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Radiation Detection and Measurement

Lecture 13

Chapter 6: Proportional Counters

What is it?

- A type of counter operated impulse mode which relies on gas multiplication to amplify the charge represented by the original ion pairs created in the gas.
- Useful in detecting low energy x-rays and spectroscopy of low energy x-rays and neutron detection.

Gas multiplication

Avalanche Formation:

- By increasing the electric field in a gas to a sufficiently high value where electrons may be accelerated to energies greater than the ionization potential of the neutral gas atoms, one electron may collide and produce more electrons, which in turn is accelerated and produces more electrons forming an avalanche.
- The threshold is ~ 10^6 V/m at atmospheric pressure.

Gas multiplication

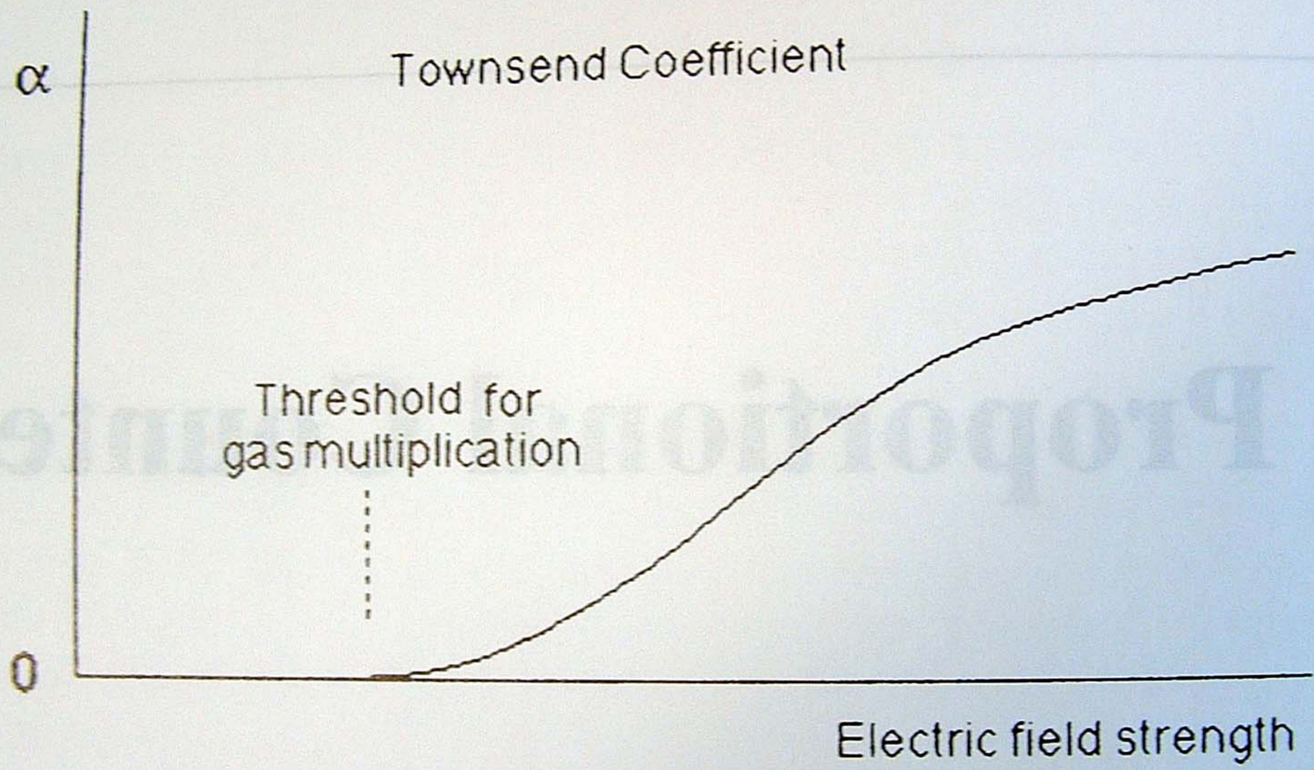

Figure 6.1 A plot of the first Townsend coefficient as a function of electric field for a typical gas.

Gas multiplication

- When a free electron can produce more free electrons through this cascade it is called a Townsend avalanche and is governed by the Townsend equation:

$$\frac{dn}{n} = \alpha dx$$

Gas multiplication

$$\frac{dn}{n} = \alpha dx$$

- which is a relation of the fractional increase in the number of electrons per unit length, where α is the first Townsend coefficient and is 0 for electric fields below the threshold, but increases with increasing field strength.
- The solution predicts the density of electrons grows exponentially with distance as the avalanche propagates

Gas multiplication

Regions of Detector Operation:

- Seen in Fig 6.2 are the differing detector regions as a function of applied voltage (for pulse mode detectors) for energy deposition of 2 different energy particles.

1. low voltage allows for recombination (where the electrons do not receive sufficient acceleration)
2. seen in chapter 5, the flat region is where ion chamber detectors reside (electron created ionization is collected)

Gas multiplication

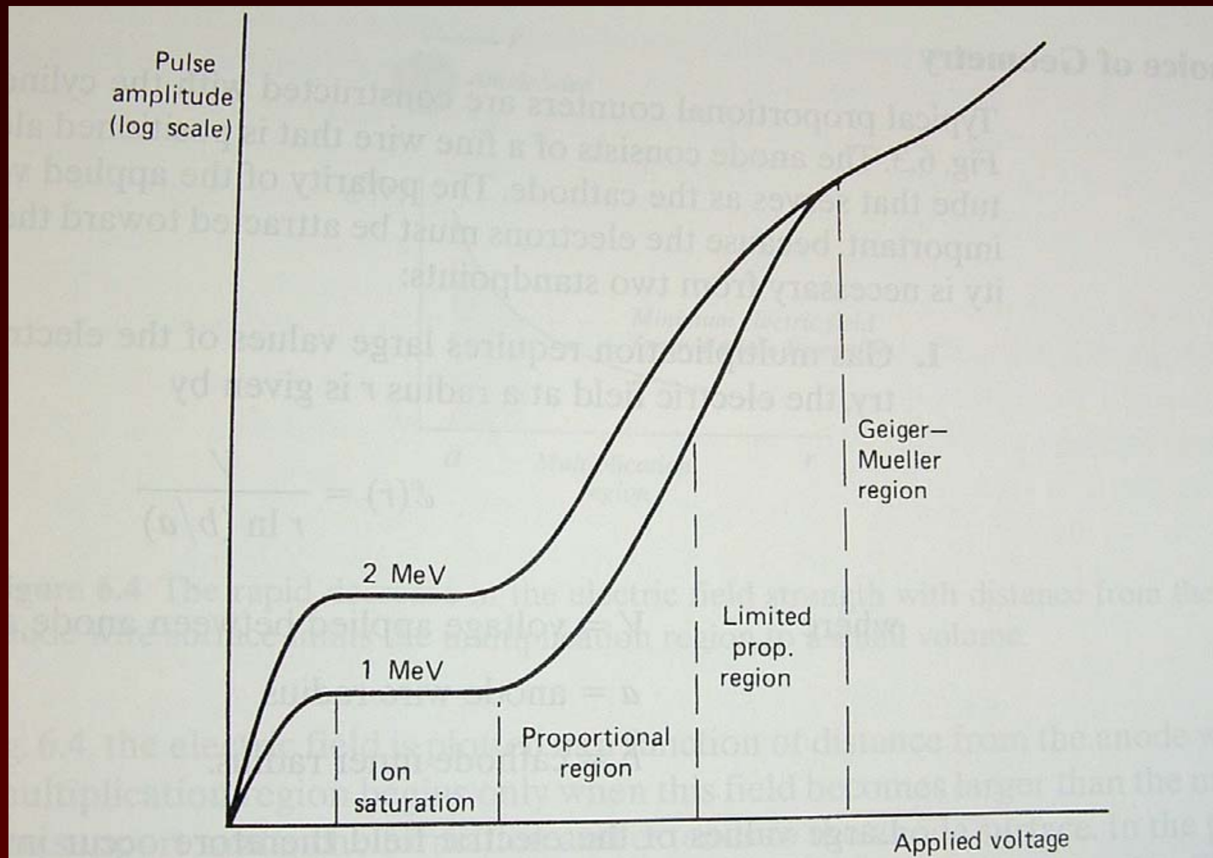

Figure 6.2 The different regions of operation of gas-filled detectors. The observed pulse amplitude is plotted for events depositing two different amounts of energy within the gas.

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Gas multiplication

3. proportional region is where the collected charge will be proportional to the ion pairs created (region of true proportionality, and is the region of operation for conventional proportional counters)
4. a higher applied voltage will enter a region of limited proportionality where non-linear effects may be created by the remaining positive ions(slow moving) which form a charge cloud in the chamber, reducing the electric field and further gas multiplication

Gas multiplication

5. With sufficiently high voltage the Geiger Muller region is entered, where the avalanche proceeds until a sufficient number of positive ions are formed reducing the potential until it is below sustainable avalanche potential. The process is self limiting and will stop when the number of positive ions formed regardless of the number of initial ion pairs, thus all energy related information is lost.

Gas multiplication

Choice of Geometry:

- For a proportional counter (of cylindrical geometry – Fig 6.3) the cathode provides a vacuum tight enclosure for the fill gas
- The output pulse is developed and measured across R_L

Gas multiplication

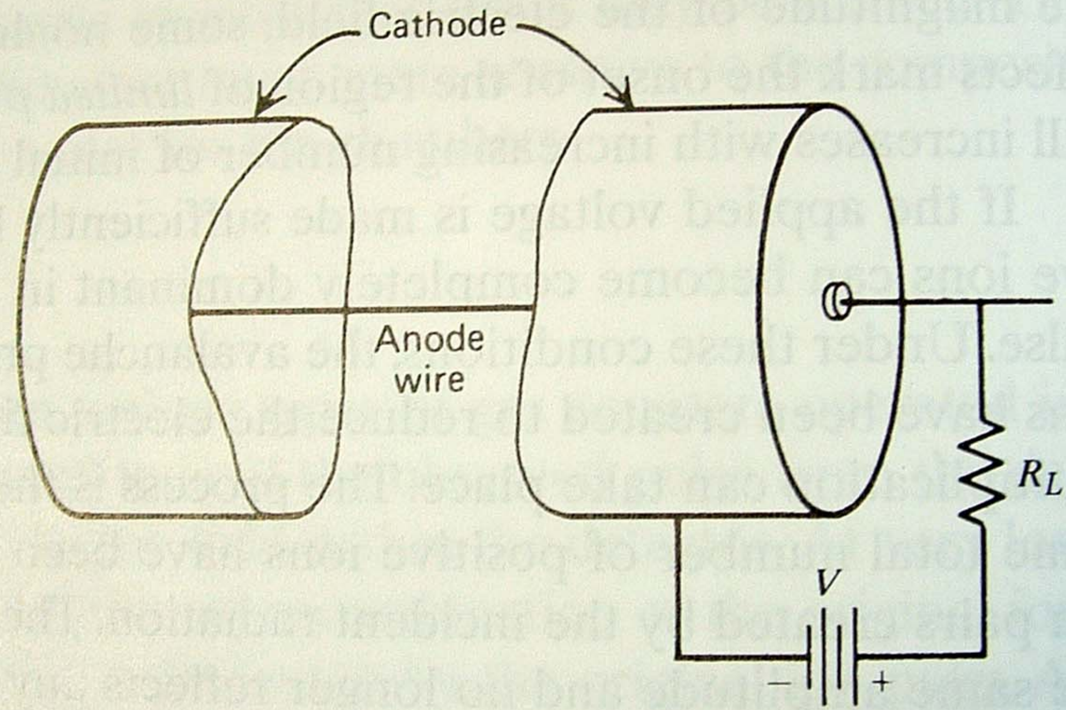

Figure 6.3 Basic elements of a proportional counter. The outer cathode must also provide a vacuum-tight enclosure for the fill gas. The output pulse is developed across the load resistance R_L.

Gas multiplication

- For cylindrical geometry the electric field E is given by:

$$V = \oint E \cdot dl = -\int_a^b E_r dr$$

but

$$\oint E \cdot da = \frac{Q}{\varepsilon_0} \Rightarrow E_r = \frac{Q}{2\pi\varepsilon_0 rL}$$

Gas multiplication

$$E_r = \frac{Q}{2\pi\varepsilon_0 r L}$$

$$-\int_a^b E_r \cdot dr' = \frac{-Q}{2\pi\varepsilon_0^2}\int_a^b \frac{dr'}{r'} = \frac{-Q}{2\pi\varepsilon_0 L}\ln(b) - \ln(a)$$

$$= \frac{-Q}{2\pi\varepsilon_0 L}\ln\left(b/a\right) = V_{\max}$$

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Gas multiplication

- V_{max} (positive charges) = - V_{max} for electrons

$$V_{\max}^{(e^-)} = \frac{Q}{2\pi\varepsilon_0 L} \ln\left(\frac{b}{a}\right)$$

but

$$Q = 2\pi\varepsilon_0 rLE_r$$

Gas multiplication

$$E_r = \varepsilon(r) = \frac{V_{\max}}{r \ln\left(\frac{b}{a}\right)}$$

– where *a* is the radius of the inner anode and *b* is the inner radius of the outer cathode

– *r* is small since the electron are attracted to the cathode and will be at small *r* values

Gas multiplication

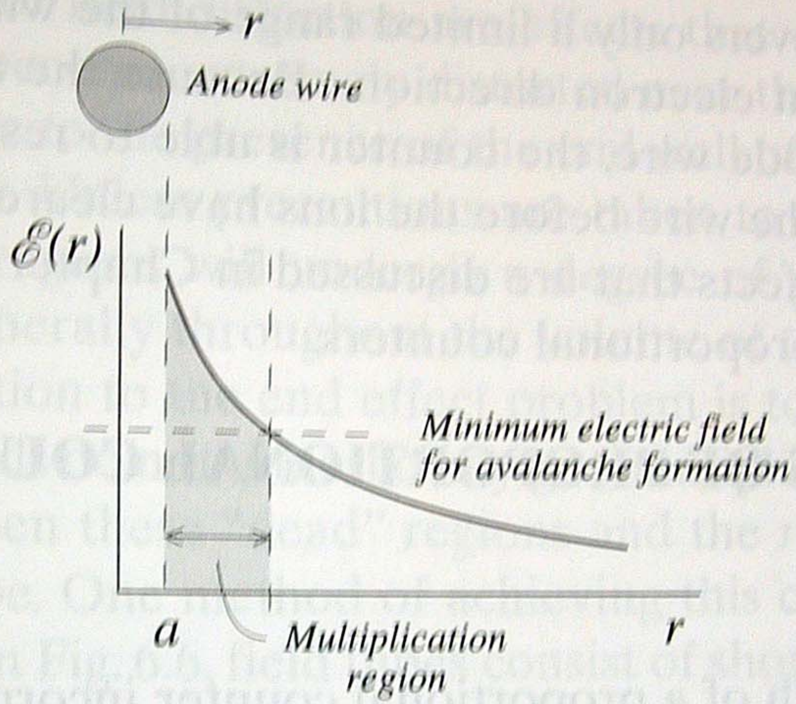

Figure 6.4 The rapid decrease in the electric field strength with distance from the anode wire surface limits the multiplication region to a small volume.

Gas multiplication

- Proportional counters require large E fields and to illustrate $V_{(max)} = 2000$ V, $a = 0.008$ cm, $b = 1.0$ cm, at the anode surface $E = 5.18 \times 10^6$ V/m
- As a comparison with a planar geometry when the *E* field is constant across the active space (1 cm separation) a voltage of 51.8 kV would be required to get the same *E* field.
- The rapid increase in *E* field is practical to reduce the excitation voltage requirements; this also limits the available volume to get a cascade.

Gas multiplication

- The limited volume is also desirable since it keeps the proportionality of the detector. This happens since the avalanche volume is small and the ionization will likely happen outside the avalanche volume and the electrons will then drift into the avalanche zone, removing positional dependence and providing a proportional reaction with the number of ion pairs.
- For an E field of 10^6 V/m , this exceeds the threshold for $r < 0.041$ cm (or about 5X the anode radius) which is only about 0.17 % of the total counter volume.

Gas multiplication

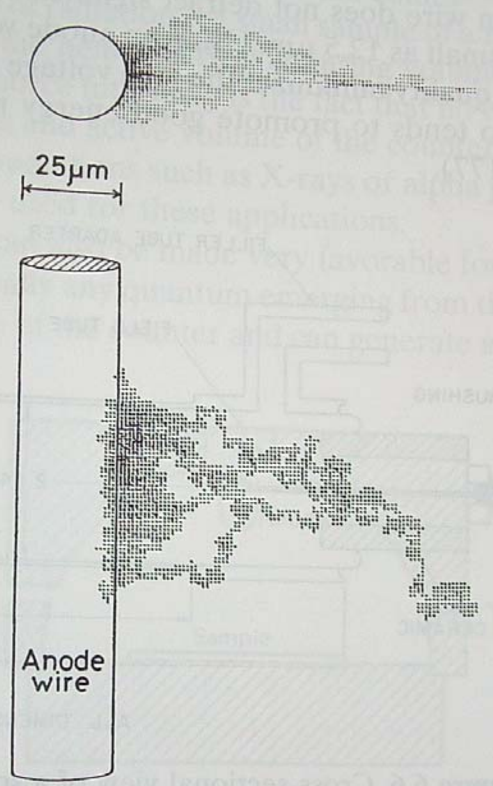

Figure 6.5 Orthogonal views of an avalanche triggered by a single electron as simulated by a Monte Carlo calculation. The density of the shading indicates the concentration of electrons formed in the avalanche. (From Matoba et al.[3])

Design features of proportional counters

Sealed Tubes:

- Fig 6.6 shows a fast neutron detector using a proportional detector design.
- Note the thin anode wire, where the ends are surrounded by a field tube (hypodermic needle fit close to the anode).
- With these designs the *E* field can be skewed where the anode enters the chamber. The field tubes render these regions "dead".

Design features of proportional counters

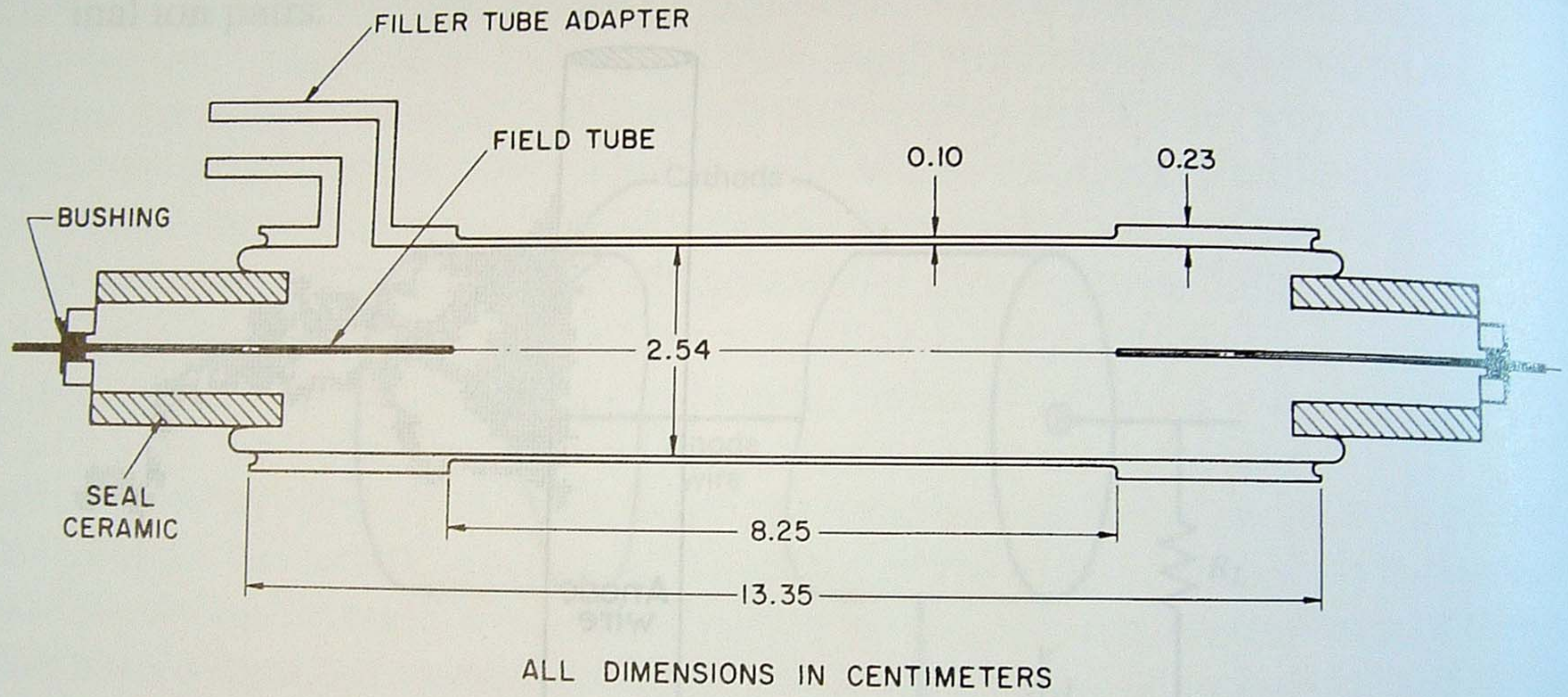

Figure 6.6 Cross-sectional view of a specific proportional tube design used in fast neutron detection. The anode is a 0.025 mm diameter stainless steel wire. The field tubes consist of 0.25 mm diameter hypodermic needles fitted around the anode at either end of the tube. (From Bennett and Yule.[4])

Design features of proportional counters

Windowless Flow Counter:

- Fig 6.7 shows a diagram of a 2π gas flow proportional counter with a loop anode wire and hemispherical chamber.
- Fig 6.9 shows a 4π gas flow proportional counter with 2 anode wires and a sample holder between them.

Design features of proportional counters

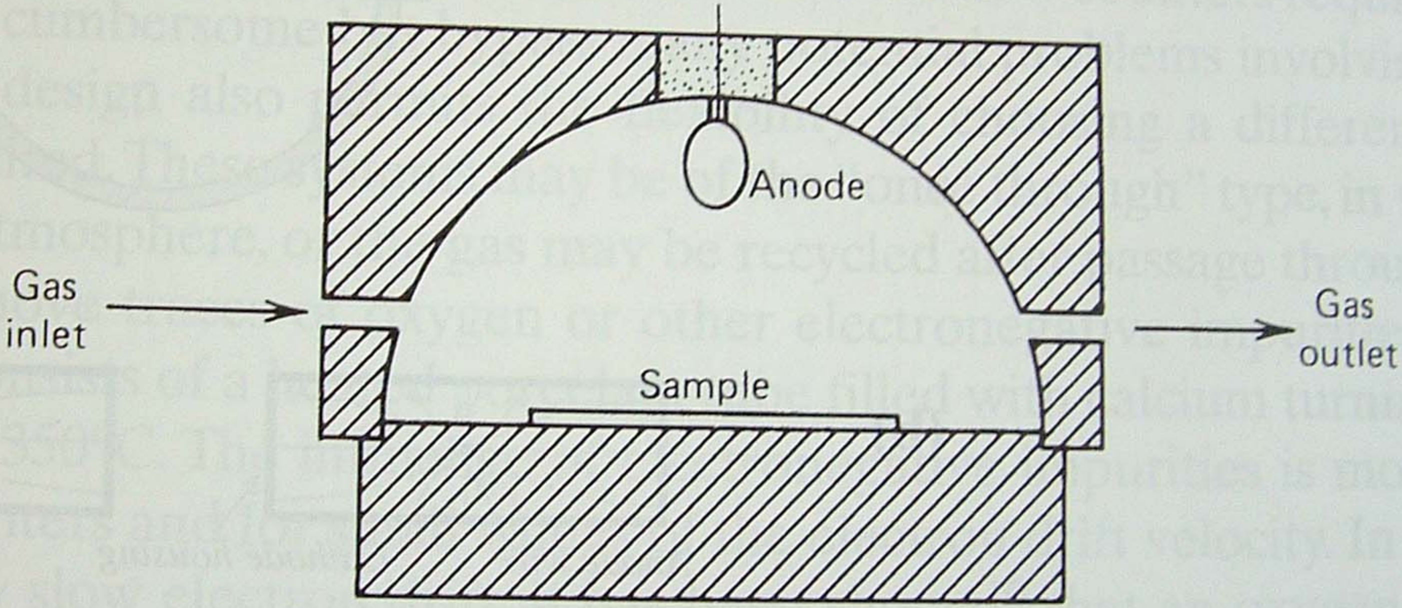

Figure 6.7 Diagram of a 2π gas flow proportional counter with a loop anode wire and hemispherical volume. The sample can often be inserted into the chamber by sliding a tray to minimize the amount of air introduced.

Design features of proportional counters

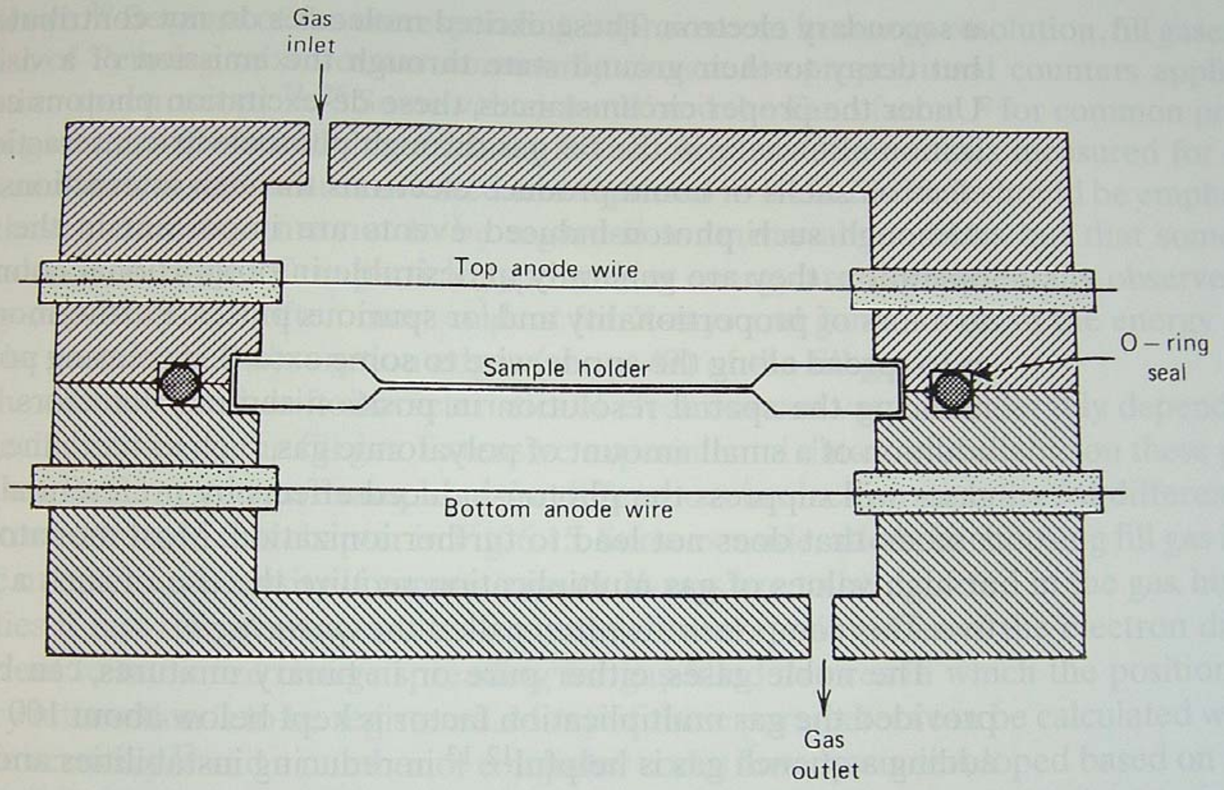

Figure 6.9 A 4π gas flow proportional counter used to detect radiations that emerge from both surfaces of the sample. The top and bottom halves are provided with separate anode wires and can be separated to introduce the sample that is mounted between them.

Design features of proportional counters

- Fig 6.8 shows a pancake proportional counter and the effect of a grid.
- The grid is a helical wire wound around the anode and is held at a voltage intermediate between the anode and cathode. This makes the field more uniform around the anode.
- These detectors have a windowless configuration, useful for measuring α's or soft x-rays, where a window would tend to attenuate these radiation.

Design features of proportional counters

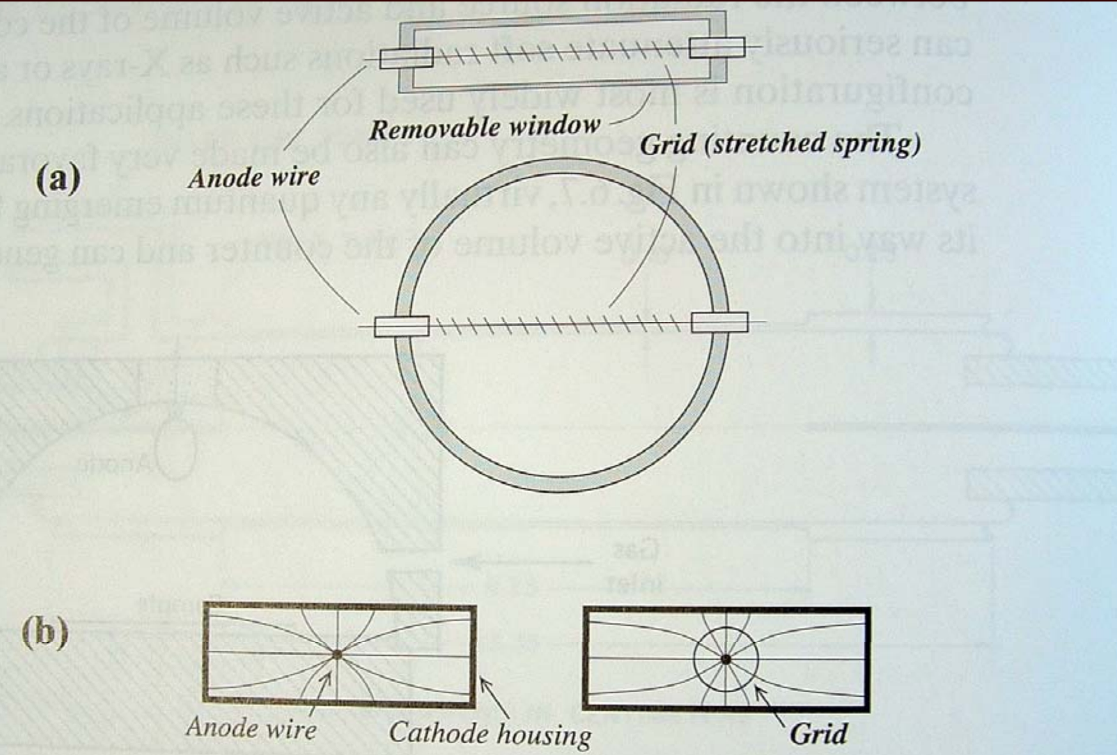

Figure 6.8 In part (*a*), the shape of the "pancake" proportional tube is shown. The effect of the grid on improving the uniformity of the electric field around the anode wire is illustrated in part (*b*).

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Fill gases

- Since gas multiplication is dependent on free electrons, the choice of a gas without an appreciable electron attachment coefficient
- Can use a sealed or flow system, sealed is less cumbersome, but flow can avoid contamination and allows for changing gas is a different fill gas required.

Fill gases

- A small amount of a polyatomic quench gas can capture photons excited from collisions which may liberate electrons from photoelectric interactions.
- Penning effect: by adding a secondary gas to a fill gas with an ionization potential less than that of the principle gas, and specifically one with long lived or metastable excited states in the principle gas.

Fill gases

- The Penning effects manifests as a collision between the metastable excited atom and a neutral atom can ionize the neutral additive atom. Therefore more ion pairs are produced instead of losing energy to photons, which may not result in further ionization.
- An example is adding a small amount of ethylene to argon, reducing W from 26.2 eV to 20.3 eV.

Proportional counter performance

- Assuming no space charge effects (not large enough to distort the electric field, the total charge generated (Q) by n_0 original ion pairs is: $Q = n_0 e M$ where M is the gas multiplication factor.
- Using the Townsend equation with r to denote a radial dependence $dn/n = \alpha dr$ and generally denoting $\alpha=\alpha(r)$ we can calculate M by:

Proportional counter performance

$$\ln M = \int_{a}^{r_c} \alpha(r)\,dr$$

– where r_c is the critical radius or as a function of the electric field (ε)

$$\ln M = \int_{\varepsilon(a)}^{\varepsilon(r_c)} \alpha(\varepsilon) \frac{\partial r}{\partial \varepsilon} d\varepsilon$$

Proportional counter performance

- introducing the variation of ε with r for the cylindrical proportional tubes:

$$\ln M = \frac{V}{\ln\left(b/a\right)} \int_{\varepsilon(a)}^{\varepsilon(r_c)} \frac{\alpha(\varepsilon)}{\varepsilon} \frac{d\varepsilon}{\varepsilon}$$

Proportional counter performance

- if we then assume linearity between α and ε we get:

$$\ln M = \frac{V}{\ln\left(b/a\right)} \frac{\ln 2}{\Delta V}\left(\ln \frac{V}{pa\ln\left(b/a\right)} - \ln K\right)$$

  - where *M* is the gas multiplication factor, *V* is the applied voltage, a is the anode radius, b is the cathode radius and *p* is the gas pressure, and *K* is the maximum value of *ε/P*, and *ΔV* is the potential difference through which an electron moves between ionizing events.

Proportional counter performance

- Both *ΔV* and *K* should be constants for a given fill gas.
- Fig.6.10 is a plot of *M* vs. applied voltage, note the semi log plot and near linearity on the portions of the curves

Proportional counter performance

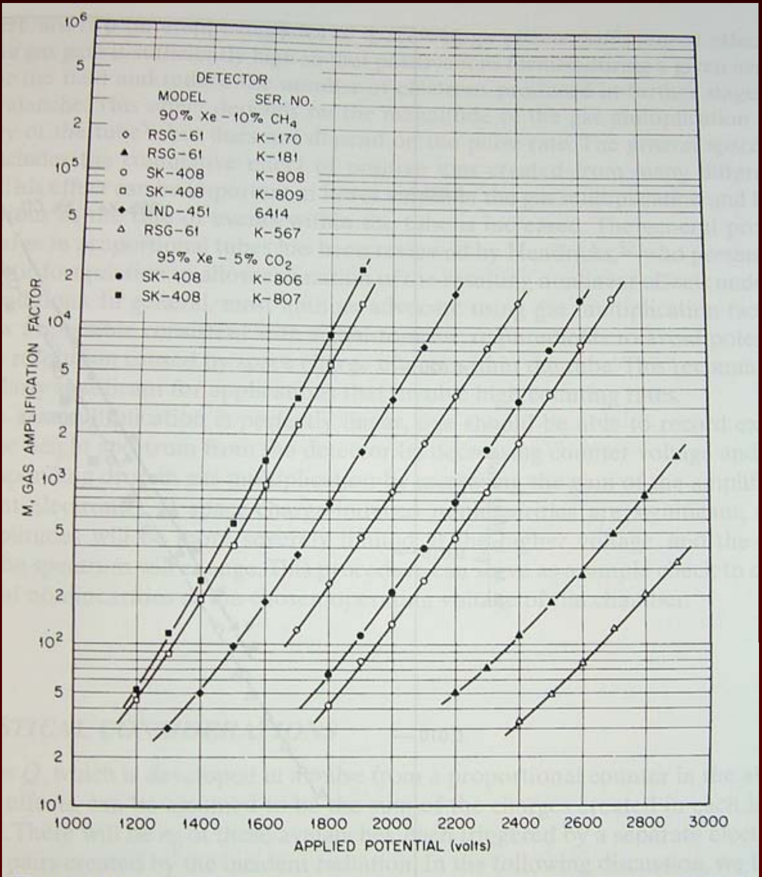

Figure 6.10 Variation of the gas multiplication factor M with voltage applied to various proportional counters. The tubes differ in their physical characteristics, but only the two indicated gases were used. (From Hendricks.[49])

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Proportional counter performance

- Table 6.1 shows several Diethorn parameters (K & ΔV), while Fig 6.11 shows a Diethorn plot where given the linearity and “x” any ”y” values one can determine the Diethorn parameters from slope and intercept.

Proportional counter performance

Table 6.1 Diethorn Parameters for Proportional Gases[a]

Gas Mixture	K (10^4 $V/cm \cdot atm$)	ΔV (V)	Reference
90% Ar, 10% CH_4 (P-10)	4.8	23.6	50
95% Ar, 5% CH_4 (P-5)	4.5	21.8	50
100% CH_4 (methane)	6.9	36.5	50
100% C_3H_8 (propane)	10.0	29.5	50
96% He, 4% isobutane	1.48	27.6	50
75% Ar, 15% Xe, 10% CO_2	5.1	20.2	50
69.4% Ar, 19.9% Xe, 10.7% CH_4	5.45	20.3	50
64.6% Ar, 24.7% Xe, 10.7% CO_2	6.0	18.3	50
90% Xe, 10% CH_4	3.62	33.9	49
95% Xe, 5% CO_2	3.66	31.4	49

[a] See Eq. (6.8).

Proportional counter performance

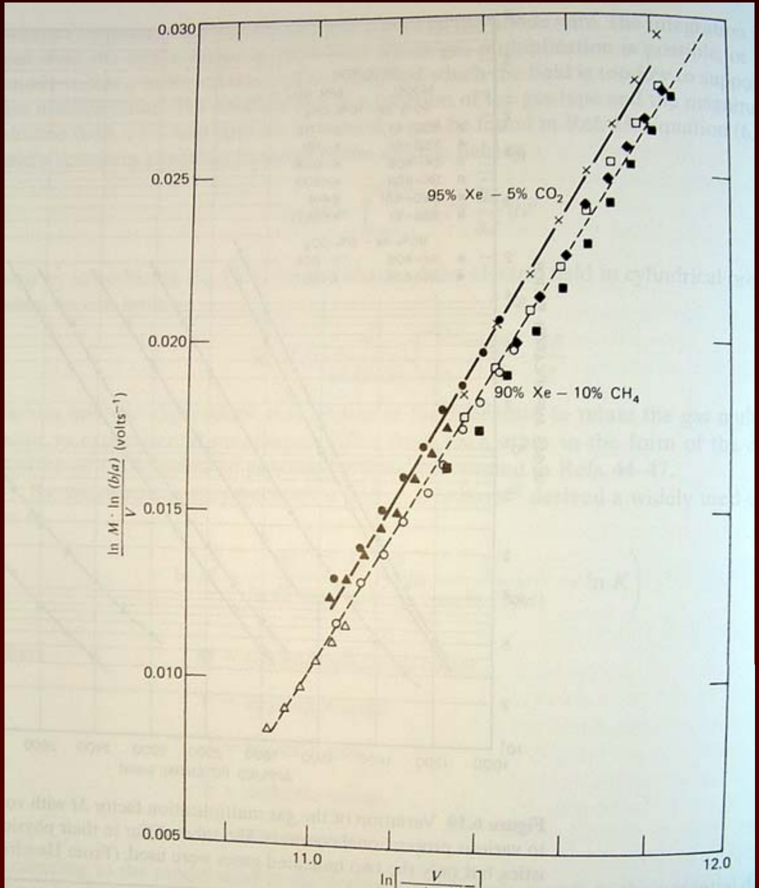

Figure 6.11 A Diethorn plot of the same data shown in Fig. 6.10. As predicted by Eq. (6.8) of [$\ln M \cdot \ln (b/a)/V$)] versus $\ln[V/pa \ln (b/a)]$ for all counters using the same gas closel es a straight line with slope of ($\ln 2/\Delta V$) and intercept $(-\ln 2)(\ln K)/\Delta V$. (From Hendric

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Proportional counter performance

Space charge effect:

- Positive ions, which are preferentially formed near the anode wire (where most of the gas multiplication takes place) reduces the *E* field and the output size.
- Self induced effects stem from the positive ions limiting the avalanche by changing the field during a given avalanche.
- General space charge effects are the buildup positive ions and the cumulative effect that stems from many different avalanches.