The Interaction of Radiation with Matter: Particle Detection and Applications

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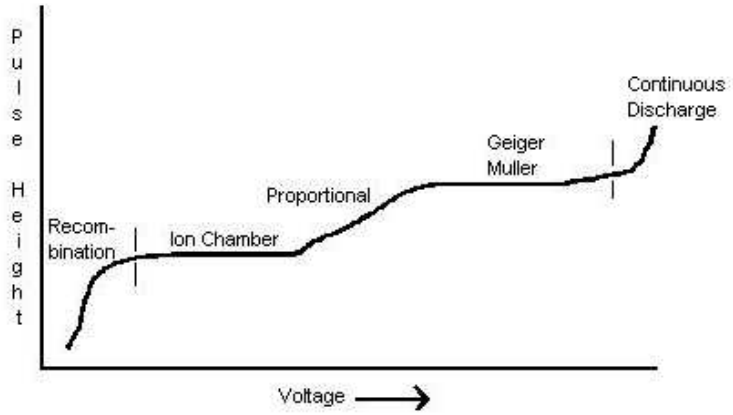
Outline

The ionization process

Involves the creation of ion-pairs - generally a free e^- and $^+$ve ion - through ionization processes.



- When an electric field, ε, is applied across a gas the e^-'s moves towards the anode, the positive ions moves towards the cathode forming a pulse of electric current. The size of the pulse depends on the strength of the electric field.

The ionization chamber dosimeter

Aim to collect all original ion pairs. Drift velocity, ν, is an average of repeated accelerations and collisions:

$$\nu = \frac{\mu\varepsilon}{P} \tag{1}$$

where μ the is the mobility constant for a particular gas and P is the pressure

- For ions $\mu \approx 10^{-4}\text{m}^2\text{atm V}^{-1}\text{s}^{-1}$
- For e^-'s $\mu \approx 10^{-1}\text{m}^2\text{atm V}^{-1}\text{s}^{-1}$

e.g. Apply 100 V across a 1 cm gap, $\varepsilon = 10^4\ \text{Vm}^{-1}$

- $\nu_{\text{ions}} = 1\ \text{m s}^{-1}$, $t =$ 10's of msec - typically much slower than time constant of circuit
- $\nu_{\text{electrons}} = 10^3\ \text{m s}^{-1}$ $t =$ 10's of μsec - typically much faster the time constant of circuit

Recombination

If electric field, ε, is too weak, get recombination of e$^-$s and ions - lose some of the pulse

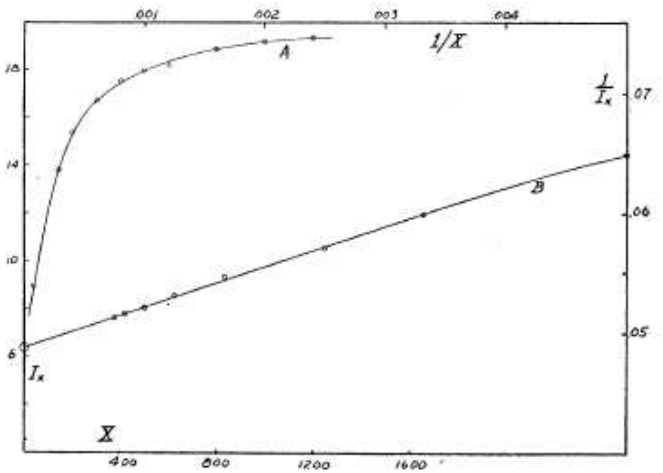
- More densely ionizing radiation (larger $S = -\mathrm{d}E/\mathrm{d}x$) needs larger electric field to prevent recombination
- Usually operated in *Current Mode* e.g. dosimetry

Determination of the Saturation Ionization Current from High Speed Electrons in Air

Last year we reported a study[1, 2] of the ionization produced in liquid carbon disulphide by x-rays produced at moderate voltage. Jaffe's[3] theory of columnar ionization furnishes the relationship

$$\frac{I_\infty}{I_x} = \frac{\alpha N}{kudXf(X)} + 1,$$

LAURISTON S. TAYLOR
National Bureau of Standards,
Washington, D. C.,
November 25, 1935.



Spectroscopy with ion-chambers

In order get spectral information from an ionization chambers, the *shape* of the pulse needs to be considered

- Two signals: one from fast moving electrons, one from slow moving ions
- As ion-pairs separate and move towards the electrodes and the potential difference between the electrodes is reduced by an amount, V_{R}- the effect appears before the charges reach the electrodes.
- In a parallel plate ionization chamber, electric field, $\varepsilon = V/d$

$$V_{\mathrm{R}} = \frac{ne}{Cd}\left[v_{+} + v_{-}\right]t$$

- The potential difference across resistive element, V_{R} is restored over a longer time-period by charge from the supplied potential difference, V, according to R-C circuit principles, i.e. $V_{\mathrm{R}} \rightarrow \mathrm{e}^{-t/RC}$

The Frisch Grid

The size of the fast and slow pulses depends on where in the chamber the ionization occurs:

- Need to use a *Frisch Grid* which divides the chamber into two sections, ionization only occurs in first section, V_{R} is only recorded as electrons drift through second section.

Pulse size usually dominated by capacitance in electronics $> 10^{-10}$F

- 1 MeV ionizing particle produces $E/W = 10^6/30 \approx 3 \times 10^4$ion pairs
- total charge $\approx 3 \times 10^4 \times 1.6 \times 10^{-19}$C
- $V = Q/C = 50\mu$V (i.e. very small)
- A 100 MeV fission fragment is detectable!

Statistics of pulse-formation and energy resolution

Signal to the detector is determined by the finite number of ion-pairs formed, i.e., $N = E/W$, where W is the average energy required to produce an ion-pair.
Production of signal carriers is a random process, and though the numbers are related to the incident particle energy, the number of charge carriers are distributed according to Poisson statistics:

- Variance = Mean
- $N = E/W$ fluctuates by $\pm\sqrt{N}$ (the standard deviation) therefore

$$\frac{\Delta E}{E} = \frac{\sqrt{N}}{N} = \sqrt{\frac{W}{E}}$$

- For good energy resolution need large N from small W - e.g. semiconductors!
- Experimentally measure full-width half-maximum
  $\mathrm{FWHM} = 2\sqrt{2\ln 2}\Delta E = 2.35\Delta E$

The Fano factor

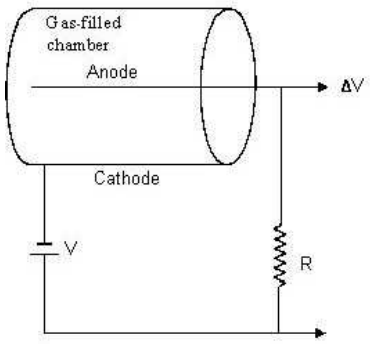
The formula assumes perfect Poisson distributions which would occur if the creation of all signal carriers was uncorrelated. In reality:

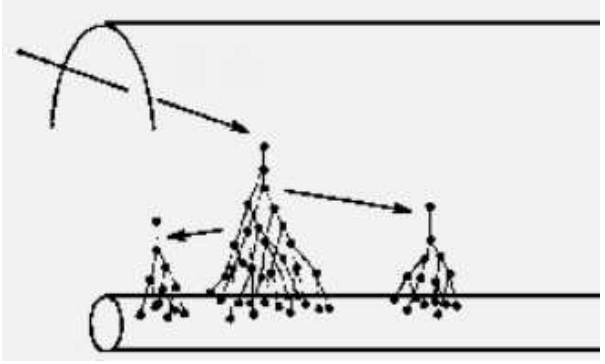
$$\frac{\Delta E}{E} \leq \frac{1}{\sqrt{N}} = \sqrt{\frac{F}{N}}$$

where $F \leq 1$ is the Fano factor - an empirically determined correction to allow for these correlations.
Fano factor for gas-ionisation chambers is typically $F \approx 0.1$

Proportional counter ionization chamber

If ε, the electric field strength, is large enough the e^-s may acquire enough E between collisions so that they create new ion-pairs - get a chain reaction, the *Townsend Avalanche*, which occurs if $\varepsilon \geq 10^6 \mathrm{V/m}$ - "Gas Multiplication"





- Proportional counter is cylindrical - get gas multiplication close to anode as $\varepsilon \propto 1/r$. Pulse is mainly formed by ions in the avalanche moving outwards as electrons then only have a short distance to move
- Total charge generated, Q, is *proportional* to number of ion-pairs created

Proportional counters cont.

- UV photons generated by excited ions can produce further ionizations leading to non-linearities, A polyatomic *quench gas,* e.g. methane, is used to absorb UV energy in vibrational and rotational states.
- If avalanche is created when electrons drift near to anode, i.e. $r \approx a$. The electrons move to a and ions move to b - conservation of energy considerations dictate:

$$V_{\mathrm{R}} = \frac{q}{2C \ln(b/a)} \ln\left(1 + \frac{2\mu V}{P \ln(b/a) a^2} t\right)$$

  which describes the initial, t small, behavior of the pulse.
- Most of the pulse formation occurs within a time scale $t = Pa^2 \ln(b/a)/(2\mu V)$ which can be optimized through chamber design,
- e.g. for electronics that functions on the μsec scale and potential, $V = 100$ V, $\mu \approx 10^{-4}\mathrm{m}^2\mathrm{atm\ V}^{-1}\mathrm{s}^{-1}$for ions:

$$a \approx (10^{-6} \times 2 \times 10^{-4} \times 100)^{1/2} = 1.4 \times 10^{-2}\mathrm{cm}$$

Statistics of the proportional counter

The energy resolution includes contribution to statistical variation from gas amplification. Given a total charge, $Q = N\overline{q}$, where $\overline{q}$ is the average charge generated per avalanche and N is the number of initiating ion-pairs. The resolution is determined by adding the contributions of N and $\overline{q}$ in quadrature:

$$(\frac{\Delta Q}{Q})^2 = \left(\frac{\Delta N}{N}\right)^2 + \left(\frac{\Delta \overline{q}}{\overline{q}}\right)^2$$

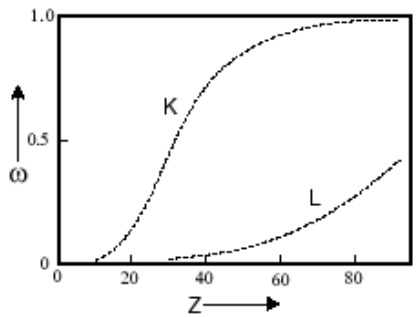
As before with the Fano factor, have b, the correlate relating to the avalanche process,

$$\frac{\Delta Q}{Q} = \sqrt{\frac{F+b}{N}}$$

In practice $F \approx 0.1$, $b \approx 0.4$. The statistical contribution to energy resolution is $2\times$ worse for proportional counter than ion-chamber

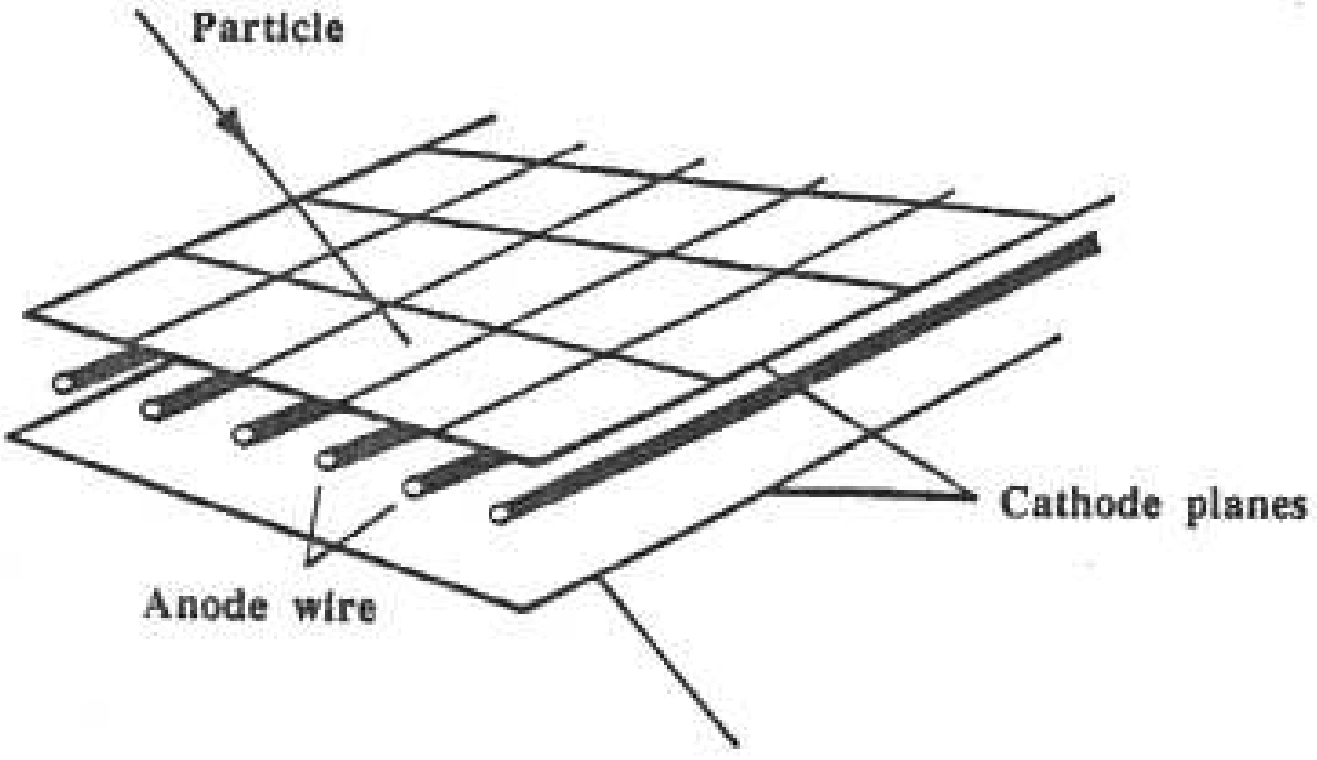
Spectrometry with proportional counters: Photon detection

- Interact via photoelectric absorption so want a high-Z gas (e.g. the noble gases, Ar, Kr, Xe) and a thin low-Z material window (e.g. Be)
- Photoelectric effect creates a fast moving $e^-$with energy $E - E_b$, where E_b is the binding energy of the atomic orbital.
- What happens to, E_b, the binding energy?



  - Auger electrons emitted which contribute to ionization
  - Fluorescence photons are created which can be absorbed or can potentially escape - leads to *escape peaks* in a pulse height spectrum
  - Escape peaks occur at $E - E_K$ for K-shell orbital electron.
  - $E_K$is a similar value to the binding energy, E_b, and for Ar is 3 keV, for Kr is 13 keV, for Xe is 30 keV

Multiwire proportional counter



Thermal neutron detection

Use a neutron sensitive gas, i.e., one that undergoes neutron capture.
e.g. the BF_3 tube:

- Use B enriched to 90% ^{10}B (natural B has around 20%)
- Thermal neutrons give the reaction

$$\mathrm{n} + {}^{10}\mathrm{B} \rightarrow \begin{array}{ll} {}^{7}\mathrm{Li} + \alpha & (Q = 2.78\ \mathrm{MeV}, 6\%) \\ {}^{7}\mathrm{Li}^{*} + \alpha & (Q = 2.3\ \mathrm{MeV}, 94\%) \end{array}$$

- The initial state has small momentum so the kinetic energy is shared between Li ion and α which have equal and opposite momentum

$$E = \frac{P^2}{M} \propto \frac{1}{M}$$

- α has 7/11 of total E, range $\approx$ 1 cm
- ^{7}Li has 4/11 of total E, range $\approx$ 2 mm

Pulse height spectra in BF3 tube

The spectrum recorded in a BF_3 tube is independent of the thermal neutron spectrum and is determined by the capture products:

- In a large BF_3 tube the pulse height spectrum gives two peaks at the Q values
- In a medium sized tube either ion can hit the wall before depositing energy as ionizations in the gas but the somewhat more mobile α-particle is more probable.

The BF_3 tube has poor efficiency. BF_3 gas can form negative ions so it needs to be operated at a reduced pressure ($\sigma = 3880$ barn)

- Though expensive ^{3}He gas is a useful alternative with greater efficiency of detection through a larger cross-section ($\sigma = 5330$ barn) and can be operated at higher pressures

$$\mathrm{n} + {}^3\mathrm{He} \rightarrow {}^3\mathrm{He} + \mathrm{p}\ (100\%),\ \text{energy released}{=}0.76\ \mathrm{MeV}$$

The Geiger-Mueller counter

Similar design to a proportional counter but operates at even higher voltages.

- Ionization through gas multiplication spreads to fill the entire chamber volume and the process stops only when collective positive charge from ions is so large that ε is reduced below the value needed for gas multiplication
- Pulses sizes are independent of the number of ion-pairs - simply counts numbers of particles
- G-M counters produce very large pulses so electronics don't't need to be complicated
- After each pulse there is a *dead time* while the positive ions drift out to the cathode - can take up to a msec. Therefore G-M counters are useful only at low count rates - application in environmental radiation surveying

Geiger-Mueller counter: Quenching

A problem with G-M counters is that they are inherently unstable, e.g. +ve ions can knock out electrons when they reach the cathode triggering multiple pulses. Need some form of quenching:

- External quenching - use electronics to switch off potential for a short time after each pulse
- Internal quenching - introduce a small amount of quench gas that preferentially absorbs +ve charge and is less likely to knock out electrons at the cathode, e.g. C_2H_5OH. Quench gas needs to be constantly replaced as it is lost through dissociation

Attenuation of electrons from β emitters

β emitters possess a spectrum of energies. When combined with range data for monoenergetic e^- fortuitously gives an exponential falloff in numbers of e^-. Need to use a Geiger counter which measures particle numbers independent of energy.

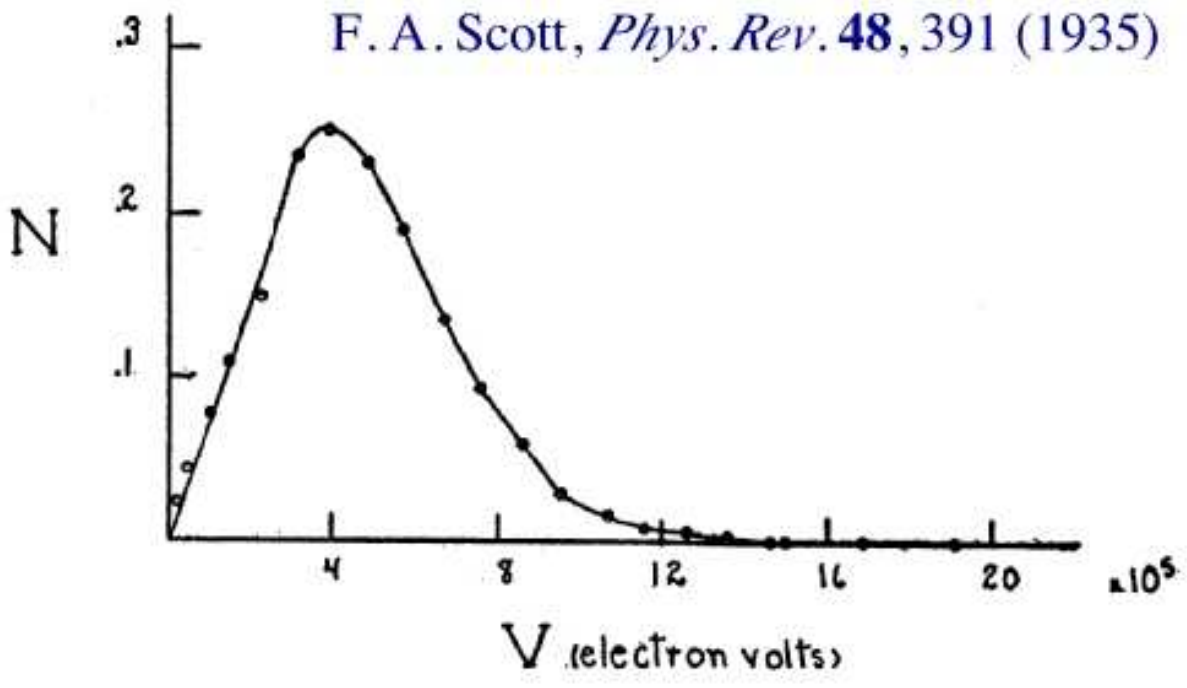
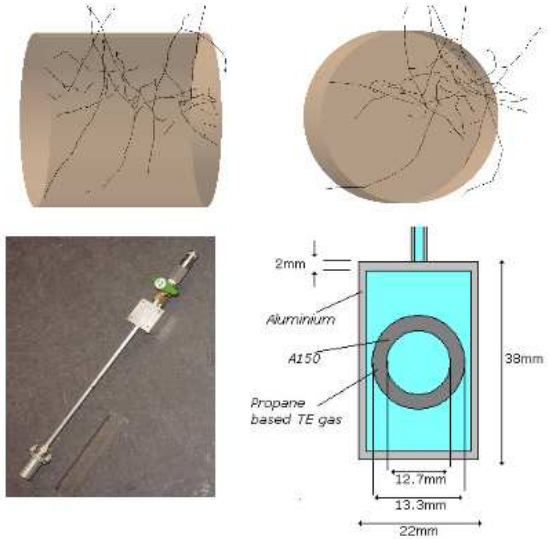
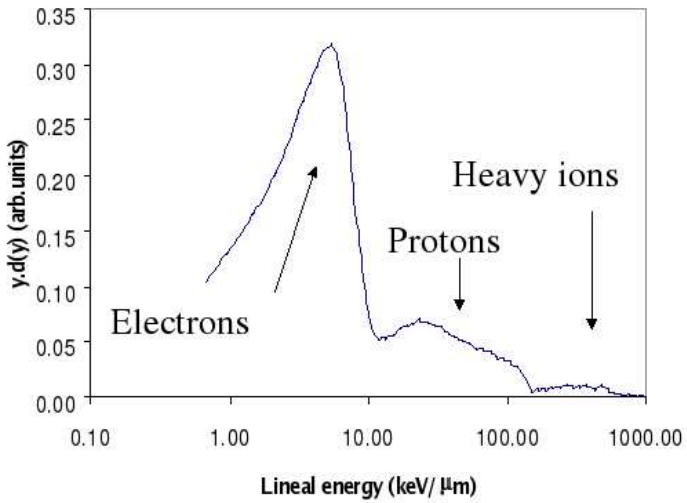


FIG. 5. Energy distribution curve of the beta-rays.

Microdosimetry





- Spectra recorded with a tissue equivalent proportional counters (TEPC) are used to predict the energy deposition in sub-cellular volumes ($\approx 1\mu$m diameter). This information predicts the likelihood of the cell undergoing some biological change such as apoptosis (a programmed cell death). The passage of a fast neutron through tissue, for example, generates electrons, protons and heavier ions such as carbon. The biological effect, per radiation dose (Gy), is the greater for heavy ions and protons than electrons

Recommended books

- Radiation Detection and Measurement, G F Knoll, (3rd Edition, Wiley, 1999)
- The Physics of Radiology, H E Johns and J R Cunningham (4th Edition, Thomas, 1983)
- The Atomic Nucleus, R D Evans (Krieger, 1982)
- Classical Electrodynamics, J D Jackson, (3rd edition Wiley, 1998)
- Fundamentals of Nuclear Science and Engineering, K Shultis and R E Faw (Marcel Dekker, Inc., 2002)