IONIZATION CHAMBERS

An ionization chamber is a device comprising a defined volume of gas containing electrodes which facilitate the collection and detection of free electrons and ions produced by the passage of ionizing radiation through the gas.

A voltage is applied between the electrodes to produce an electric field in the gas volume. When ionization occurs, the freed electrons and the ions drift, respectively, to the anode and the cathode. The term "ionization chamber" is used only for those chambers where the electric field is weak enough throughout the volume so that the electrons (and ions) do not attain sufficient energy between collisions to cause secondary ionization. This condition is met typically with field gradients less than 10^6 V/m. When the field is stronger and secondary ionization is used to amplify the ion current, the device is called a *proportional counter*. When the field is so strong that the initial ionization triggers an ionization avalanche, the device is a Geiger counter, and the amplitude of the output current pulse is more or less independent of the number of ions in the initial ionization event.

If the anode and cathode are well insulated from each other, and the ionization chamber is isolated from any external circuit, it is, in effect, a capacitor with a gas dielectric. It can be charged to a preset voltage and then disconnected from the charging circuit. As ions are collected, the voltage is reduced by an amount $V = Q/C$, where Q is the collected charge and C is the capacitance.

When an ionization chamber is attached to an external circuit, the collected electrons and ions cause a current to flow in the circuit. This may be a continuous current or a pulse depending on the time distribution of the incident radiation relative to the collection time of the ions. Typically the electrode configuration is either (a) cylindrical, with a center wire anode and a coaxial cathode, or (b) a set of parallel plates. Other geometries are possible. Multiwire configurations with parallel anode wires strung between cathode plates, or alternating anode and cathode wires, are often used for charged-particle detection, but these configurations are used with gas multiplication, so they are classed as multiwire proportional counters.

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

USES

Ionization chambers are most commonly used in radiation dosimeters and in portable radiation survey meters (see Fig. 1). They are also used as fixed radiation monitors where they can be adapted to use with various kinds of radiation.

An isolated ionization chamber is particularly useful for measuring time-integrated radiation dosage. The device is simple and can be made quite small. Such chambers are used for monitoring the radiation dosage of personnel working in radiation areas. A typical pocket dosimeter is a cylindrical ionization chamber, about the size of a thick pen, with air between the anode wire and the coaxial cathode. The device is charged to a preset voltage before the worker enters the radiation area. After the possible radiation exposure the voltage is read on an electrometer. The reduction of voltage is proportional to the number of ion pairs created in the gas volume by the well-known equation for a capacitor, $V_i - V_f = Q/C$, where Q is the total charge collected from the ionization and C is the capacitance of the chamber. For a given type of radiation the collected charge is proportional to the radiation dose, and the device can be readily calibrated by exposure to standard radiation sources. Some pocket dosimeters have built-in electrometers that can be viewed by looking into one end.

Ionization chambers are also commonly used in radiation survey meters to measure radiation dose rate. This application requires an external electronic circuit to measure and indicate on a meter the current from the chamber. For a given type of radiation the current is proportional to the dose rate. A virtue of an ionization chamber compared with a proportional counter or a Geiger counter is that the current is insensitive to the applied voltage. Thus, it is a simple and stable device.

Ionization chambers can also be used for detection of individual charged particles. In this case the collection of the ionization from the particle traversal of the chamber causes a current pulse in the electronic circuit. As long as the average time between particle traversals is longer than the collection time of the ionization, the output will appear as current pulses. For this purpose it is more common to use proportional counters or Geiger counters because the pulses are much larger.

IONIZING RADIATION

The physical process that makes ionization chambers work is the ionization of gases by radiation. Different forms of radiation cause ionization though different mechanisms.

Ionization by Charged Particles

Charged particles (e.g., electrons, protons, and ionized atoms) lose energy mainly by scattering from electrons in the gas, causing excitation or ionization of the atoms. The interaction is through the Coulomb force, which is long range, so scattering can occur even when the charged particle is far outside the nominal radius of the atom. The theory of energy loss of charged particles in matter is a complicated subject in its own right. For the purpose of understanding the performance of ionization chambers it is necessary only to have some grasp of the magnitude of the rate of energy loss and how it depends on the particle type, the particle energy, and the kind of gas. An approximate formula due to Bethe for the rate of energy loss, also called *stopping power,* is

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{mv^2} NZ \ln \frac{1.123\, mv^3}{ze^2\omega}$$

where m, z, and v are the mass, charge, and velocity of the ionizing particle. Z and N are the atomic number and the number of atoms per unit volume of the material that is being ionized. ω is a constant characteristic of the atoms being ionized. A more complete formula, the Bethe–Bloch formula, can be found in many physics textbooks.

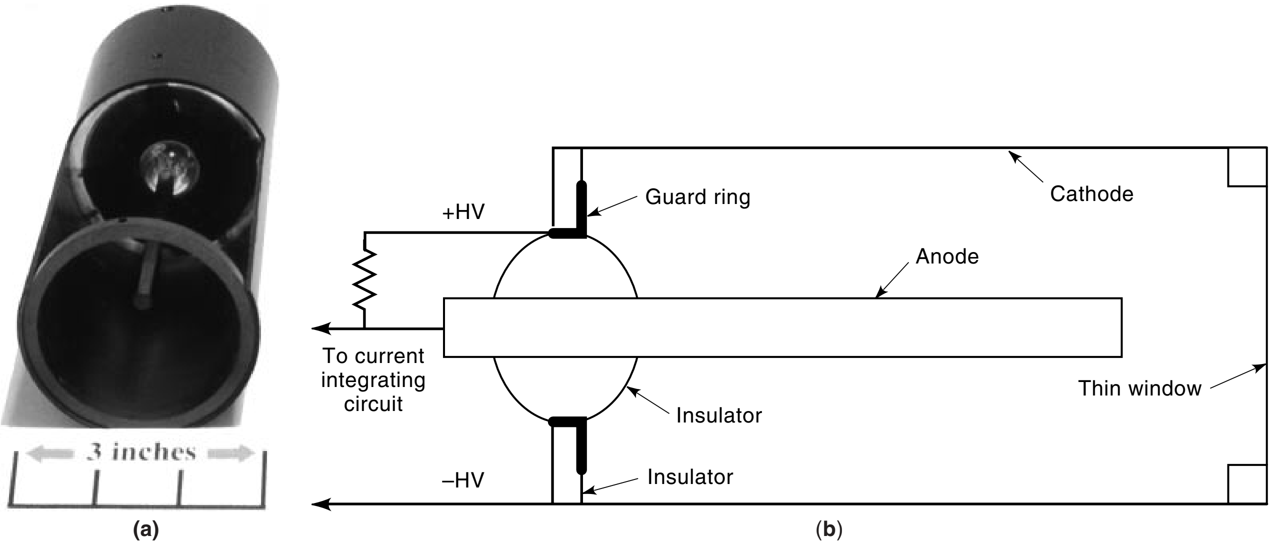

Figure 1. Photograph (a) and sketch (b) of an ionization chamber used in a portable radiation survey meter. Part of the cathode cylinder has been cut away and the thin end window has been removed to show the interior. The cathode is a thin, conductive, carbon film deposited on the inside of a rigid plastic cylinder. (Photograph by C. C. Foster.)

An important characteristic of stopping power is that as a particle loses energy, its rate of energy loss increases and reaches a maximum just before the particle stops. The increase is quite sharp at low energy, creating the so-called Bragg peak. This is illustrated in Fig. 2 for protons and for alpha particles in neon gas. It is obvious, therefore, that the number of ion pairs produced in a chamber depends on the particle energy and the particle type, and it will be largest if the particle stops in the chamber. For particle kinetic energies considerably above the particle rest energy the rate of energy loss goes through a minimum, and at higher energies it is nearly independent of the particle energy. Cosmic ray muons are minimum ionizing particles and constitute the major background radiation in environments away from artificial radiation sources.

Ionization by Electromagnetic Radiation (photons)

An atom or molecule can be excited by absorbing or scattering a quantum (photon) of electromagnetic radiation. However, unless the photon can impart at least as much energy as the binding energy of the least bound electron in an atom, ionization will not occur. The energy of a photon is given by the Planck relationship $E = h\nu = hc/\lambda$, where h is Planck's constant, ν is the frequency, c is the velocity of light, and λ is the wavelength.

The photons of radio waves and even of visible light are not energetic enough to ionize a gas. To get some feeling of the energies involved, the energy of a 1 GHz radio wave photon is 4 μeV. The energy of a 460 nm photon (blue light) is 2.7 eV, but the energy required to ionize a nitrogen gas molecule is 15.5 eV. Thus, radio waves and visible light are not ionizing radiation, and ionization chambers are not suitable for detecting them. X rays and gamma rays are, however, ionizing. The ionization may occur through one of three processes: the photoelectric effect, Compton scattering, or pair production. The dominant process depends on the energy of the photon. The electrons produced in the primary ionization event then lose their kinetic energy through ionization of the gas in the chamber. Thus the total number of ions produced by the traversal of an X ray or gamma ray depends in a complicated way on the energy of the photon.

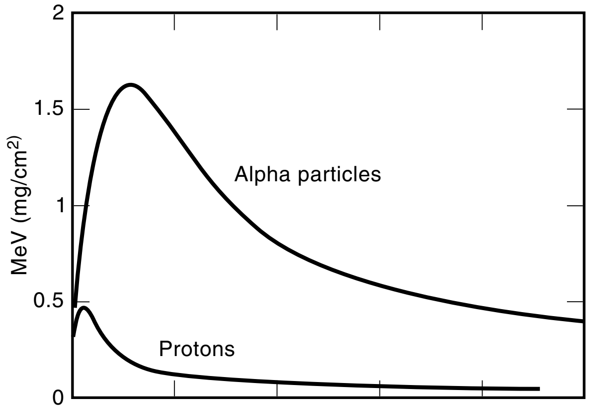

Figure 2. Rate of energy loss versus particle energy for protons and alpha particles. Data from Ref. 1.

The photoelectric effect is the dominant ionization process for X rays and dominates for photon energies less than about 0.1 MeV. In this process a photon is absorbed by the atom and an electron is emitted, leaving a positive ion behind. The excess energy above that required to remove the electron from the atom appears as kinetic energy of the electron.

For somewhat higher energies up to about several MeV the dominant ionization process is the Compton effect. In this process, the photon scatters from a bound electron and imparts sufficient energy kinematically to free the electron. The scattered photon, since it has lost energy, emerges with a lower frequency or longer wavelength. The energy imparted to the electron depends on the angle of scattering, which is random. The scattering obeys the laws of conservation of energy and momentum, where, in the kinematical equations, the momentum of the photon is $h\nu/c$.

For yet-higher energies the dominant process is pair production in which the photon is absorbed on an atom and an electron–positron pair is produced. This obviously requires a photon of energy greater than the rest mass of the electron–positron pair (1.022 MeV).

In considering the response of an ionization chamber to photons, at the design stage one should note that a primary ionization event is more likely to occur in the dense walls of the chamber than in the low-density gas. However, this is not likely to be a practical problem, since calibration will be done with the complete chamber.

Response to Neutrons

Neutrons, being electrically neutral, do not directly produce ionization. Nevertheless, ionization chambers are useful for dose measurements of slow neutrons. For this purpose a gas containing a nucleus with a very large cross section for absorbing thermal neutrons is introduced into the chamber. Boron trifluoride (BF_3), which serves both as the chamber gas and as the reaction target, is commonly used for this purpose. The nuclear reaction that takes place is $^{10}B(n,\alpha)^{7}Li$. The alpha particle and ^{7}Li ion produce the ionization in the gas. Boron trifluoride chambers can be used for broad-spectrum neutron dose monitors. In this case, the chamber is surrounded with plastic or another material rich in hydrogen to moderate the neutrons down to thermal energy where the $^{10}B(n, \alpha)$ reaction will take place. Another useful reaction for thermal neutron dosimetry in a gas counter is $^{3}He(n,p)^{3}H$.

High-energy neutrons can produce nuclear reactions in any material, but high-energy neutron detection is generally done with liquid or solid organic scintillators rather than gas counters. Here the neutron scatters from a proton in the scintillation material. Through the same mechanism a hydrogen-filled gas counter will respond to high-energy neutrons, but, because of the low density of the gas the detection efficiency is extremely small.

FURTHER CONSIDERATIONS

Guard Rings

In parallel plate chambers, guard rings may be used to define the volume from which electrons are collected and/or to minimize leakage current. For example, in a circular chamber, the guard ring would be a flat metal ring of slightly larger diameter than the anode (collector) placed around the anode. This is set to an electrical potential approximately equal to the anode potential. This extends the uniform electric field region outside the area of the anode so that edge effects are eliminated. Since the anode is insulated from the guard ring, a guard ring is also useful for minimizing the electric field across the anode insulator, thus reducing possible leakage current.

Drift Velocity

The electrons in the gas will gain energy as they are accelerated by the electric field and lose energy through collisions with gas molecules. In this process of gaining and losing energy they will acquire an average drift velocity that depends on the ratio of electric field strength to gas pressure. Very roughly, for nitrogen at atmospheric pressure, a voltage gradient of 10^4 V/m results in an electron velocity of about 10^3 m/s. The positive ions travel roughly a thousand times slower.

Gridded Chambers

Because of the finite drift time of the electrons, the pulse shape from a chamber operated in the pulse mode depends on the position and orientation of the particle track. In the early days of ionization chambers, considerable attention was given to introducing grids at some potential between the anode and cathode. This divided the chamber into two parts. The primary ionization event would take place in the region between the grid and the cathode, and the electrons would drift through the grid and then always fall through the same potential difference to produce the pulse. This particular problem seems to be of little concern now, since essentially all particle detection applications use proportional counters. In fact, the drift time is often measured and exploited in multiwire drift chambers to determine the position of particle tracks between wires. A gridded chamber may, however, be useful for measuring drift times. Reference 2 shows such an application and also shows that it is possible to construct an ionization chamber with a liquid dielectric.

Recombination and Attachment

Two processes that can cause loss of electrons are recombination and attachment. If an electron encounters a positive ion on its path toward the anode, it may recombine and is thus lost. This is an unlikely process unless the density of ions is large. A situation in which this process might be of some significance is if the particle tracks are densely ionizing and parallel to the electric field. Attachment cross sections are very small for most gases, and this process is usually not important. However, oxygen has an appreciable attachment cross section and this effect should be considered in a chamber containing oxygen.

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2. E. Shibamura, A. Hitachi, T. Doke, T. Takahashi, S. Kubota, and M. Miyajima, Drift velocities of electrons, saturation characteristics of ionization and *W*-values for conversion electrons in liquid argon, liquid argon–gas mixtures and liquid xenon, *Nucl. Instrum. Methods,* **131**, 249–258, 1975.

Reading List

The classical texts on ionization chambers are: B. B. Rossi and H. H. Staub, *Ionization Chambers and Counters,* New York: McGraw-Hill, 1949; and D. H. Wilkinson, *Ionization Chambers and Counters,* Cambridge: Cambridge University Press, 1950. These books are quite old but contain much detailed information. A new reference intended for physics students that discusses ionization chambers, proportional counters, multiwire chambers, and drift chambers is W. R. Leo, *Techniques for Nuclear and Particle Physics Experiments,* Berlin: Springer-Verlag, 1994. Tables of ionization potentials of various gases can be found in the *CRC Handbook of Chemistry and Physics,* 75th ed., Boca Raton, FL: CRC Press.

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IONIZATION, ELECTRON IMPACT. See ELECTRON IMPACT IONIZATION.

IONIZATION RADIATION DAMAGE TO SEMICONDUCTORS. See RADIATION EFFECTS.

IONIZING RADIATION DETECTORS. See RADIATION DETECTION.

IONOSPHERE. See ELECTROMAGNETIC WAVES IN THE IONOSPHERE.

IONOSPHERE ELECTROMAGNETIC WAVES. See ELECTROMAGNETIC WAVES IN THE IONOSPHERE.

IONOSPHERIC RADIO PROPAGATION. See SKY WAVE PROPAGATION AT MEDIUM AND HIGH FREQUENCIES.

ION-SELECTIVE ELECTRODES. See ELECTROCHEMICAL ELECTRODES.

IRON-SILICON. See SOFT MAGNETIC MATERIALS.

IRRADIATION MEASUREMENT. See RADIOMETRY.