

Ionization Chambers

The ionization process in gases

- The ionization chamber has come to mean, exclusively, the type of detector in which ion pairs are collected from gases.
- After a neutral atom is ionized, the resulting positive ion and free electron are called an ion pair.
- Practically we use the number of ion pairs created along a track of radiation, note table 5.1 shows various values for several gases.
- W value is the average energy absorbed per ion pair, which accounts for several processes of differing energies (~ 10 eV for weakest bound e^- and processes which don't produce an ion pair).

Fano Factor:

- If we assume the foundation of ion pairs is a Poisson process, the number of fluctuations associated with the number of ion pairs formed should go as the square root of the average number of pairs formed.
- The fano factor is an empirical constant one must multiply by the predicted variance to obtain the experimentally observed variance.
- In gases the fano factor is observed to be <1 so that the fluctuations are smaller than what would be predicted by the Poisson distribution.
- The significance of the fano factor is only in pulse mode operation, since an ionization chamber is generally run in current mode, we postpone this discussion until proportional counters, where energy resolution and pulse mode operation are more important factors.

Diffusion, Charge Transfer, and Recombination:

- Ions have a tendency to diffuse away from areas of high density through random thermal motion, which is more pronounced in free e^- 's since their average thermal velocity is much greater.
- A point-like collection of free electrons will spread out into a Gaussian spatial distribution where $\sigma = \sqrt{2Dt}$, where t is the elapsed time and D the diffusion constant predicted from kinetic gas theory.
- Several charge transfer collisions (Fig. 5.1) can also occur after ionization:
 - Charge transfer- the positive ion interacts with a neutral atom transferring the positive charge.
 - electron attachment - the electron attaches to a neutral atom and forms a negative ion (Oxygen)

- Recombination - an electron interacts with a positive ion and produces a neutral atom or a positive and a negative ion interact to form two neutral atoms.
- Since the collision frequency is proportional to the product of the concentration of the 2 species involved the recombination rate can be written as:

$$\frac{dn^+}{dt} = \frac{dn^-}{dt} = \alpha n^+ n^-$$

Where $n^{+(-)}$ is the number density of the positive (negative) species and α is the recombination coefficient.

- There are two types of recombination loss, columnar or initial and volume.
- Columnar is highest along the high density of ion pairs formed along the initial track and is worse for highly ionizing particles (α).
- Columnar is only based on local conditions and not on the rate of which the tracks are formed.
- Volume is recombination after the ions have diffused away from the initial track and increases with importance with irradiation rate.

Charge Migration and Collection

- The drift velocity of ions in a gas can be accurately (fairly) predicted by $v = \mu E / p$, where μ is the mobility, E the electric field strength, and p the gas pressure.
- μ tends to remain fairly constant over wide ranges of p , E and charge sign of the ion. Typical values are between 1 and $1.5 \times 10^{-4} \text{ m}^2 \text{ atm} / (\text{V} \cdot \text{s})$ for detector gases of medium atomic number.
- A typical ion transit time for $E = 10^4 \text{ V/m}$ at 1 atm is 10 ms.
- Free electrons are lighter than ions so μ tends to be ~ 1000 time greater pushing typical collection time to μs .
- For free electrons, in some cases e^- may reach a saturation effect (reduction of drift velocity with increasing E strength) and with increasing E field there may result an anisotropy in D between the parallel and perpendicular direction with respect to the electric field direction. Such diffusion will result in a spread in position when reaching the collecting electrode.

The Ionization Current:

- In the presence of an electric field the drift of ions or e^- constitutes a current.
- Under the conditions where recombination is negligible and the ions are collected efficiently, the steady state current is an accurate measure of the rate at which ion pairs are formed in the volume.
- Measurement of this current is the basis for a DC ion chamber (schematic seen in Fig. 5.3).

- Increasing the voltage (electric field strength) will increase the current of the system, and at low voltages the ion pairs will undergo recombination of diffusion.
- Once a high enough voltage is reached, all the ion pairs are collected and no increase in current is observed. This is the ion saturation region and the current is then an accurate representation of the rate of ion pairs formed. This is conventionally the region ionization meters are run in.

Factors Affecting the Saturation Current:

- Recombination (minimized when a large enough electric field is everywhere in the chamber).
- Chambers run with ambient air as the gas will also be affected by moisture in the air (humidity).
- As the positive charges drift to the cathode negative charges toward the anode, the increase in density and the electrodes will produce a diffusion gradient (away from the electrode and opposite the applied electric field) and produces a perturbation in the ionization current given by:

$$-\frac{\Delta I}{I} = \frac{\varepsilon k T}{e V}$$

Where ε is the ratio of the average energy of the charge carrier with the E field present to that without the E field present, k is the Boltzman constant, T is temperature, e is the electron charge, and V is the applied voltage between the electrodes.

- A plot of the $1/I$ vs. $1/V$ can be used to extrapolate the true saturation current of a chamber by determining a value for infinite applied voltage (0 on the $1/V$ axis).

Design and Operation of DC Chambers

General Considerations:

- One can modify many parameters to suit ones needs including fill gas, geometry, applied voltage, and recombination effects of the intended radiation and gas.

Insulators and Guard Rings:

- Due to the small values of ionization current, leakage current must be smaller.
- A guard ring is designed to be at the same potential as the central electrode, to minimize the leakage current.
- Any leakage through the insulator is returned to the voltage source without going through the current meter (ammeter).
- Thus only ionization current passes through the ammeter and the leakage current does not affect the measurement.

- In practice the current is measured indirectly by an electrometer, which measures the voltage across a series resistor V_R (Fig. 5.6).
- The chamber capacitance and any stray line or current capacitance is represented by C . if the ion current remains constant over several measurement time constants (RC) the steady state value of $I = V_R/R$.
- One can also get more stable amplification of the signal by using a dynamic capacitor or vibrating reed electrometer seen in Fig. 5.7.
- The V oscillations across the RC circuit are then measured (assuming a long RC time constant) and proportional to the steady-state signal current I_{ss} .
- At equilibrium: $V=I_{ss}R$ and the charge stored in the capacitor is $Q=VC$.
- We now allow the capacitance to change rapidly with the time constant, the corresponding change in V across C is given by:

$$\Delta V = \frac{Q}{C^2} \Delta C = I_{ss} \frac{R}{C} \Delta C$$

- If C is varied sinusoid ally about an average value C ($\Delta C = \sin(\omega t)$) then the amplitude of the AC voltage is proportional to I_{ss} .
- If we make $R = \infty$ (Fig. 5.6) any ionization current from the chamber is integrated across the capacitance C . the total voltage across C is a measure of the integrated ionization current or total charges created.

Electret:

- This is a piece of dielectric material with a charge “frozen” in place. (One heats the material, applies an electric field, i.e. 1000 V, then cools the piece). One might use Teflon of 1 cm. diameter by 1 mm. thick disk.
- The electret is then placed in contact with the outer electrode of the chamber, producing an electric field in the chamber.
- By measuring the voltage change on the electret before and after measurement, the electret can be calibrated in terms of the ionization change produced in the chamber.
- Electrets (with proper encapsulation) can be stable for over a year or more, even in the presence of high humidity.