Appendix A: Gas Detector Operation

All detectors which use gas as their working media for the detection of ionizing particles take advantage of the fact that the electromagnetic interaction cross-sections involved in the process are quite large: on the order of megabarns. Gas detectors such as those used in the CE-06 experiment exploit the correspondingly high probability of such interactions to achieve the detection of heavily-ionizing particles with 100% intrinsic efficiency. This appendix describes the operating principles of gas detectors in general (full details are given in [Sa77]) along with specific characteristics of the highly efficient low-pressure detectors.

A.1 General Principles

For energetic, charged particles[1] incident upon a gas volume (or material in any state of matter), the dominant energy loss mechanism is via inelastic collisions with atomic electrons. Here, "inelastic" refers to the fact that in such a process, an atom or molecule may become excited or ionized. Typical ionization energies for commonly used gases are approximately 10 eV, but the *average* energy loss needed to produce one electron-ion pair is about 30 eV, due to the fact that molecular or atomic excitation is much less likely to produce a free electron. Therefore, on the average, a particle losing energy E in the gas volume produces $N_{\text{pair}} \propto E\,[\text{eV}]/30$ electron-ion pairs. A detector such as the PC used in the CE-06 experiment "counts" the number of pairs produced, following which the ionizing particle's energy can be reconstructed. The average ionization potential of 30 eV is the inherent limiting factor in the energy resolution of such a detector.

The transport of electron-ion pairs through the gaseous medium is the active rôle played by the detector, thus the consideration of this mechanism heavily influences the design and operating parameters. Without an externally applied electric field, both the

[1] This discussion is limited to particles and ions with $m \gtrsim m_\mu$ and heavier.

ions and electrons produced by the incident radiation quickly lose their extra energy and attain equilibrium via repeated collisions with other gas molecules. Using classical "billiard ball" arguments, the mean free path for ions or electrons in the gas at pressure P and temperature T can be written

$$\lambda \propto \frac{kT}{P}. \tag{A.1}$$

Typical values for ions in gases at NTP are roughly 0.1 μm, with somewhat larger paths for the negligibly sized electrons. With thermal velocities of $v_{\text{ion}} \approx 500\,\mu\text{m}/\mu\text{sec}$ and $v_{\text{e}^-} \approx 200 \cdot v_{\text{ion}} \approx 100$ mm/μsec (the factor of 200 due to the electron-ion mass difference), thermal equilibrium occurs on the time scale of less than one nanosecond.

At this point, the electrons and ions begin to diffuse and recombine, the latter occurring typically in a few hundred nanoseconds. The ions may recombine with the ionization product electrons, or pick up electrons from other gas molecules, which themselves recombine later. In either case, the signature of the ionization event is soon lost.

A gas detector overcomes the thermal recombination by application of an electric field to the working gas volume, which produces a phenomenon known as *drift*. The thermal motion of the ions and electrons is random and thus favors no particular direction, but an electric field breaks the symmetry and causes the average velocities of the ions and electrons along a particular direction to be non-zero. A drift velocity is attained rather than a "drift acceleration" due to the frequent collisions with gas molecules, which tend to restore the ions and electrons to their (random) thermal motions.

The drift behavior of ions and electrons is quite different, however. For ions, $v_{\text{drift}} \approx 10\ \mu\text{m}/\mu\text{sec}$, which is much smaller than thermal velocities, so that the application of the field doesn't significantly change the velocity magnitude, kinetic energy, diffusion, or recombination of the ions. For electrons, however, the drift velocity can become comparable to thermal velocities. For example, at typical field values of 1 kV/cm, the electron drift velocities can range from 20 to 150 mm/μsec, depending on the particular working gas. As such, it is possible to modify the electron transport significantly, and collection of the electrons, upon which the proper operation of most gas detectors depends, can occur before recombination takes place.

Even with an external field, however, an electron can also be absorbed by electronegative molecules. These are neutral molecules with atoms that have almost-full electron shells and which tend to be more stable as negative ions. After absorbing an electron, they may in turn finally recombine with a positive ion! The presence of these gases (for

example, water vapor) can severely limit detector performance.

The current resulting from the collection of all the electrons generated in the ionization event is still extremely small; most detectors rely on electron "multiplication." This increase in the number of free electrons is accomplished via the strong electric field surrounding a biased, thin wire (the anode): As the average electron energy increases through acceleration toward the anode, inelastic collisions with molecules (producing excitations or ionizations) become more likely. Energetic atomic decay photons can cause secondary ionization and excitation by interaction with the metallic components of the detector. The net effect is an avalanche: the number of electrons increases exponentially as the drift continues toward the anode. Noble gases such as argon produce larger multiplication factors since there are no radiationless molecular excitations to "absorb" electron energies. Furthermore, the relatively large excitation energies in noble gases generate decay photons that can easily produce more electrons from the cathode metal. In contrast, polyatomic gases often have many vibrational and rotational modes and tend to impede multiplication; they are often used mixed with noble gases to provide stability in operation, especially for atmospheric pressure detectors.

Detectors can be classified according to the magnitude of the electron multiplication. Proportional counters are those that maintain a linear relationship between the original number of electrons produced and the electrons that are collected, thus yielding a signal proportional to the energy deposited in the medium. Avalanche counters use such high values of multiplication that space charge distorts the field of the anode and proportionality is limited. The large signals and short total drift times of the electrons allow for good position and timing accuracy, however.

A simple model of the avalanche development in a proportional counter is useful for a first-order analysis of typical signal characteristics. Consider a simple cylindrical geometry (see Fig. A.1), where typically the cathode radius is $b \approx 1$ cm and the anode radius is $a \approx 20$ μm. The field due to the wire for $r > a$ is

$$\mathcal{E} = \frac{CV_0}{2\pi\epsilon_0}\,\frac{1}{r} = -\frac{d\phi}{dr},$$

where the capacitance per unit length is

$$C = \frac{2\pi\epsilon_0}{\ln(b/a)}. \tag{A.2}$$

The electrostatic energy of a cylinder of length l, $E_{\mathrm{cyl}} = (1/2)\,ClV^2$, is a constant during the process of signal formation since the power supply is usually too slow to keep the

cylinder voltage constant on a nanosecond time scale. A charge[2] Q which moves toward the anode from radius r to $r + dr$ ($dr < 0$) gains energy $dE_Q (> 0)$ so that the cylinder loses energy $dE_{\rm cyl} = -dE_Q$.

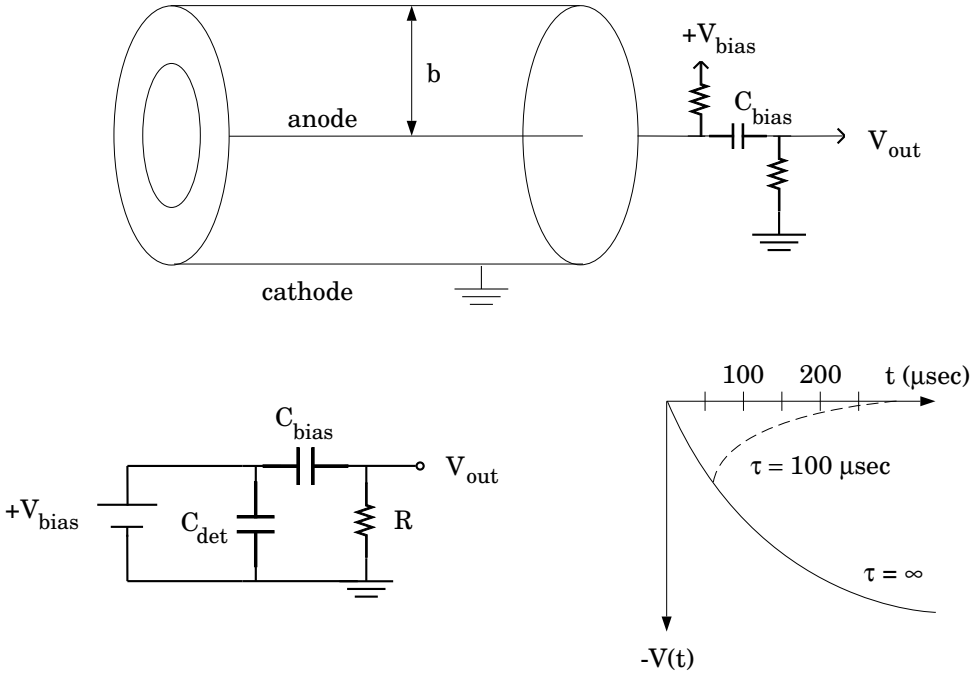

Figure A.1 The simple cylindrical wire chamber. Also shown is the equivalent circuit and the resulting signal development for a proportional mode counter.

An important thing to note is that the signal formation is via induction and not actual charge collection: energy conservation requires that the cylinder energy (and hence voltage) decrease as the electrons' average energy increases. Assuming that the change in cylinder voltage is small compared to the bias voltage V_0, the change in energy of the cylinder is given by

$$dE_{\rm cyl} = ClV_0\, dV$$

and

$$dE_Q = Q\, d\phi = Q\frac{d\phi}{dr}\, dr,$$

so that

$$\frac{dV}{dr} = -\frac{Q}{ClV_0}\,\frac{d\phi}{dr} = \frac{Q}{2\pi\epsilon_0 l}\,\frac{1}{r}. \tag{A.3}$$

Electron multiplication typically occurs within a few μm of the anode surface, i.e., for $(r - a) \lesssim r_0 \equiv 1\ \mu$m. The collection time is thus $t \approx 1\ \mu{\rm m}/v_{e,{\rm drift}} < 1\,{\rm nsec}$, and so the

[2] As used here, Q is the absolute value of negative charge, $Q = |e| \times$ # of electrons.

total contribution to the induced signal by the electrons is small and confined mainly to the initial attack of the signal. The positive ions drift all the way to the cathode in a time scale of 0.5 msec and so produce most of the total integrated signal: with typical values for a, r_0, and b, $V_{e^-}/V_{\rm ion} \approx 0.01$. The induced signal is thus

$$V(t) \approx V_{\rm ion}(t) = \int_{r(0)}^{r(t)} \frac{dV_{\rm ion}}{dr}\, dr = \frac{-Q}{2\pi\epsilon_0 l} \ln \frac{r_{\rm ion}(t)}{a}. \qquad \text{(A.4)}$$

Since the ions' velocities are typically proportional [Sa77] to the field $\mathcal{E}$, $dr_{\rm ion}/dt \propto \mathcal{E} \propto 1/r$ and $r_{\rm ion}(t) = (c_1 + c_2 t)^{1/2}$, where c_1 and c_2 are constants.

Figure A.1 shows the resulting time development of the induced signal in (A.4). Typically, the readout circuit differentiates the tail of the pulse to allow for fast readout of other pulses. The pre-amp circuits used for the CE-06 PC provided an effective differentiation time constant of 20 μsec, for a maximal event rate per wire of about 10 kHz.

The resulting output signal is suitable for further shaping and introduction into a peak-sensing ADC: $\max(V(t)) \propto Q \propto E$, where E is the deposited energy. Alternatively, the signal can be integrated over a selected portion of the development time, since the integral of Eq. (A.4) is also proportional to Q. Assuming that the intrinsic charge pulse risetime of the detector is much smaller[3] than the pre-amp time constant, and that this risetime does not depend appreciably on the total charge deposited, the proportionality is maintained by integration of any portion of the signal. For the CE-06 experiment, the PC pre-amp outputs were integrated in a 750 nsec window near or encompassing the signal peak.

The multiplication factor m, defined as the collected charge divided by the original ionization charge, is given [Sa77] by

$$m \propto e^{CV_0}.$$

Through Eq. (A.2), this implies that m is sensitive to changes in b, the cathode-to-anode distance, according to

$$\frac{\Delta m}{m} \approx \frac{1}{2}\frac{\Delta b}{b} \ln m.$$

For the PC used in the CE-06 experiment, $\Delta m/m \approx 4 \cdot \Delta b/b$, so that a 0.5 mm change in the cathode-to-anode distance produces a 40% variation in the multiplication gain. This sensitivity required the non-trivial PC calibration of Ch. 4: Fig. 4.6 shows that the actual distance variations for the CE-06 experiment were typically 0.2 mm.

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[3] The PC intrinsic risetime was on the order of 0.1 μsec, while the pre-amp time constant was approximately 20 μsec.

A.2 Low-Pressure Detectors

Both of the detectors used in the CE-06 experiment are low-pressure detectors: the PC operated with 20 to 100 torr of carbon tetrafluoride (CF_4), and the PGAC used 3 torr of isobutane (C_4H_{10}), in contrast to the more common types of wire chambers that operate at or slightly above the ambient atmospheric pressure. For gas detector operation, there are essentially three realms of gas pressures: atmospheric ($P \gtrsim 500$ torr), low-pressure/proportional (20 torr $< P <$ 200 torr), and low-pressure/saturated ($P <$ 10 torr). Each region involves different choices of physical parameters and gases.

For atmospheric detectors, noble gases such as argon are often used to provide for large signal gain. Maximum multiplications are soon reached, however; the ultraviolet photons emitted by de-exciting argon atoms produce enough photo-electrons from the cathode to sustain a permanent discharge. Typically a "quenching" polyatomic gas is added to absorb the ultraviolet radiation without secondary emission. These complex molecules can efficiently transfer charge from ionized noble gas atoms due to their relatively low ionization potentials. A large proportion of quenching gas yields very good stability to sparking, but the signal size is reduced greatly.

In the low-pressure regimes, however, the inverse dependence on P in Eq. (A.1) implies higher mean collision times for electrons (and hence larger average drift velocities), resulting in much higher secondary ionization rates, i.e., bigger multiplication factors. The effect is so pronounced that the use of pure noble gases is precluded and quenching gases such as isobutane, propane (C_3H_8), and CF_4 can be used as the sole working gas. The latter has the advantage of an effectively high-Z molecule and, consequently, a large stopping power relative to most other commonly used gases. The large value of dE/dx is useful in the case of low-pressure proportional counters: the thickness of the active gas volume can remain reasonably small without the need for excessively large pressures. Absolute pressures of more than 100 torr are mechanically difficult to contain with thin entrance windows. Even atmospheric detectors, which are usually not so constrained by the thickness of their entrance windows, are typically operated only a few torr above the ambient pressure. Isobutane has somewhat less stopping power than CF_4 but is well-suited for a low-pressure chamber operating in the limited proportionality or saturated mode, where the amount of deposited energy is not an important factor (this information is discarded in this region of operation).

Down to absolute pressures of about 20 torr, the proportionality between the deposited

charge and collected charge can be maintained. Below roughly 10 torr, however, the variations in output pulse height with changes in applied bias are negligible: the saturation point is reached for any reasonable signal size. In this region of operation, as in the case of the PGAC, position and timing measurements are usually desired, and the bias level is set fairly close to the sparking breakdown voltage to maximize the induced signal size and minimize the signal risetime.

All low-pressure detectors, when used for the detection of highly-ionizing ($Z \gg 1$) particles, afford several experimental advantages:

a) the detectors are virtually 100% efficient for these particles while remaining relatively insensitive to protons and γ-rays;
b) extremely fast timing is possible, especially with avalanche-mode detectors. Typical resolutions for large area detectors such as the PGAC used in CE-06 are roughly 0.5 nsec, and better than 200 psec has been achieved in small detectors [Br82];
c) fairly high counting rates ($\gtrsim$ 10 kHz) can be tolerated with little performance degradation.
d) the achievable position resolutions for these detectors are good: typically, about 1 to 2 mm depending on the particular method of readout.[4]

There are technical challenges that must be met in order the realize these advantages, however. Primary among these is the need to provide a complete vacuum enclosure, since the detector gas pressures are typically 1 to 100 torr. Another difficulty involves the use of extremely thin ($t \approx 100$ μg/cm^2) foils for pressure isolation. While thin enough to minimize undesired ion energy losses, the foils must be strong enough to withstand large differential pressures (for the PC used in CE-06, on the order of 50 torr). The pump-down and venting of the vacuum enclosure which contains the detectors must be done with great care so as to not the break the foils. Most detectors which employ foils of this type use support grids to help balance the pressure. The PGAC and PC detectors incorporated 100 μm tungsten wires spaced at 2.54 cm and 1.0 mm, respectively, as support grids.

[4] High-pressure chambers are usually superior in this respect, though. The large electron drift velocities imply short collection times but tend to worsen the position resolutions via the longer mean free paths.