Gaseous Detectors

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1. Introduction

a. Radiation Detectors

Radiation: photons, charged particles, neutral particles.

Detection mechanism:

Radiation interaction with matter gives rise to:

- Ionization
- Light emission/conversion

b. Types of Detectors

Based on	Type	Medium	N^o of electrons (photons) freed per cm
Ionizations	Gaseous	Noble gas, Hydrocarbons	Several
	Solid state	Silicon, Germanium	Several
	Silicon microstrips	Silicon, Germanium	Thousands
	Liquid Argon	Liquid noble gases	Several thousands
	Bubble Chambers	Liquid hydrogen	Track of bubbles
Light emission/conv.	Scintillation Counters	glass, plastic	(Hundreds)
	Photo multiplier	cadmium, rare earth	Thousands
	Transition radiation	Thin plastic foils	(Tens)
	Cerenkov Counters	gas, plastic	(Hundreds)

2. Gaseous Detectors

a. Definition:

Where radiation is detected through its interaction with a gaseous medium. A typical gaseous detector consist of a fine wire electrode, the anode, inside a gaseous volume limited by a second extended electrode, the cathode (Fig. 1) When the anode is set to a positive voltage, with respect to the cathode, the intense electric field created around it will cause multiplication of any free electron inside the gas volume.

3. Detection in a Gaseous Medium

The detection process can be described as occurring in four distinctive stages:

Ionization: A charged particle interacts with the atoms of the gaseous substance and leaves a trail of electron-ion pairs, more or less uniform, in its wake. A photon on the other hand will knock out an electron through either the photoelectric effect, or through Compton scattering. The number of electrons released by a photon are rather independent of the thickness of the gas volume.

Drift: Electrons drift towards the anode, ions towards the cathode.

Amplification: High electric field energizes electrons which then start an avalanche process, producing thousands, even millions of others ion-pairs.

Signal Generation: Liberated charges are collected on the anode and cathode, producing electronic pulses in both.

a) Ionization

One can study the passage of an ionizing particle, through a gas volume by means of the following concepts:

i) Mean free path

λ, the ionization mean free path is related to α_λ, the ionization cross section, through

$$\lambda = \frac{1}{N\sigma_\lambda},$$

where N is the number of molecules per unit volume.

The number of encounters n, in a path L, follows Poissons's statistics

$$P(n;\mu) = \frac{\mu^n}{n!}e^{-\mu},$$

where μ is the mean number of occurrences. In our case $\mu = \frac{L}{\lambda}$ and

$$P(n;\frac{L}{\lambda}) = \frac{(l/\lambda)^n}{n!}e^{-\frac{L}{\lambda}}.$$

The probability of zero encounters in a track of length L is

$$P(0;\frac{l}{\lambda}) = e^{-\frac{L}{\lambda}}$$

Thus λ can be determined by measuring $P(0;\frac{L}{\lambda})$ for several values of L.

ii) Primary and Secondary Electrons

A minimum ionizing (min-i) particle interacts with $1/\lambda$ molecules/cm along its path, producing n_p electron-pairs. These electrons are called **primary electrons** and are energetic enough to, in turn, interact with other gas molecules and liberate other electrons, which are then called **secondary electrons**.

The total number of electrons, n_t, produced by the particle is simply $n_t = n_p + n_s$, where n_s is the number of secondary electrons per cm of path.

The number of primary electrons, per cm of track, is with very few exceptions (xenon, for instance)

$$n_p \approx 1.5Z,$$

where Z is the atomic number of the gas. While n_s varies from less than 2 to about 10 and is often around 3 (see Table 1).

iii) Effective ionization energy

A min-i particle looses a certain amount of energy ΔE in traversing the gas medium. A useful parameter for any gas is the effective ionization energy, ω_i, defined by the ratio

$$\omega_i = \frac{\Delta E}{n_t}$$

As can be seen in Table 1, ω_i is about twice as large as the corresponding ionization potential.

Experimentally it is found that ω_i is independent of the initial energy for electrons above a few keV.

The value of ω_i is determined for each gas by measuring the ionization produced by a stopping electron of a given energy.

A min-i particle looses such a small fraction of its energy in a gas layer that this can not be measured as the difference between initial and final energy.

Table 1

Properties of several gases used in proportional counters (from different sources, see the References section). Energy loss and ion pairs (i.p.) per unit length are given at atmospheric pressure for minimum ionizing particles

Gas	Z	A	δ	E_i	I_0	ω_i	dE/dx		n_p	n_t
			$(\frac{g}{cm^3})$	(eV)			$\left(MeV\frac{cm^2}{g}\right)$	$(\frac{keV}{cm})$	$(\frac{i.p.}{cm})$	$(\frac{i.p.}{cm})$
H_2	2	2	8.38×10^{-5}	15.9	15.4	37	4.03	0.34	5.2	9.2
He	2	4	1.66×10^{-4}	24.5	24.6	41	1.94	0.32	5.9	7.8
N_2	14	28	1.17×10^{-3}	16.7	15.5	35	1.68	1.96	(10)	56
O_2	16	32	1.33×10^{-3}	12.8	12.2	31	1.69	2.26	22	73
Ne	10	20.2	8.39×10^{-4}	21.5	21.6	36	1.68	1.41	12	39
Ar	18	39.9	1.66×10^{-3}	15.7	15.8	26	1.47	2.44	29.4	94
Kr	36	83.8	3.49×10^{-3}	13.9	14.0	24	1.32	4.60	(22)	192
Xe	54	131.3	5.49×10^{-3}	12.1	12.1	22	1.23	6.76	44	307
CO_2	22	44	1.86×10^{-3}	13.7	13.7	33	1.62	3.01	(34)	91
CH_4	10	16	6.70×10^{-4}	15.2	13.1	28	2.21	1.48	16	53
C_4H_{10}	34	58	2.42×10^{-3}	10.6	10.8	23	1.86	4.50	(46)	195

iv) Energy Loss

Among the formulas to describe the energy loss by a charged particle, the oldest and best known are the Bethe-Block formula, from which the more useful in our case, the **restricted energy loss rates** can be deduced (see the Particle Properties Data Booklet)

$$-\frac{dE}{dx}|_{E_{max}} = 4\pi N_A {r_e}^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}(ln(\frac{\sqrt{2m_e c^2\beta^2\gamma^2 E_{max}}}{I}) - \frac{\beta^2}{2} - \frac{\delta}{2})$$

where:
m_e and r_e, are the electron mass and classical radius
N_A is Avogadro's number
Z and A are the atomic number and weight
I is the ionization constant
z is the charge of the incoming particle
β,γ, and c, are the usual relativistic parameters
δ is the parameter called 'density effect'

b) Drift

In the absence of electric fields electron-ion pairs recombine and the net liberated charges disappear.

In a uniform electric field the motion of electrons and ions alternate between acceleration and collision with the gas molecules. The resulting motion, in both cases, is a uniform velocity which depends on the intensity of the electric field and the properties of the gases.

$$\mu \propto \varepsilon \quad \textbf{for low field}$$

The ratio $\mu \equiv \left(\frac{\varepsilon}{u}\right)^{-1} = \frac{u}{\varepsilon}$ is a useful parameter and it is called **mobility**.

i) Ion Drift

For high electric fields $u \propto \sqrt{\varepsilon}/p$, where p is the gas pressure, and the ion mobility is around 1 $cm^2V^{-1}s^{-1}$

ii) Electron Drift

Drift velocity increases almost linearly with ε/p, reaches a peak and then remains fairly constant.

iii) Electron Attachment

Small amounts of contamination can produce big effects in a chamber's performance. The main cause is the loss of electrons to **attachment** to the contaminant molecules.

Mechanisms:

Two-Body

$$e^- + M \rightarrow M^- \qquad \leq 1eV$$
$$e^- + M \rightarrow A^- + B \qquad \geq 1eV$$

Three-Body, example:

$$e^- + O_2 \rightarrow O_2^*$$
$$\searrow$$
$$O_2^* + X \rightarrow O_2^- + X$$

The reason some gases, such as oxygen, are good at capturing electrons is that they have low binding energies; it is $\sim 0.5eV$ for oxygen, which is one of the worst impurities to have in a chamber.

c) Amplification or Electron Multiplication

When an electron reaches the region of very high field, $10^4 - 10^5$V/cm, it will multiply at the rate of

$$\frac{dN}{dr} = \alpha N,$$

where α is the number of new electrons produced per cm of path (α is also known as the **First Towsend Coefficient**)

The total number of new electrons produced is

$$N = N_0 e^{\int_{r_{min}}^{a} \alpha dr}$$

and the gain G is then

$$G \equiv \frac{N}{N_0} = e^{\int_{\varepsilon_{min}}^{\varepsilon} \alpha (\frac{dE}{dr})^{-1} d\varepsilon} \tag{1}$$

α is in general a function of ε: $\alpha = \alpha(\varepsilon)$.

i) The Diethorn Formula

A useful expression for the gain was deduced by W. Diethorn. If we assume $\alpha = \beta\varepsilon$ we get, integrating (1)

$$\ln G = \frac{\beta\lambda}{2\pi\varepsilon_0} \ln \frac{\lambda}{2\pi\varepsilon_0 a E_{min}}$$

which, in terms of V will read

$$\frac{\ln G \ln (b/a)}{V} = \beta \ln \frac{V}{\ln (b/a)\ a\varepsilon_{min}}$$

ii) Amplification Regions

For any given detector the characteristic properties of the charge amplification phenomena depend on the electric field intensity in the vicinity of the anode:

Saturation : where the losses through recombination and absorbtion, balance the amplification effect.

Proportional : Where the amplification is constant is constant, and the size of the output pulse is a measure of the number of electron liberated in the gas volume

Streamer : where a very localized discharge is triggered by a few electrons

Geiger-Mueller : where a global discharge involves temporarily most of the anode
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iii) Angular Spread

As the cloud of electrons drift towards the anode wire, it will spread in all directions, due to diffusion and UV emission/absorbtion. for lower values of the amplifying voltage the electron cloud has typically an angular spread, around the anode wire of about 100^o. For the highest voltage it will surround the wire completely.

d) Signal Generation

The signal coming out of the anode wire is caused by the movement of the charges from the avalanches.

The change in electrostatic energy produced by a charge q, that travels between points 1 and 2 in an electric field **E**, reduces the electric energy of the system by the amount

$$\Delta\varepsilon = q\Delta V_{12} = \int_1^2 qEdr$$

This change in energy gives rise to the signal.

The electrons are generated very close to the anode, therefore their contribution to the potential difference is very small. Thus the movement of the positive ions, which have to travel a large distance, away from the anode, is the actual source of the anode signal.

The energy generated as a function of time can be written

$$\Delta\varepsilon = \int_a^{R(t)} qEdr = \frac{q\lambda}{2\pi\varepsilon_0} \ln \frac{R(t)}{a}$$

To find $R(t)$ let's write $dt = \frac{1}{u}dr$ if we now assume $u = \mu E = E_a \frac{a}{r}$ then

$$t = \frac{1}{\mu E_a a}\int_a^R r dr \rightarrow \frac{R(t)}{a} = \left(1 + \frac{2\mu E_a}{a}t\right)^{\frac{1}{2}}$$

and we obtain:

$$\Delta\varepsilon = \frac{q}{2}\frac{\lambda}{2\pi\varepsilon_0}\ln\left(1 + \frac{t}{t_0}\right),$$

$$t_0 \equiv \frac{a}{2\mu E_a}, \quad \textbf{characteristic time} \sim 1nsec$$

or, as a function of V, the anode voltage

$$\Delta\varepsilon = qVF(t), \qquad F(t) \equiv \frac{\ln\left(1 + \frac{t}{a}\right)}{2\ln\frac{b}{a}}$$

Two limiting cases:
Small R_2C_2, R_2C_1 (current source)

$$\Delta\varepsilon = \Delta QV \quad \Rightarrow \quad I(t) = \frac{d\Delta Q}{dt} = q\frac{dF(t)}{dt} = \frac{q}{\ln(b/a)}\frac{1}{(t+a)}$$

Large R_2C_2, R_2C_1:

$$\Delta\varepsilon = q\Delta V \quad \Rightarrow \quad \Delta V(t) = \frac{\Delta\varepsilon}{Q} = \frac{\Delta\varepsilon}{C_1 V} = \frac{q}{C_1}F(t)$$

4. General Characteristic

a) High Voltage Plateau

The performance of a gaseous detector can be readily determined by measuring its high voltage plateau. This is simply a plot of the counting rate vs the anode voltage.

For counters with gas layer larger than a few mm, a flat plateau normally means a fully efficient counter.

A wide plateau is a good indication of a stable detector. From the plateau curve one normally determines the optimum operating conditions for the detector.

b) Gas Mixtures

The operating characteristics of a gaseous detector are highly dependent on the gas mix. One can select it for one or more of the following criteria:

- Stability; low tendency to spurious discharges, small dependency on atmospheric condition.

- good detection efficiency; usually means good amplification.
- drift velocity; could be either slow (e.g. for good position measurement in a drift chamber) or fast, for small dead time.
- non-flammability; for safety.
- low diffusion; for better time and/or space resolution.
- good lifetime; for longer operational life of the detector.
- cost, etc.

i) "Quenching" power

During the amplification process many UV photons are created which can then ionize other regions of the chamber or extract electrons from the cathode surfaces. A gas that can absorb these UV photons is called a quencher gas. Most Hydrocarbons have this property. Ethylic alcohol, as well as other liquids with similar properties, is commonly used (letting the gas bubble through it before reaching the detector chamber) to improve the quenching power of certain gas mixtures.

c) Rate Effects

Right after the charge amplification has occurred, the lingering ion cloud has a shielding effect on the anode: if another particle crosses the detector very near the previous track the probability that it will also be detected gets reduced. This effect limits the rate at which the counter is fully efficient, and is more noticeable the larger the distance between the anode and cathode. The lowest rates are a characteristic of Geiger-counters (1KHz/cm), while the highest rates can be achieved with gas microstrip chambers ($\gg$ 1 MHz/cm)

d) Lifetime

Detectors exposed to high levels of radiation show a decrease in gain, which could translate into detection inefficiency. This is due to deposits of polymerized substances on the anode or cathode surfaces.

Even with great deal of care most wire chambers will start showing ageing effects after about 1 $Coulomb$ of charge deposited in $1cm$ of wire.

Extensive amount of research have been done on the causes of chamber ageing, and most cases can be traced to the presence of inappropriate materials in the chamber construction or in the gas system.

5. Description of most Common Detectors

a) Geiger-Mueller Counters

The oldest and simplest gaseous detector which demonstrated the basic detection mechanism in all existing wire chambers, namely that a thin wire held at a large positive voltage can produce multiplication of any free electron in the gas volume. It is still the most widely used in common applications in medicine, x-rays, survey meters, etc. It consists of a gas tight metallic cylinder, with a thin wire along its axis insulated from the the cylinder. This same configuration with the wire at somewhat lower voltage will operate as a simple cylindricaL proportional counter.

b) Multiwire Proportional Chambers (MWPC's)

This is an extension of the cylindrical proportional counter idea: to arrange many thin wires parallel to each other and in the same plane. When the wires are set to high voltage each one of them acts as a proportional counter, and the position of the wire that gets hit will help us to determine the trajectory of the detected radiation. Space resolution of better than 1 mm can be readily achieved. This is still widely used in nuclear and high energy experiments experiments.

c) Drift chambers

The fact that the liberated electrons take some time to drift towards the anode wire is used in these devices to determine the position of the ionizing track. With a favorable geometry and timing resolutions of the order of nanoseconds, one can achieve space resolutions under 50 μm, even with wire spacing as large as several centimeters. Thus they are the preferred detectors when good space resolution and large coverage are needed.

d) Streamer Tubes

Sturdy and lowest cost for large areas. Operate in a region of gas amplification lower than a Geiger counter but about 10 times larger than the proportional chambers. Their main distinctive features are:

- each wire is surrounded by plastic walls covered with a conductive paint.
- the streamer mode operation allows for easy extraction of the signal from induction strips or pads through the use of inexpensive electronic readout system.
- design suitable for low cost, large scale production.

e) Parallel Plate chambers

An example of a gaseous detector without anode wires. The electric field is created by two flat electrodes with extremely high surface resistivity; the gap between the two planes is about $1mm$ and need about 10KV of potential difference to efficiently detect most radiations. Its unique advantage lies in its fast response: timing resolution better than 1 $nsec$ can be achieved.

f) Induction Pad chambers

An extension of the MWPC's, brought about mainly by the advances in microelectronics. Very similar in operation to the streamer tubes except that here the anode voltages are lower. It achieves position resolution of $\sim 50mum$ by weighting the signals from several adjacent strips.

g) Microstrip Gas Detector

Highest rate capability ($10^6 p/mm^2$) and highest granularity ($0.1mm$ anode spacing). Thin anodes and wider cathode strips are deposited through photolithographic methods on a insulating substrate (glass or plastic); another cathode plane is located a few mm above and parallel to the substrate, delimiting the gas volume.

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