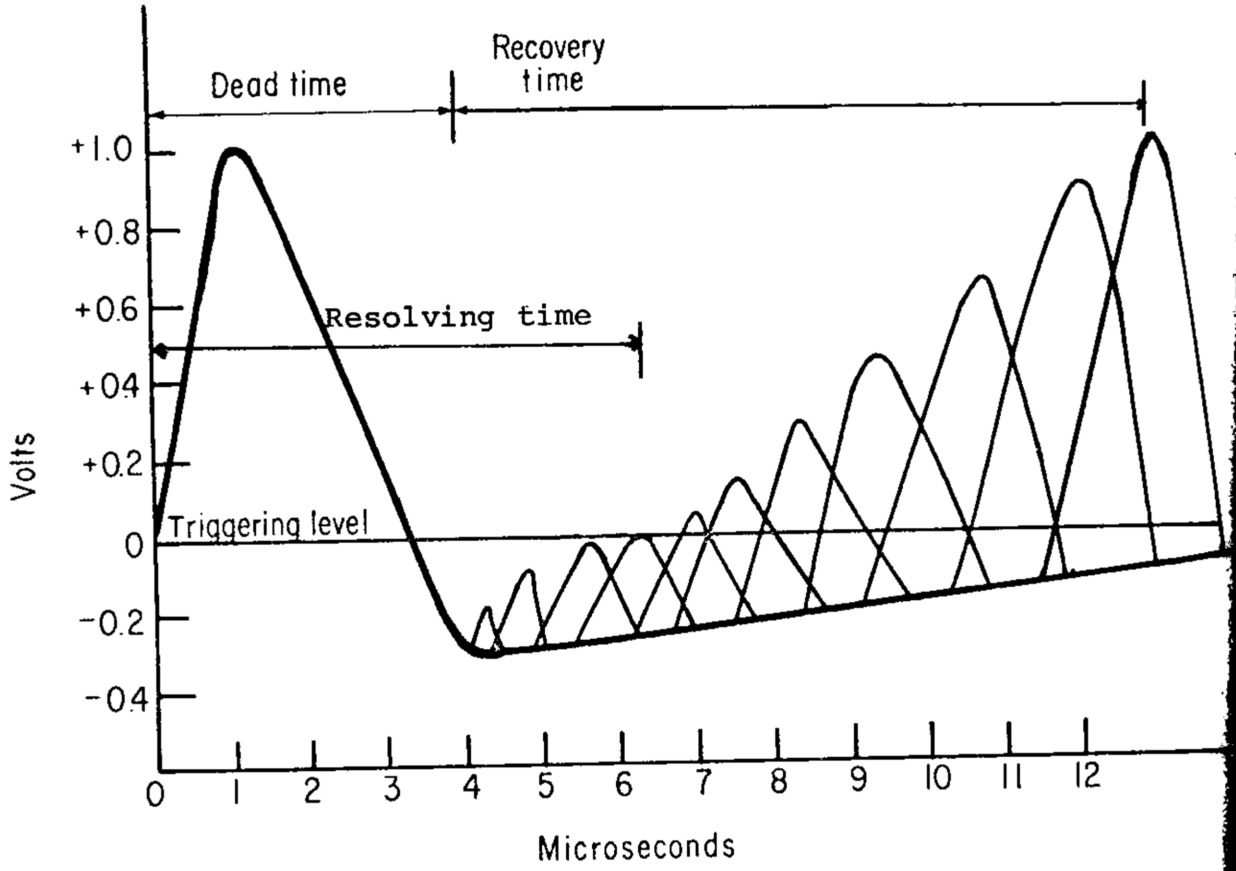


FIG. 7. Illustration of pulse shapes in a typical proport

counter system.

Dead time - time interval during which the detector is completely insensitive to additional ionizing particles.

Recovery time - that additional time beyond the dead time required for the pulse to regain its original amplitude.

Resolving time - average time interval for which the electronic detection system is insensitive (resolving time depends on the triggering level).

Resolving time determination - requires two standard sources of known activity

$$\tau = \frac{R_1 + R_2 - R_{12}}{2(R_1 R_2)} \qquad (2)$$

τ = resolving time in sec

R_1 = cnt rate source 1 (cps)

R_2 = cnt rate source 2 (cps)

R_{12} = cnt rate of combined sources 1 and 2 (cps)

Typical dead time for a proportional counter 1-10 μsec

C. Geiger-Muller Counters

1. Pulse size the same for all initial ionization whether 6 MeV alpha particle or 50 keV X-ray.

2. Large output pulse - requires less external amplification.

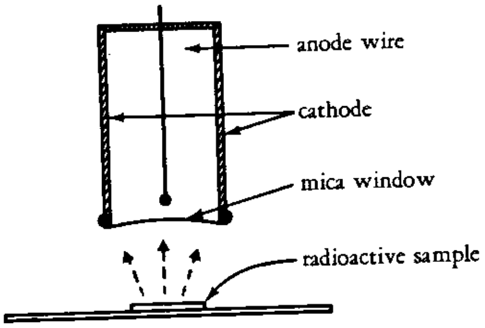


FIG. 8. Counting arrangement for an end-window Geiger counting tube.

3. Further avalanches prevented by quenching

$$Ar^{+} + (EtOH)^{\circ} \longrightarrow Ar^{\circ} + \underset{\text{Fragments}}{\underset{\downarrow \text{ dissociation}}{(EtOH)^{+}}}$$

4. Much longer dead time than proportional counter

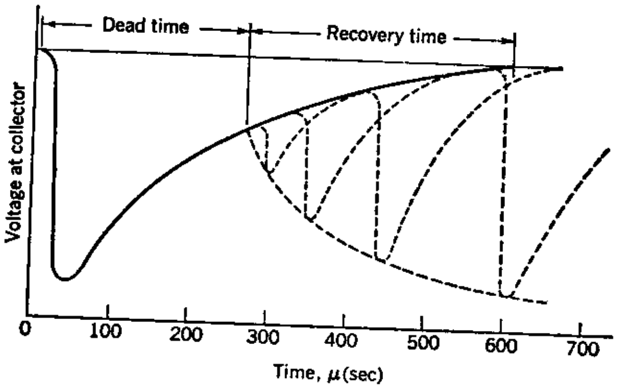


FIG. 9. Illustration of pulse shapes in a typical Geiger tube operating at a high counting rate. The dead time and recovery times are determined by the Geiger tube characteristics, but the resolving time depends on the triggering level of the electronic recording system.

5. Use primarily for beta counting

    1. Alpha particles excluded by mica windows

    2. Gamma rays - have too low a probability for ion pair formation per unit path length

SECTION II

Scintillation Counters: Theory of Operation

Requires the use of scintillators, organic or inorganic crystals with special properties. The nuclear radiation must be absorbed in the scintillator with subsequent re-emission of light photons.

The necessary properties of scintillators are:

1. high cross section for energy absorption
2. transparent to own radiation
3. emission of luminescent radiation must occur with high efficiency
4. radiation must have a wavelength to which the photomultiplier tube is sensitive

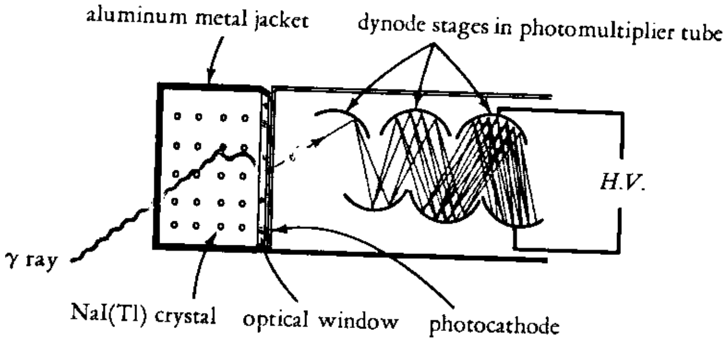
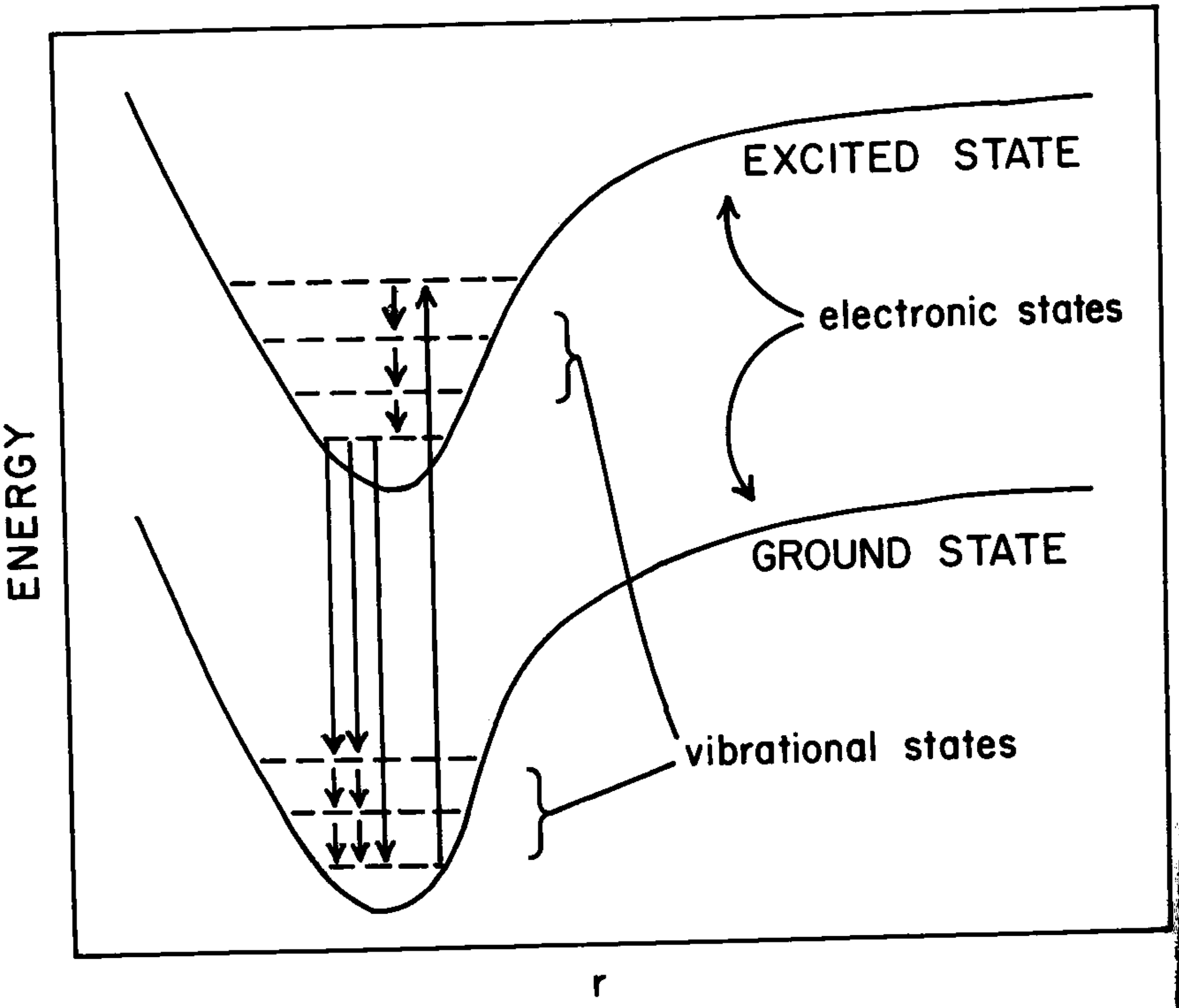


FIG. 10. A scintillation crystal with a photomultiplier tube. For simplicity, an electron multiplication (gain) of two at each dynode stage is shown; in practice, the gain is eight to ten per stage, with as many as ten dynode stages.

A. Organic Crystals (Phosphors)



Internuclear Distance

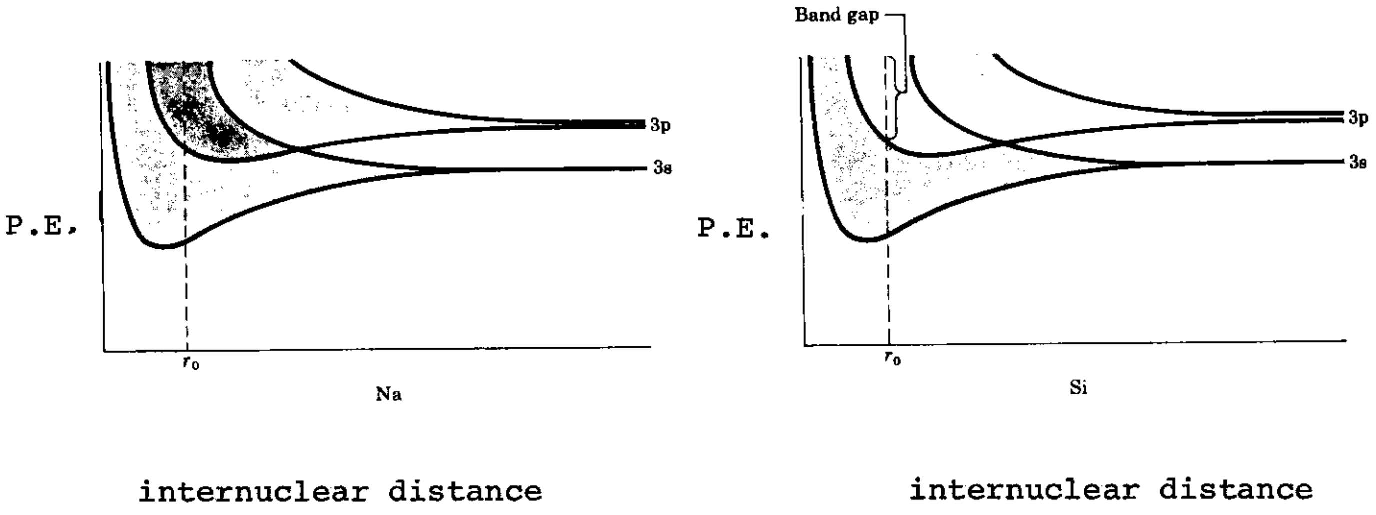
FIG. 11. Possible absorption and emission steps in phosp

Properties of Some Common Organic Phosph~~e~~ors

TABLE I

Material	Density (g/cm^3)	Wavelength of maximum emission (Å)	Decay time for emission	Relative pulse height from β particles
Anthracene	1.25	4400	3.2×10^{-8}	100
Stilbene	1.16	4100	6×10^{-9}	60
Plastic phosphors	1.06	3500-4500	$3\text{-}5 \times 10^{-9}$	28-48
Liquid phosphors	0.86	3500-4500	$2\text{-}8 \times 10^{-9}$	27-49

B. Inorganic Crystals (Phosphors)



(a) Metal

(b) Non-metal

FIG. 12

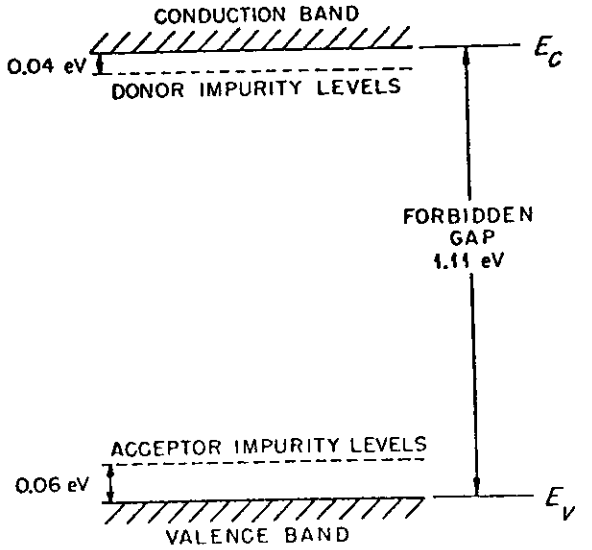


FIG. 13. Electronic Band Scheme for Non-metal.

Acceptor impurities: atoms with < 4 e's in valence shell "accept" additional e's, e.g. B in Si.

Donor impurities: atoms with > 4 e's in valence shell so donate e's; e.g. P in Si.

Properties of Some Common Inorganic Phosphors

TABLE II

Material	Density (g/cm^3)	Wavelength of maximum emission (Å)	Decay time for emission (seconds)	Relative pulse height from β particles
NaI(Tl)*	3.67	4100	2.5×10^{-7}	210
ZnS(Ag)*	4.10	4500	1×10^{-5}	200

*(Tl) and (Ag) indicate small amounts of these elements added as impurity activators

C. Types of Scintillation Counters

1. Flat Solid - NaI(Tl) crystal

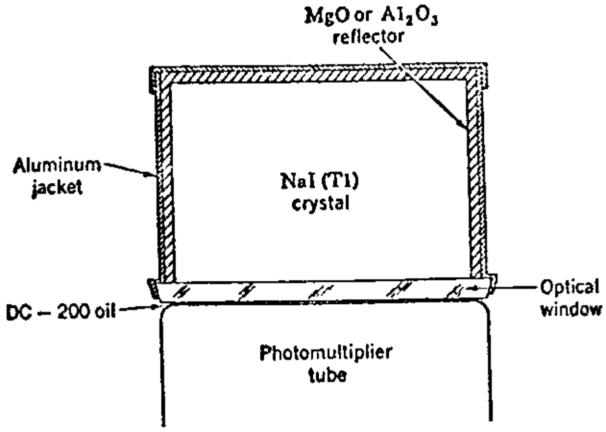


FIG. 14

2. Well Crystal

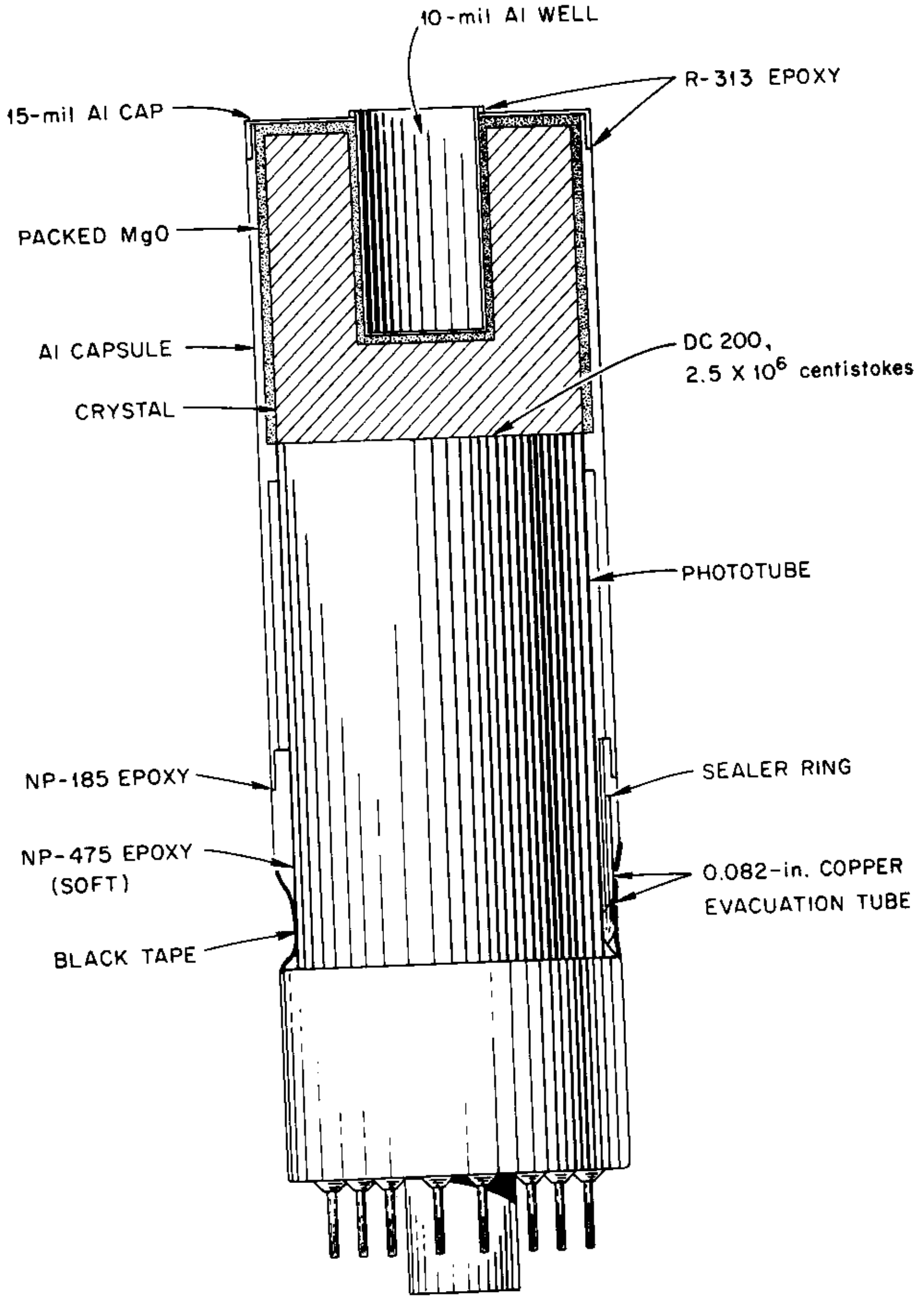
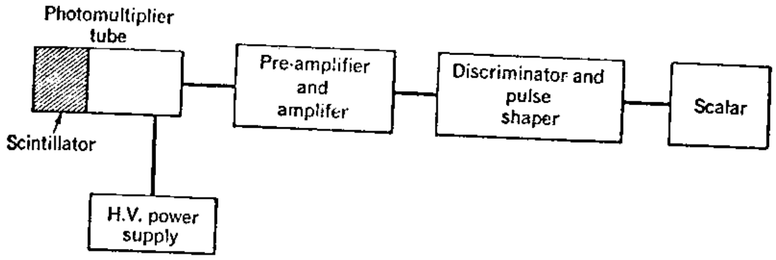


FIG. 15

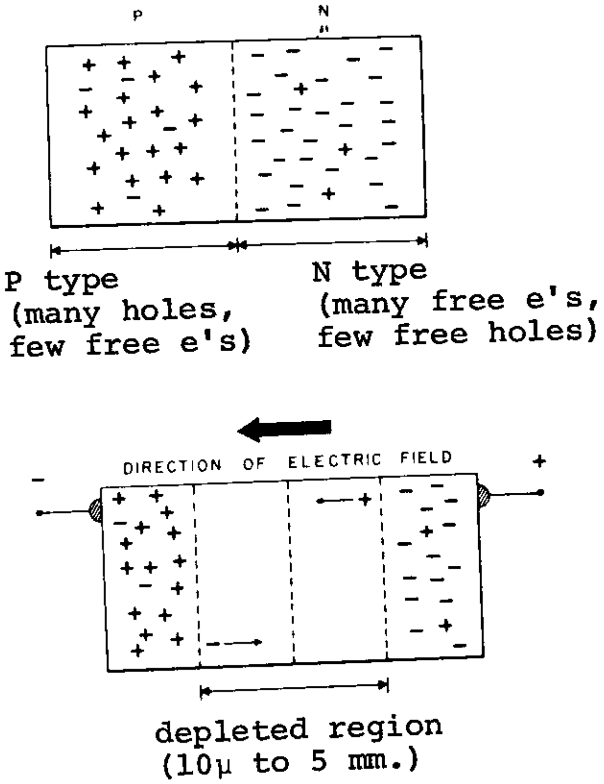
C. Total Measuring Circuit



G. 16. Schematic diagram of a scintillation counting system.

SECTION III

Solid State Counters



(a) no bias voltage

(b) reverse bias

FIG. 17

SECTION IV

Comparison of Radiation Detection Devices

TABLE III

	Counter				
	Ionization chamber	Proportional	G.M.	Scintillation	Solid State
Normal detection state	gas	gas	gas	liquid or solid	solid
Radiation usually counted	a,β	a,β	a,β,γ	a,β,γ	a,β,γ
Multiplication of primary charge	1	10^4	10^8	10^8	10
Complexity of total system	medium	high	low	high	high
Particular advantages	simplicity	high count rates	simplicity; adaptability	high count rates; high counting efficiency	excellent energy resolution

Problems

1. How many ion pairs are formed in a gas by a 5.4 MeV alpha particle?

2. Why does secondary ionization provide so much larger a percentage of the total ionization for beta particles than for alpha particles?

3. If the efficiency for a Geiger tube is $1 - e^{-N}$ where N is the number of primary ion pairs, calculate the efficiency for N = 1,2,3,4, and 5. What does this tell you about the relative efficiency of Geiger-Muller counters for alpha, beta, and gamma rays (assuming they penetrate the window)?

4. The equation for the pulse size in a detector operating in the proportional region is

$$\Delta V = M \frac{ne}{c}$$

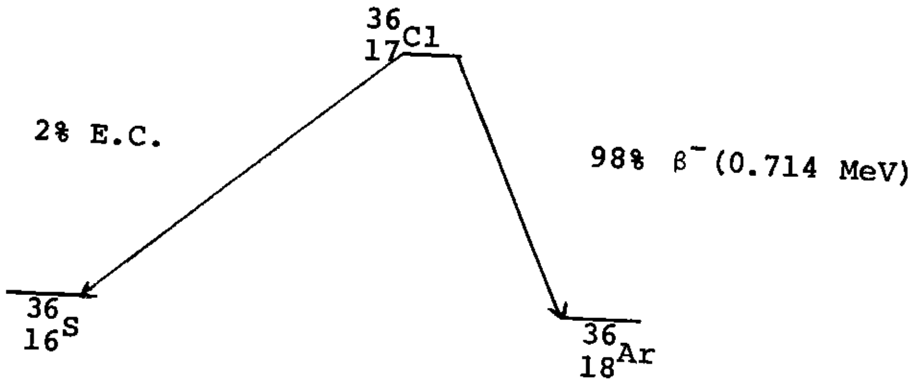
where M = gas multiplication factor, 10^4
n = number of electrons from the primary ionization
e = electronic charge, 1.6×10^{-19} coulombs
c = capacitance of the counter.

5. What is the total charge released when ^{244}Cm emits a 5.8 MeV alpha particle in an ionization chamber with air at 1 atm as the counting gas?

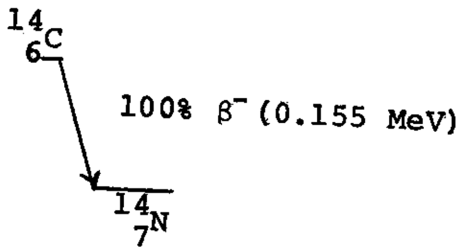
6. What is the range of a 5 MeV proton in aluminum?

7. What type of instruments would you consider best for counting each of the following and why?

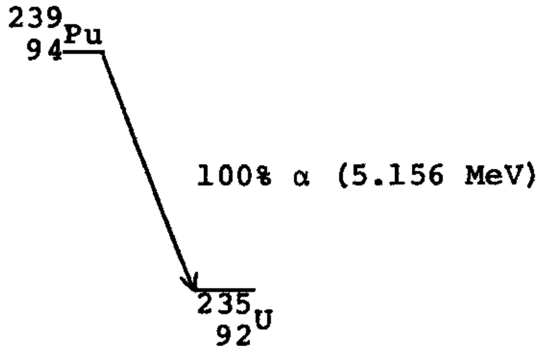
a. detection of 10^{-3} μc $^{36}_{17}$Cl



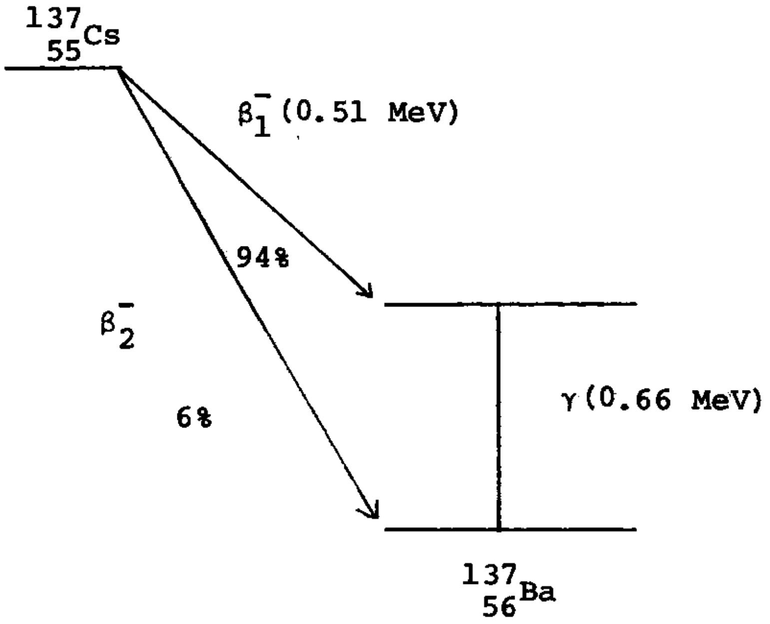
b. detection of 0.1 μc of $^{14}_{6}$C



c) detection of 10^{-5} μc of $^{239}_{94}\mathrm{Pu}$



d) detection of 10^{-2} μc of $^{137}_{55}\mathrm{Cs}$



e) What could be an alternative method of detection of each of the above radionuclides?