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A Study of the Gas Amplification in
Cylindrical Proportional Counters for several
Argon Based Gas Mixtures.

Eric F. Ritchie
1986

A thesis submitted to the Faculty of
Graduate Studies and Research in partial
fulfillment of the requirements for the degree
of Master of Science.

Department of Physics

Carleton University
Ottawa, Ontario
January, 1986

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"A STUDY OF THE GAS AMPLIFICATION IN
CYLINDRICAL PROPORTIONAL COUNTERS FOR SEVERAL
ARGON BASED GAS MIXTURES"

submitted by Eric F. Ritchie, B.Sc.
in partial fulfilment of the requirements for
the degree of Master of Science

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Abstract

The gas amplification in a cylindrical proportional counter has been measured for several different argon based gas mixtures as a function of three variables, namely the voltage applied to the counter, the pressure of the gas in the counter, and the radius of the anode wire of the counter. For each gas mixture the measured gas gain has been fit to a six parameter function of these three variables. The measurements were extended to ten separate gas mixtures ranging in concentrations from 70% to 95% argon, using as minority gas components methane and carbon dioxide. Separate eighteen parameter fits have been made to the complete set of gas gain data for mixtures of argon with methane, and mixes of argon with carbon dioxide. These results suggest that the gas gain depends on the concentration of argon in the gas mixture and not on the type of minority gas. A single 18 parameter global fit to all of the gas gain data for the ten gases studied is presented. In addition the onset of space charge gain saturation effects has been examined for each of the ten gas mixtures, as a function of pressure.

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Introduction

We have investigated the phenomenon of gas amplification in cylindrical proportional counters. Our goal was to experimentally determine the gas gain as a function of the voltage, the gas pressure, the radius of the anode wire, and the type of gas in the counter.

The determination of gas gain for applications in particle detector chamber design provides one of the motivating factors for this thesis. A second motivating factor is that one hopes to gain a better understanding of the underlying physics of the gas gain mechanism and of the variables that affect it.

This thesis looks at the consequences of varying each of the independent variables over some range. In particular two wires have been selected for this experiment, namely a ten micron radius wire, and a one hundred micron radius wire. For each of these wires four to eight different gas pressures have been selected ranging from 0.5 to 3.0 atmospheres for the ten micron wire, and 0.05 to 1.5 atmospheres for the 100 micron wire. For each of these pressures the voltage applied to the tube has been varied in approximately equal steps such

that the dependent variable the gas gain has varied from gains of approximately 100 to 10^6 . These measurements have been repeated for each of ten separate gas mixtures which have argon as the majority component and carbon dioxide and methane as the minority components.

The range of conditions over which the gas gain has been measured as a function of the independent variables is considerable. The thesis has been structured to look at the dependence on these variables and parameterize it, as well as to briefly describe some of the underlying physics. Chapter 1 examines the gas mechanism in proportional wire chambers and introduces a set of variables which simplifies the parametrization of the gain. In chapter 2 the measurement of these independent variables is described, as well as the measurement of the dependent variable gain. Chapter 3 uses the formalism of chapter 1, and the measurements of chapter 2 to develop the analysis for the thesis. The gas amplification is first studied for individual gas mixtures, and then examined for a dependence on the type of gas. In chapter 4 the upper limit of useful gas amplification for use in particle detectors is analyzed.

Chapter 1.

1.1 Gas Ionization Counters.

A gas ionization counter can be thought of as a black box used to measure certain properties of particles passing through its volume. In practice, the counter is constructed out of one or more wires stretched on some sort of frame. A simple example is that of a single wire, cylindrical proportional counter. A wire is strung down the center of a cylindrical tube, and high voltage applied between the wire and the tube, which is filled with an appropriate gas. Under certain conditions, if a charged particle enters or passes through the volume of the tube, an electric pulse will be formed on the wire. The basic purpose of this thesis is to examine some of the factors that control the operation of this detector.

Gaseous counters were originally of the type called "Geiger" counters. Through time, they have evolved into, proportional counters, multiwire proportional counters, and drift chambers. Geiger counters were used to simply "count" particles. The more modern chambers, however, also can determine the positions of particles as well as the energy loss per unit distance (dE/dX) travelled in the gas.

A typical proportional counter consisting of an anode wire strung coaxially down the center of a cylindrical cathode tube is shown in figure 1a). When a negative high voltage is applied to the outer cathode tube, leaving the anode at ground, an electric field is set up throughout the gaseous volume. If a charged particle passes through the gas, ionization of the gas molecules or atoms occurs creating electron-ion pairs. Due to the electric field, the electrons will be attracted to the anode wire and the positive ions to the cathode. When the electrons are collected at the anode wire an electric pulse is formed which can be measured by appropriate electronics.

A multiwire proportional counter is similar to the one just described, but the configuration of the anode and cathodes is slightly different. The cathodes are usually of the form of two parallel plates, at negative high voltage, and a set of anode wires strung equidistant from, and between the two planes, as in figure 1b). The position of the particle is given by which ever wire produces the electric signal. Thus the chamber has a position resolution equivalent to the wire spacing.

One further extension of this multiwire chamber is the drift chamber. The major improvement gained from using the

Figure 1. a) Anode wire, b) cathode tube, c) anode wire counter, d) cathode tube counter.

drift chamber is in spatial resolution, combined with a decrease in the number of anode wires. The configuration in this case consists of sets of equally spaced wires, which replace the above cathode planes, and the placement of the anode wire at one end of the chamber as in figure 1c). The cathode wires are set up in such a way as to create a uniform electric field, with the lines of the field running parallel to the cathode planes, and originating on the anode wire. If the field is set up properly, a charged particle passing through the gas creates electron-ion pairs, and the electrons will drift ~~to the anode~~ with constant velocity. Thus, if the drift time is measured with appropriate electronics, the original position where the particle passed through the gas can be determined. The limiting factors in this case are mechanical tolerances in building the chamber, and the diffusion of the electrons drifting through the gas.

To yield the maximum usefulness from this type of chamber, several could be stacked together. This would allow a measurement of the energy deposited in each cell, since the number of ion pairs produced depends on energy deposited per unit length (dE/dX). dE/dX measurements allow the velocity of the particle to be determined, and if the drift chambers are placed in a magnetic field the radius of curvature of the

particle trajectory can be measured which in turn determines the momentum of the particle. Knowledge of the momentum and the velocity of the particle allows a determination of the mass of the particle and thus the particle is identified since mass is quantized.

This brief description of some "particle detectors" and their properties and applications has introduced some important parameters in the design and operation of these detectors. At present, much work is being done to determine drift velocities, and diffusion for various gases. In addition, dE/dX and the amount of primary ionization are parameters that are dependent on the composition of the gas as well as the initial energy of the ionizing particle.

All of these parameters are dependent on the type of gas used, and in the design of these chambers some effort is expended in optimising them. For instance, a "saturated" drift velocity is usually required to protect against instabilities in the high voltage power supply, or temperature deviations in the gas. Diffusion may be minimized by operating the chamber at pressures at or above one atmosphere. In addition, all three of these types of chambers benefit if the proportional region of chamber operation is at sufficiently high gas gain to allow fairly

easy readout of the output pulse. The mechanism of gas amplification is considered at greater length in the following section and throughout the remainder of the thesis.

1-2 Gas Gain.

The operation of proportional and drift chambers depends on signal amplification at the anode wire. In the case of very low electric fields, the output signals from the chamber are just due to the primary ionization. If only a few primary electron-ion pairs are created in the gas, it can be very difficult for a set of electronics to detect the small charge signal: this neglects the possible effect of recombination of the electrons and ions.

If, on the other hand, the surface fields on the anode wire are sufficiently high, the electrons after drifting into the high field region near the anode wire, acquire enough energy to further ionize the gas, causing amplification of the original signal. In the case of moderate electric fields, the final number of electrons can be proportional to the initial number of electrons. Thus the reason for the name "proportional counter". This is of major importance in the measurement of dE/dX since strict proportionality is required.

If the electric field is turned up even higher, the proportionality begins to break down with the onset of space charge effects from the positive ions produced near the anode wire. Turning up the fields even higher pushes the chamber into the "Geiger" region, where the output pulse is the same no matter what the initial charge deposited in the chamber. The gain mechanism is best summarized in the graph of figure 2.

The curve of amplification versus applied high voltage can basically be broken down into five different regions:

-region 1: the electrons freed by ionization are not all collected at the anode wire. The majority of losses are due to recombination effects, however this effect is reduced by increasing the applied voltage.

-region 2: recombination is no longer an appreciable effect.

All of the electrons are collected by the anode. The chamber is being operated as an ionization chamber.

-region 3: the voltage has become high enough that the electric field in the vicinity of the anode wire is sufficient to give the ionized electrons, enough energy to further ionize the gas. A multiplication process takes place: the charge collected is many times the initial ionization created in the gas. This is the proportional

Figure 2 A general graph of the gas amplification versus voltage for an hypothetical proportional counter. The curve has been broken into the five regions outlined in the text.

region: the charge collected at the anode wire is proportional to the initial number of ions in the gas, and thus also proportional to the energy loss dE of the particle in the gas.

-region 4: the gain becomes dependent on the derivatives of the electric field as well as the field itself. This region is called the semi-proportional region. Space charge effects becomes the major obstacle to obtaining a direct functional dependence of the gain on the electric field. The boundary between this region and the previous region is by no means sharp and usually very difficult to determine.

-region 5: in this region the charge collected at the anode wire is more or less a constant. The counter is operating in the Geiger-Mueller region.

Attempting to optimize drift velocity, diffusion, and the gas gain simultaneously, requires controlling the gain versus voltage curve rather than just choosing an operating region.

Gas gain is an exponential process, sometimes described by a parameter z , where z is defined by:

$$dN = zNdS, \quad 1.1,$$

where dN is the infinitesimal increase in the number of electrons N in moving an infinitesimal distance dS . z is

commonly called the ionization coefficient. z is not a directly calculable quantity, although a numerical simulation [1] is possible, since it results from the statistical averaging of many microscopic or atomic processes. For this reason it is normally determined empirically.

A problem that generally limits an empirical approach is that z is usually taken to be solely dependent on the electric field and not on its derivatives. In this case the ionization coefficient is equivalent to the first Townsend coefficient, α . Thus the effect of the changing electric field in a wire proportional chamber on the energy distribution of the electrons may not be properly accounted for.

1-3. The Gas Gain Mechanism and the Townsend Coefficient

Beingessner [2] has recently discussed the gas gain mechanism in considerable detail.

There are three basic gain regions that need be considered. The first case, described in this section, is where the gas gain is independent of the amount of charge collected at the anode wire, and of the derivatives of the electric field in the chamber. In the second case, considered in the next section, the gas gain may depend on

the derivatives of the electric field near the anode wire, but still be independent of the amount of the initial ionization. The final case, where the gain also depends on the total charge present near the anode wire, is considered in section 1-6, under the title, space charge.

J. S. Townsend originally proposed the differential equation, $dN = \alpha N dr$, where dN is the increase in the number of electrons N , if the electron swarm traverses a distance dr . In a constant electric field, as in the parallel plate geometry, with pressure and temperature fixed, the simple solution is:

$$N = N_0 \exp(\alpha r).$$

The above conditions constrain the secondary avalanche electrons, to have the same multiplication characteristics as the original ionizing electrons. This implies that they have the same probability of causing further ionization in the gas, and are therefore part of the same energy distribution.

In a cylindrical proportional counter, the same differential equation is assumed to apply for the gas gain at the anode wire. The difference is, that α is no longer constant but depends on the value of the electric field E at each point, with E varying as the inverse distance to the wire. α would cease to be a useful parameter if it were to

depend on additional parameters, such as the detailed geometry of the chamber, and possible second order processes. To avoid this, α is defined to be independent of the initial number of electrons, and of the derivatives of the electric field. With this assumption only a simple integration need be performed to determine the gain, G :

$$G = \exp\left(\int \alpha dr\right).$$

This calculation does require prior knowledge of $\alpha(E)$.

The Townsend coefficient, α , corresponds to the mean number of ion pairs produced by an electron drifting in the direction of the electric field, E . This should not be confused as the inverse of the mean free path between ionizing collisions. It is a macroscopic quantity resulting from the averaging of many microscopic collisions. The motion of an electron is basically a random walk, with a slight perturbation due to the effect of the electric field. The number of non-ionizing collisions invariably outnumber the number of ionizing collisions.

1-4 Thin Wires: The Non-Equilibrium Case.

In chapter 3, some evidence will be given that the gas amplification depends not only on the electric field, but also on the spatial derivative of the electric field near the

anode wire. A more general ionization coefficient K is needed to take this additional dependence into account.

In the case of "thin" anode wires, the electric field varies so rapidly near the anode wire that the drifting electrons do not achieve equilibrium with the field. In the case where the electrons do reach equilibrium with the field, this ionization coefficient K becomes equal to the Townsend coefficient, α .

The case of varying electric field is initially not very severe. As the electron drifts into a stronger and stronger electric field, the field is only changing by small increments as the electron swarm moves small distances. The swarm need only change its energy by small amounts to remain in equilibrium with the field.

Thus, how fast the electric field changes determines whether α is sufficient to determine the gain, or the more general ionization constant K is required. It is obvious from this discussion that defining a sharp boundary between these two regions is fairly difficult, and probably why it has rarely been discussed before [3].

1-5 Scaling: preferred variables.

The notation used throughout this thesis is described in this section. It follows the formalism of Beingessner [4].

The electric field near the center of a long cylindrical proportional counter is given by:

$$E = \frac{V}{r \ln(R_c/R_a)}$$

where r is the distance radially outward from the center of the tube, R_c is the cathode tube radius, R_a is the anode wire radius, and V the applied voltage between the anode and cathode. Setting $K=V/\ln(R_c/R_a)$ gives the proportionality constant between the electric field E and $1/r$.

In the preferred set of variables, the distance parameter is redefined to be $S=P*r$, where P is the gas pressure in the chamber. The total collision cross section for an electron in a gas is given by $\sigma = 1/\ell N_m$, where ℓ is the mean distance between collisions and N_m is the number of molecules per unit volume. The preferred transformation would be $r \rightarrow N_m*r$, to absorb the density into the definition. Recalling the ideal gas law: $N_m = P/RT$, where P is the pressure, and T , the temperature. For fixed temperature, P is directly proportional to N_m , so in order to maintain compatibility with most literature, define $S=P*r$.

All data used in the thesis has been scaled to $T_0 = 0$ deg, Celsius = 273.15 K by multiplying the pressure by T_0/T .

With the new unit of length, the equations describing the

other chamber parameters are also modified. The energy gained by the electrons in moving from $S=S_1$ to $S=S_2$ is given by the difference in the scalar potential: $V=V(S_1)-V(S_2)$. To define the new electric field from this potential one gets:

$$\begin{aligned}\bar{X} &= -\nabla_s V(s) \\ &= -1/P \cdot \nabla_r V(s) \\ &= E/P = k/S\end{aligned}$$

where E is the usual electric field.

For geometries other than the cylindrical proportional counter, the parameter k can be defined, $k=E_{ca} r_a = X_{ca} S_{ca}$, where E_{ca} is the electric field at the surface of the anode wire. The assumption is that in the neighborhood of the anode wire the electric field varies approximately as $1/S$.

Completing the transformation, the ionization coefficient is the number of ionizations per unit distance. Setting Z to be the transformed coefficient, the differential equation describing avalanche growth is:

$$dN = Z \cdot N \cdot dS$$

using $ZdS=Kdr$ gives $Z=K/P$. The electric field and its derivatives are defined in terms of k and S , from which it follows that the ionization coefficient, K , is also a function of k and S . The gain is therefore given by:

$$\begin{aligned}
 \ln G &= \int K(k, S) dr \\
 &= \int_0^{S_a} Z(k, S) dS \\
 &= \ln G(k, S_a) , \text{ where } S_a = P \cdot R_w.
 \end{aligned}$$

This is the general scaling law for proportional chamber gain with respect to pressure, and wire radius in a proportional counter.

In certain cases, a breakdown of the k, S scaling relationship is expected to occur. For instance, space charge occurs when some of the initial electrons deposited in the gas produce a large avalanche near the anode wire. The later arriving electrons observe a modified electric field due to the positive ions left behind by the earlier electrons. The scaling is broken because the electric field from the point charge of positive ions falls off as $1/r^2$, so that the resultant electric field due to the wire plus space charge is no longer of a $1/r$ form.

If the gain shows a dependence only on k and S_a , then the problem reduces from three dimensions (k, P, R_w) to two dimensions (K, S_a). A further reduction is possible in the case where $K = \alpha$. In this case Z is a function of the single variable $X = k/S$, and not of k and S_a separately. In future the subscript a is dropped from S_a and R_w for simplicity.

Recall, $S = k/X$

$$dS = -k/X^2 dx$$

$$\ln G = \int Z(X) dS$$

$$= -k \int Z(X)/X^2 dx$$

$$= kY(X_a)$$

or rearranging $Y = \ln G/k$.

This result indicates that in the gain region where the Townsend coefficient α applies, the quantity $\ln G/k$ can be described by a function of the single variable X_a . This result will be used in chapter 3 to define a "Townsend" proportional gain region.

The ionization coefficient can be obtained from a fit to the experimental gain data by differentiation:

$$Z = -d(\ln G)/dS$$

or if the electrons are in equilibrium with the field:

$$\alpha/P = X^2 dY/dX.$$

1-6 Space charge and other second order effects.

Townsend proposed a second ionization coefficient to describe so called second order processes. Four separate processes can be treated with almost exactly the same functional dependence. They are: secondary ionization by positive ion impact in the gas, the emission of electrons from the cathode during the neutralization of positive ions,

the emission of electrons from the cathode by the photoelectric effect, and finally, ionization by double electron impact. These four processes have been considered in some detail by Beingsner [5]. His conclusion was that in normal operation of a proportional counter, these effects are all negligible.

Space charge differs from the above effects, due to the fact that it causes a lack of scaling of the gas gain with pressure and distance. Space charge effects increase with increasing pressure. To demonstrate this fact, consider Poisson's equation:

$$\nabla_r^2 V = -\rho'/\epsilon_0, \text{ where } \rho' \text{ is the charge density.}$$

Again the distance parameter is converted to $S=Pr$, thus

$$1/P^2 \nabla_r^2 V = -P\rho'/(\epsilon_0 P^3)$$

$$\nabla_s^2 V = -P\rho'/\epsilon_0$$

and

$$\rho = Ne/S^3 = ne$$

where N is simply the net number of positive ions less the number of negative ions. To bring space charge into perspective define an effective charge:

$$q = Pe,$$

hence

$$\nabla_s^2 V = -nq/\epsilon_0$$

and space charge increases linearly with pressure.

In this thesis, the magnitude of gas gain at which space

charge effects become observable is measured by the onset of pressure distance gain scaling deviations. There is no detailed study of the properties of the gain in the presence of significant space charge.

1-7 Parameterizing the gas gain.

In order to effectively parameterize the proportional gas gain, it is necessary to consider how the gain is expected to behave over the broad operating conditions of this experiment. The range of gain measurements extend over several orders of magnitude, and involve a wide range of operating voltages and gas pressures. In addition the gas composition is to be varied.

The gas amplification is to be measured in two separate operating regions. The first is the proportional region, considered in chapter 3, where measurements of the gain are made for several pressures and voltages, and for two wire radii to verify scaling. In chapter 4, the onset of space charge is considered. This imposes further constraints on the values of operating pressures and wire radii to be used in this study. Four operating pressures were selected for measurements to be made with the thin 10 micron wire. In order to examine carefully the onset of space charge, gain

data are obtained with a thicker, 100, micron wire which is expected to reduce the space charge effects by lowering surface fields on the anode wire. The operating pressures for the thicker wire are selected by requiring that $S=P \cdot r$ be approximately the same for both wires. This allows the thick and thin wire comparison of the k, S_a gain scaling to be observed with ease.

The second part of each of these topics(chapters) is aimed at comparing the effects of using different gas mixtures. In particular the effect of varying the minority gas components, and their concentration, on the gas amplification is measured.

Avalanche multiplication will occur in any gas [6]. For this reason any gas or composition thereof, can be used in a proportional counter. Experimental constraints such as low working voltage, high gain capabilities, and good proportionality usually limit the choice to several families of compounds.

Avalanche multiplication is known to occur in noble gases at much lower electric fields than in complex molecules: this is a consequence of the many non-ionizing modes of energy dissipation in polyatomic molecules. For this reason, a mixture of gases using a noble gas such as argon as the

majority component is suggested. A pure argon counter does not allow stable operation of the counter with gains in excess of $10^3 - 10^4$.

The reason for this [7] unstable operation is as follows. During the avalanche process some atoms are excited and some are ionized. The excited atoms return to their ground state by emitting a photon. The energy of this photon is above the threshold for the ionization potential for most cathode materials (11.6ev for argon versus 7.7ev for copper). Photoelectrons can therefore be extracted from the cathode, initiating new avalanches, shortly after the original one.

Argon ions also pose a problem, since as they arrive at the cathode, they are neutralized by electrons on the cathode surface, and the balance of the energy can be used in photo emission, causing further ionizations to occur.

Polyatomic molecules, when added to a noble gas such as argon, modify the operation of the counter completely, due to their large number of non-radiative modes of energy dissipation (rotational and vibrational excited states). The ability of these polyatomic molecules to absorb photons, and stop secondary emission at the cathode, allow the counter to be operated up to gains of 10^6 .

The gain of the proportional counters, appears to be due

mostly to the argon, with slight modifications for the secondary components. This should be true, so long as electronegative components are not added to the gas mixture. Any electronegative components tend to gobble up the primary ionization electrons reducing the total charge arriving and hence measured on the anode wire.

Chapter Two

2-1. Introduction

In recent years, a number of measurements[8] have been made which attempt to parametrize the gas gain for a given proportional chamber gas. In this chapter the experimental apparatus is described and the experimental method is developed for the gain measurements of ten gases.

The experimental technique is straight forward. The proportional counter has been installed in a general test facility in the laboratory. The apparatus both mechanical and electronic is described in the following two sections. Section 2-4 develops a prescription for the accumulation of experimental gas gain data. The last two sections of the chapter examine the quality of the data, and the preliminary analysis of the data.

2-2. Mechanical Description of the Apparatus:

a.) Pressure vessel and fittings.

The pressure vessel consisted of a steel cylinder 96 cm long, 1.27 cm thick, and 22.2 cm inner diameter. Steel flanges were double welded at each end of the cylinder and machined flat to present surfaces for O-rings. Two aluminum

face plates, each 0.95 cm thick, with O-ring grooves machined on one surface of each of the plates, were used to seal up the ends of the tank. Two additional 0.95 cm brass plates were attached to the body of the pressure vessel. The vessel included low and high voltage feed throughs and gas conduits. The dimensions of the tank and face plates are summarized in figure 3a).

The gas inlet manifold consisted of four Saunders-Edwards vacuum valves mounted on half inch copper pipe. All connections to gas bottles were made through quarter inch copper tubing and Swagelock connections to the Saunders-Edwards vacuum valve fittings. The manifold itself was connected through an NPT pipe fitting to the pressure vessel. The gas outlet was handled through an exhaust manifold which allows the user to siphon off a sample of the gas or to evacuate the chamber using a standard rotary vacuum pump.

In addition, there were two pressure sensing devices. The first was the medium vacuum head for a Balzers vacuum guage. This was used mainly to monitor evacuation of the chamber before adding new gas to the chamber. The second device was the pressure head for the Datametrics 1400 manometer which was used to monitor the pressure in the chamber during runs using the built-in digital display, and

Figure 3 a) Mechanical Apparatus with dimensions for the gas gain experiment. b) Proportional tube and wire support for the gas gain experiment.

also remotely using an output connector off the back of the unit.

The low voltage electrical connections to the vessel were mounted on a side plate and were used to monitor the temperature. The high voltage feed throughs were mounted in holes machined in the end plates using O-rings. Two feed throughs were mounted at each end, one at the center of each plate, the second 3.0 cm above the first.

On the inside of the face plates two threaded holes were tapped into the aluminum. These were used to anchor two threaded 610 rods. These rods were used to support the proportional tubes.

b.1 Proportional tubes

The proportional tubes were of simple construction as shown in figure 3b). A piece of 6.0 cm inner diameter aluminum tube, 40.0 cm long was used as the cathode for each of the two proportional tubes. The first anode was stainless steel wire of 200 ± 1 micron diameter. It is referred to as the 100 micron wire. The second anode, previously called the 10 micron wire, was a 18.0 ± 1 micron diameter gold plated tungsten wire. Each of the wires were strung down the centers of the cathode tube, fastened at each end using gold solder

connectors mounted in plexiglass holders. The 10 micron wire was strung to a tension of 49.0 grams. The 100 micron wire was strung with a tension of 300 grams.

c.) X-ray source and collimator.

Measurement of the gas gain requires a knowledge of the initial charge deposited in the gas and the final charge collected at the anode wire. The final charge collected was measured using the electronics described in section 2-3 c). The initial charge deposited depends on the mechanism for ionization.

In order to predict this number it was necessary to select a source which gives a stable and reliable source of ionizing particles. Fe55 is one such radioactive source. A sample spectrum is shown in figure 4. It has been selected for its unique two peak structure. The larger of the two peaks commonly referred to as the "photo-absorption" peak, and the smaller as the "photo-escape" peak. The spectrum is basically an energy spectrum, with the center of the photo absorption peak corresponding to 5.9 kev. The scale is in femto-coulombs corresponding to the charge, measured after gas amplification, collected at the anode wire.

The radioactive decay begins with the electron capture reaction:

Figure 4 Typical Fe55 spectrum taken using the 100 micron wire. The pressure was 225 torr, using the gas mixture Argon 10% methane. The results of a fit are also shown.

This reaction has a half life of 2.7 years. When the manganese de-excites a 5.9 keV photon is emitted. This photon is most likely to be captured in the argon rather than the methane or carbon dioxide since it has a mean free path of 2 cm in argon while it has a mean free path of approximately 200 cm in either methane or carbon dioxide. The dominant process is for the photon to be absorbed by the argon with a K shell electron being ejected.

This electron will have an energy of 2.7 keV, which is the difference between the binding energy (3.2 keV) and the photon energy (5.9 keV). The L shell electrons have two states ($j=1/2$ or $3/2$) which have binding energies of 0.246 or 0.244 keV. Thus the mechanism of fluorescence allows for radiation of a photon with an energy of 2.954 keV or 2.956 keV, which is below the argon K shell edge and so has a high probability of escaping the proportional tube (thus the name for the smaller of the two peaks in figure 4, "escape peak"). There is one other competing process which is the Auger effect. The lower orbital electrons can rearrange themselves so that one electron escapes with almost the full remaining 3.2 keV. This process gives rise to the main or "photo-absorption" peak shown in the sample spectrum of figure 4.

In order to calculate the initial number of electrons before amplification it is necessary to understand the way in which the gas is ionized by two electrons of several keV energy. One of the most common ways to consider thermalization of electrons is the concept of mean energy, W , required to produce an electron-ion pair. Sauli [9] gives, $W=26$ eV for argon, $W=28$ eV for methane and $W=33$ eV for carbon dioxide. Using these numbers the mean number of initial electrons produced by two electrons of a total energy of 5.9 KeV is given for the ten gases of this experiment, in table 2-i. The numbers are approximate but sufficient for calculating chamber gain.

Table 2-i The mean number of electron-ion pairs produced in each of ten gases.

Gas Type	Mean number of electrons
Ar/CH4 95/05	226.0
Ar/CH4 90/10	225.1
Ar/CH4 80/20	223.7
Ar/CH4 70/30	221.9
Ar/CO2 95/05	224.4
Ar/CO2 90/10	222.3
Ar/CO2 80/20	217.0
Ar/CO2 70/30	214.2
Ar/CH4/CO2 90/05/05	223.8
Ar/CH4/CO2 80/10/10	220.7

The width of the photo-peak, shown in figure 4, is quite small. For each of the ten gases involved, the minimal width of the spectra appears to be approximately 7% in agreement with the calculations of Beingsner [10]. This small width makes Fe55 a good choice for gain measurements.

One additional consideration of this section is the count rate in the detector. The count rate depends primarily on the photon absorption probability in argon which has a mean free path of about 2 cm. This is two orders of magnitude smaller than the mean free path of photons in carbon dioxide or methane. Both geometry and pressure are considerations in adjusting the rate. In this experiment the rate must satisfy certain criteria. It must be fast enough to allow for efficient data acquisition, but not so fast that distortion of the resolution occurs due to pile up.

In order to adjust the count rate a collimator was constructed by drilling out the center of a brass screw. The screw was cut off to a length which allowed sufficient statistics to be accumulated in approximately two minutes at a pressure of 750 torr. It is possible to select the length of a collimator provided that a measurement of the rate is available plus the size of the collimator used to obtain this rate:

$$N_0 = N / [1 - 1 / (1 + \frac{2}{X})^{1/2}]$$

l is the length of the collimator, initially 5 mm, X is the radius of the collimator, 0.651 mm, and N is the initially measured rate, 50 events per second. N_0 is thus determined to be 12500 events per second. Substituting in the new

desired value for N of 1000 events per second gives $l=4.0$ mm.

The collimator was then cut down to this length.

2-3. Electronics:

a.) High voltage input to the proportional counters

The high voltage was supplied to the proportional tubes by two 0-5000 volt Lambda power supplies. The negative output from the supply is used and passed through a low pass filter to eliminate noise and allow the current draw on the power supply to be monitored. The circuit schematic is given by figure 5.

b.) Signal output and calibration electronics

A schematic block diagram of the electronics used in this experiment is also given in figure 5. The diagram is simply a generic summary of the electronics configuration, with the actual components summarized in table 2-ii. The Ortec amplifier-preamplifier combination gave the user access to a higher region of the gas gain than was available with the Tennelec electronics. Together they covered the gas gain region of interest.

Figure 5 Schematic Block diagram of the gain measurement electronics

Table 2-ii Summary of the electronics used in this gas gain experiment. (N/A = not applicable)

preamp	amplifier	dis- criminator	Gate Generator	multi channel analyser
Tennelec 171 (#1)	203BLR (#1)	N/A	N/A	Lecroy qVT 3001 (#1 or 2)
Tennelec 171 (#2)	203BLR (#2)	Ortec 417	Lecroy 222	Lecroy qVT 3001 (#1)
Ortec 113	450	Ortec 417	Lecroy 222	Lecroy qVT 3001 (#2)

A low pass filter and current monitor was introduced just before the cathode. This reduced noise on the wire, and allowed the user to monitor the wire for breakdown.

Modifications have been made to several of the components. The Tennelec preamplifiers have had their 50 ohm input resistors changed to 6.8 kilo ohm resistors. They have also had their high voltage bias input grounded through 150 Megaohm resistors to prevent charge build up on the anode wire. The Ortec 113 preamplifier was also modified, with a one mega ohm resistor, to maintain the anode wire at ground.

A single pulser, model PB-3, Berkeley Nucleonics, has been used in the calibration process. It was reliable for calibration, since it was a calibrated, discretely adjustable voltage source. A three way switch selected which of the amplifiers was to be calibrated.

The remaining electronics in the system provided readout of the Lecroy qVT, into a K.O. Mair, LSI 11/23 microcomputer, and onto floppy diskette.

c.) Time constant correction.

The time constants for the amplifiers were adjustable. In all cases in this experiment the integrating and differentiating times were set to the same value, namely 2000 nsec. for the main wire amplifiers and 250 nsec. for the monitor wire. Since the positive ion signal [11] was the one of interest, it was necessary to consider its effect on the time structure of the anode pulse.

Positive ions are produced near the anode wire during the avalanche process. The output signal is finished when the positive ions have been collected at the cathode. This can take from one to ten msec for a 3 cm anode-cathode separation. Since the time constant for the Ortec and Tennelec amplifiers is only two microseconds it is necessary to correct for the fact that only the initial part of the counter signal is sampled. This correction has been considered elsewhere and only a synopsis of the result is presented here.

The basic assumption needed to perform the time constant correction is that the positive ion mobility is constant over large variations in the electric field. The drift velocity of positive ions is described by:

$$dR/dt = \mu E/P$$

$$= \text{Muk}/\text{RP}$$

Integrating the above equation gives

$$\frac{R(t)}{R_a} = (1 + t/t_0)^{0.5}$$

where

$$t_0 = \frac{R_a^2 P}{2\text{Muk}}$$

with Mu , the positive ion mobility, P the gas pressure, and K the proportionality constant between the electric field and $1/R$.

The charge induced at the cathode, and consequently released from the anode, by a charge Q_0 at $R(t)$ is given by,

$$\begin{aligned} Q(t) &= Q_0 \{ \ln[R(t)/R] / \ln[R/R] \} \\ &= 0.5 Q_0 \{ \ln[1+t/t_0] / \ln[R/R] \} \\ &= Q_0 C \{ \ln(1+t/t_0) \} \end{aligned}$$

The naive calculation presented above is fairly accurate. The correction for the active filters found in the Ortec and Tennelec amplifiers is straight forward. It requires the numeric evaluation of the convolution

$$Q(t) = Q_0 C \frac{T}{2} \int_0^t \ln(1+t'/t_0) \exp[-(t-t')/T] \times \{ \sin[(t-t')/T] + \cos[(t-t')/T] - 1 \} dt'$$

which has been done previously [12].

The correction is different for each gas since the positive ion mobility varies from gas to gas. Sauli [13],

has considered the contribution to the mobility for mixtures of several gases. For the gas mixtures in this experiment the mobility of the minority gas components need only be considered since the ionization potentials for carbon dioxide (13.7 eV), and for methane (13.1 eV) are both lower than that for Argon (15.8 eV). Thus by the mechanism of positive ion exchange, it is energetically more likely for the minority components to carry the charge.

The positive ion mobility, μ_+ , for mixtures of gases is then given by:

$$\mu_+ = 1 / \left[\sum_{j=1}^n P_j / \mu_{+j} \right]$$

where P_j is the volume concentration of gas j in the mixture.

The triplet mixtures cause a problem in this calculation and have therefore been estimated assuming that the positive ion mobility is split equally between each of the minority components. Any error in this estimate is probably not significant since the gain only has a logarithmic dependence on the positive ion mobility, μ_+ . Table 2-iii summarizes the values for the positive ion mobilities for the gases used in this experiment.

Table 2-iii: Positive ion mobilities used in the time constant correction for this experiment.
 N.B. * indicates that the numbers are estimates.

Gas Type	Positive ion mobility μ $\frac{\text{cm}^2}{\text{V sec}}$
Ar/CH ₄ 95/05	1327.
Ar/CH ₄ 90/10	1338.
Ar/CH ₄ 80/20	1362.
Ar/CH ₄ 70/30	1387.
Ar/CO ₂ 95/05	1176.
Ar/CO ₂ 90/10	1144.
Ar/CO ₂ 80/20	1084.
Ar/CO ₂ 70/30	1031.
Ar/CH ₄ /CO ₂ 90/05/05	* 1367.
Ar/CH ₄ /CO ₂ 80/10/10	* 1043.

d.1 Pressure and temperature sensors.

There is a critical dependence of gas gain on temperature, pressure and voltage measurements. As shown by the simple calculation of the Appendix, a 1% error in the voltage leads to a 18% error in the gas gain. A similar calculation yields a 6.2% error in the gain, for a 1% error in the pressure. For this reason it is necessary to measure these variables very well.

In this section, we consider measurements of the pressure and temperature or more precisely the density or P/T . The devices used to accomplish this task were an Analog devices AD590L semiconductor temperature probe, mounted inside the pressure vessel, implemented with a suitable electronic circuit to trim out some of the non-linearity, and a Datametrics model 1400 manometer pressure transducer.

A schematic of the temperature circuit is given in figure 6. This circuit basically converts the output of the transducer from degrees Kelvin to degrees Celsius having two trim pots for calibration. The output from this circuit was fed into a Hewlett-Packard model 3460A digital voltmeter. An additional check on the temperature was made using a Fisher mercury thermometer mounted on the outside of the pressure vessel. This only served as an approximate check of the temperature since the temperature inside the tank need not be the same as that outside.

The output from the 1400 manometer was displayed on a built-in digital display. This output was checked by passing the output from the back of the unit (BNC coaxial connector) to an Ortec model AD811, 11 bit, analog to digital converter (ADC) mounted in a Camac crate. This signal was first attenuated using a resistor divider to reduce the dc level to be compatible with the ADC.

2-4. Operation of the apparatus:

a.) How to accumulate a single Fe55 spectrum.

Each data point has a number of parameters that must be fixed before commencing to accumulate an Fe55 spectrum. The first parameter is the gas type or mix. The second parameter

Figure 6 Schematic of the temperature sensor circuit used to monitor the temperature inside the pressure vessel.

is the wire radius. In this experiment either a 10 micron or 100 micron wire is selected to be the main wire with the other serving as a monitor wire for that given series of data runs. The operating pressure is partially predetermined by the wire radius since overlapping regions of $s = P \cdot r$ for the two wires are desired. The pressure is therefore selected from one of the two subsets given below. This leaves one remaining free parameter, the high voltage applied to the wire. Once this is chosen the amplifier gain is fixed by the requirement that the spectrum appear at about channel 600 on the qvt display.

A fortran data acquisition program accumulates the necessary information by readout from a Camac crate, and by query of the operator. The total spectrum accumulation time runs between 2 and 10 minutes approximately with the timing being performed by an internal clock in the computer. Below is a list of pertinent information that the operator must key into the computer.

- Wire radius
- Amplifier time constant
- Type of amplifier (Ortec or Tennelec)
- Type of preamplifier (Ortec or Tennelec)

- Discriminator threshold
- High voltage setting
- Amplifier coarse gain setting
- Amplifier fine gain setting
- Qvt noise cut channel
- Approximate position of the main peak
- Full width at half maximum of the main peak
- Approximate position of the escape peak
- Full width at half maximum of the escape peak
- Pressure from the 1400 manometer
- Room temperature

The above data are entered at the computer terminal by the operator for both the main wire and the monitor wire. The first set is entered only on accumulation on the first spectrum of a data set. The second set must be entered for each spectrum accumulated.

Accumulation of the data is followed by calibration of the electronics using the pulser. The attenuators and dials are adjusted to give a pulse, of known voltage, which appears just above channel 200 on the qvt display. The computer reads out the qvt, and performs an arithmetic mean to find the center of the peak and its width. It then clears the qvt. The pulser signal voltage is then increased to give a second peak in a slightly higher channel on the qvt. This is repeated to give between five and ten calibration points. The monitor wire readout electronics is also calibrated in turn.

b.) Together 120 Fe55 spectra constitutes a gain curve.

In order to study the gas gain for a given gas mixture some range of values of the variables must be selected. One of the principle considerations of this experiment is to directly compare the gas gain on the 10 micron wire to that

of the 100 micron wire. This basically requires common values of the variable $S=Pd$. To start, data was taken on the 10 micron wire at pressures of 375, 750, 1500, and 2250 torr. The corresponding values for the 100 micron wire are 37.5, 75, 150, and 225 torr. In order to make the measurements of gas gain in the Townsend region, for low values of $X=E/P$, it is necessary to take additional data on the 100 micron wire at pressures around 750 torr.

For each pressure a succession of Fe55 spectra were taken adjusting the amplifier gain setting and high voltage supply output. For the Tennelec amplifier the fine gain was left set at 1.0 and the coarse gain was stepped through the settings 2000, 500, 200, 50, 20, and 5. With the Ortec electronics in place, the fine gain was set to 1.5. The coarse gain was stepped through the settings 1000, 500, 200, 100, 50, 20, 10, and 5, where the low amplifier gain settings were only used when the gas gain did not saturate, or cause break down in the chamber. For each setting of the amplifier gain the high voltage was adjusted to give a spectrum such that the main peak appeared at about channel 600 on the qvt display.

A series of gain settings as given above forms the basis for one data file. The data acquisition code opened two

files on a floppy diskette. The first six alpha-numeric characters were the same for both files. The qvt output was written to a file labelled with the three letter extender '.DAT'. The remaining data was written to a file with the three letter extender '.ANS'.

c.1 Gas Types and Mixing Procedures.

One goal of this experiment was to measure the effect of modifying the minority gas concentration on proportional counter gains, using Argon as the majority gas component. We also sought to investigate the effect of changing the type of minority gas component.

This experiment was performed using mixtures of Argon with Methane in the ratios, 70:30, 80:20, 90:10, and 95:5. Gain curves were also obtained with mixtures of Argon and Carbon dioxide in the same ratios. Two cases of three component mixtures were also analyzed for gas gain. These were mixtures of Argon with Methane and Carbon dioxide, in the ratios 80:10:10 and 90:5:5. These percentages were only approximate and for several of the gases an exact break down was available thanks to G. Gardner of the Analytical Chemistry Division, of the NRC. The results of the analysis by Gas Chromatography are given in table 2-iv as are the estimates for the remaining gases.

Of the ten gases used in this experiment, four of them were available, premixed by Matheson. The remaining gases were mixed by partial pressures, using the pressure vessel as a mixing tank. Before starting any of the runs the chamber was evacuated to 0.01 torr. For the premixed gases, this practice was followed every time the pressure was changed. In all other cases the tank was evacuated and the mixing by partial pressures done in such a way as to bring the pressure up to 2250 torr. The 95:5 mixtures were created by mixing 1125 torr of the 90:10 mixtures with the same amount of Argon. The three component mixtures were mixed with equal amounts of the premixed 80:20 mixtures, to give the 80:10:10 and the 90:5:5 mixtures were obtained by mixing equal amounts of the 90:10 mixtures. The 70:30 mixtures were mixed using 87.5% of the 80:20 premix with 12.5% with the corresponding pure minority gas component.

2-5. Quality of the Data:

a.) Gas Quality and Quantity.

A summary of the gas mixture component percentages is given in table 2-iv. There was a small differences between the expected percentages of the mixed gases, and that measured. Some check was also made for possible oxygen contamination.

Table 2-iv The gases have been broken down by minority gas component and analyzed for oxygen (O₂) content. The third column (GorC) indicates whether the breakdown is by gas (G) chromatography or calculation (C).

Gas Type	Nominal %	GorC	% CO ₂ /Vol	% CH ₄ /Vol	O ₂ (PPM)
Ar:CH ₄	95:5	G	nil	5.95±.02	NR
Ar:CH ₄	90:10	G	nil	10.95±.01	<200
Ar:CH ₄	80:20	C	nil	20.0 ±1.0	NR
Ar:CH ₄	70:30	C	nil	30.8 ±1.1	NR
Ar:CO ₂	95:5	G	5.14±.02	nil	NR
Ar:CO ₂	90:10	G	9.54±.02	nil	<200
Ar:CO ₂	80:20	G	20.52±.19	nil	<200
Ar:CO ₂	70:30	C	31.2 ±.2	nil	NR
Ar:CO ₂ :CH ₄	80:10:10	C	9.43±.2	10.8±0.6	NR
Ar:CO ₂ :CH ₄	90:5:5	C	4.4 ±0.1	5.9 ±0.1	NR

In mixing gases by partial pressures, the pressure in the tank dropped slightly in the first few minutes following the filling of the tank. For mixed gases this occurred at a pressure of 2250 torr. The most probable cause was a reseating of the end-plate O-rings in changing from vacuum pressure to positive pressure. A simple calculation indicates that in filling the tank with what was thought to be 50% proportions of two gases, was actually 54.0±0.3% for the first component and the balance for the second component. This was determined using results of the gas chromatographic analysis. These numbers were in turn used to do similar calculations of the mixture components where analysis was not available.

Three of the gases were analysed for oxygen content. The results of the analysis were all negative with the measure of oxygen content being less than the resolution available by

gas chromatography (20@ppm). This does not necessarily infer that no oxygen contamination occurred. The samples were taken with the pressure vessel at an operating pressure of 2250 torr, after the data was taken at this pressure. This was only the first of some ten pressure settings. For the premixed gases this should not be too much of a problem since the chamber was evacuated between each of the pressure settings. The user mixed gases were performed with a single fill to 2250 torr, followed by evacuation of the excess gas to obtain the next pressure setting. Thus user mixed gases may have been subject to some contamination and the analysis for oxygen by this method would still yield a null result. In order to minimize the possibility of oxygen contamination, the data was accumulated in two stages, on two separate days. On the first day, gas gain measurements at pressure settings of 750 torr and above were completed so that the O-rings would not have to reseal. On the second day, the remaining gas gain measurements were completed.

b.) Systematic Checks of the Counter Electronics.

i) Calibration.

Calibration of the amplifier gain was performed following each and every data point as per section 2-4a). This data allows the calculation of the slope of charge versus qvt

channel to be obtained, and the zero channel. For a fixed amplifier gain setting, the slope and zero channel should remain the same. To check for long term stability of the gain measurement electronics the following plots were made. Figures 7 a), b), c), and d) show the slopes and zeroes of the calibration curves plotted against the amplifier gain settings for the Ortec and Tennelec amplifiers. On a log-log scale a slope of -1.0 is expected on the slope versus gain curves, and both of these plots are in substantial agreement with this figure. The standard deviation of individual measurements from a straight line fit for these plots is 2.1% for the Ortec, and 4.2% for the Tennelec. The root mean square deviation of the average deviation of the zero channels is about 15 channels. The fits to the calibration data have been used to correct the actual data in those cases where the actual calibration deviates from the fitted calibration by more than two standard deviations.

ii) Standard runs.

When data accumulation was first started, it was realized that some systematic check would be necessary to ensure the stability and repeatability of the electronics. It was decided that a standard run would best provide the test. The standard run basically amounts to repeating a standard set of gas gain points in which all of the parameters remain fixed.

Figure 7 a) and b) Calibration stability checks for the Tennelec electronics, c) and d) stability of the Ortec electronics for all of the gas gain measurements made for this thesis.

The standard gas selected for this purpose was Ar:CH₄ 80:20. The pressure was always scaled so that the pressure was equivalent to 750 torr @ 298 K. Data was taken on the 10 micron wire. A summary of the amplifier gain settings, high voltage settings, and results of monitoring over a period of three and a half months, are given in table 2-v. This indicates that the measured gas gain is reproducible to 3% for these standard run conditions.

Table 2-v: Summary of the gas gain data taken for 14 standard runs. The amplifier fine gain was fixed at 1.0 for both amplifiers.

	Tennelec			Ortec		
Amplifier coarse gain	500	50	5	500	50	10
Mean wire gain	1418	14941	160685	15664	163627	592531
% deviation from mean	2.6	3.4	2.5	2.2	2.4	1.9
High voltage (volts)	1500	1800	2100	1800	2100	2300

iii) Monitor wire.

The purpose of the monitor wire was to monitor the chamber for any time dependent change of parameters during a given data set. The amplifier was used as a fixed gain amplifier with the fine gain set at 1.0 and the coarse gain usually set at 50. Once the pressure was selected for a given run, the high voltage for the monitor was adjusted so that the main peak of the Fe55 spectrum was located at about

channel 600 on the qvt. The monitor wire was left with the same settings while the main wire was stepped through its various settings for a given run. No significant changes in the wire gain were observed throughout the course of the data taking. A change of the wire gain on the monitor wire would have been indicative of a leak in the pressure vessel or of oxygen contamination.

c.) Calibration of support electronics.

There were several tests administered to check the calibration of the support electronics. To begin with the high voltage power supplies were checked for linearity and zero offset. Plots of measured high voltage versus power supply setting yield straight lines with slopes deviating from 1.0 by only about 1.4%. The deviation from a straight line fit is approximately 1 part in 10000. Figure 8 a) and c) give the linear fits and figures 8 b) and d) give the deviations from the linear fits for the high voltage power supply calibrations. The fits have been incorporated into the analysis software.

The temperature sensor poses additional problems, in that there is no other calibrated temperature sensor mounted in the pressure vessel to compare with. The output of the

Figure 8 High voltage power supply stability for the 10 micron (top) wire, and the power supply stability for the 100 micron (bottom) wire.

AD590L temperature transducer was fitted to the Fisher thermometer. The basic premise in doing the fit is that over the period of data taking, the temperature inside the tank is equal to, on average, the temperature outside the pressure vessel. The plot is given in figure 9 and the deviation from a least squares straight line fit is also given. The result of the least squares fit has been incorporated in the analysis program.

Long term drift of the 1400 manometer was monitored using an Ortec AD811 11 bit analog to digital converter. The main purpose of ADC was to serve as a check for typographical error in manual input of the pressure. Manual input provided higher resolution than the ADC. A fit to the data yielded a standard deviation of 0.01%. The data is displayed in the plot of figure 9 and the deviation from the fit is also given.

A second check on the pressure sensor was performed by comparison of the 1400 manometer to a Kulite pressure transducer. The pressure was varied throughout the operating range of the transducer, from 10 to 2250 torr. 1400 manometer output was plotted against kulite output in figure 10 a) and deviation from a straight line fit shown in figure 10 b).

Figure 9 Long term drift and calibration fits for the temperature and pressure sensors.

Figure 10 Linearity check of the 1400 manometer against a kulite pressure transducer.

2-6 Preliminary Analysis.

The data was first transferred to a Vax 11/780 by one of two methods. An LSI 11/23 serves as the front end of the VAX and is normally just used to reboot it, but it has a floppy drive and so floppy disks could be used to transfer the data to the VAX's hard disk. About two months after the data taking was started a DECNET link became available between the K.O. Mair LSI 11/23 and the VAX. This was the primary facility used for data transfer.

The analysis of the gas gain data begins with fitting of the qVT spectrum. The results of the fit are then saved for further analysis. Fitting the Fe55 spectrum is a three stage process in order to maintain reliability. A gaussian fit is made to each of the main photopeak and the escape peak. During the data acquisition, the operator estimated the location of the centers of the peaks, and widths of the peaks using the qVt display. The first fit uses this information as starting values. A second fit is then done on the peaks, beginning with the assumption that the qVt channel with the most counts is the center of the peak. From the best of these two fits an estimate of the center of the main peak was extracted. A final fit was then carried out using this new estimate, but only using data within one standard deviation

of the centroid, with the standard deviation equal to the fitted value. This step should eliminate any bias due to low level background.

One result of the above gaussian fitting routine is that the width of the Fe55 photo-absorption peak can be plotted as a function of voltage for the purpose of examining system resolution. Figures 11 a) and b) merely confirm an earlier result, namely that the mean width of the Fe55 photo-absorption peak is about six to seven percent. In addition there seems to be a slight dependence on the applied voltage, with the width increasing with the applied voltage. This is most likely due to corona effects in the electronic circuits associated with the voltage power supply.

The remaining calculations to obtain the gas gain are basically as follows. The calibration data is fitted so that the charge corresponding to the center of the peak can be determined. This is then corrected for the amplifier time constant factor and then the gain is determined by dividing by the initial charge deposited in the gas. The parameters pressure and temperature recorded during the experiment.

Figure 11 The photoneak width as a function of the voltage for two sample gases, a) Argon 10% methane and, b) Argon 10% carbon dioxide.

Chapter 3.

3.1) Introduction.

The first two chapters, introduced the basic concepts and the measurements. In this chapter, we begin by exploring some of the general features of the data. Some additional motivation is given for the development of the preferred variable set of section 1-5. The third section develops a standard parameterization for the 'proportional' region of operation of the proportional counter. In the final section an investigation is made of how the gas amplification varies with gas type.

3.2) General Features of the data.

One of the simplest ways to exhibit some general trends in the data is used in figures 12 and 13. Here the experimentally measured gas gain is plotted as a function of the electric field at the surface of the anode wire, $E_a = K/R_{anode}$, where $K = V/\ln(R_{cathode}/R_{anode})$, as defined in chapter 1.

The data displayed in these plots is a selected fraction of the total sample. It is restricted to data accumulated with the ten micron wire, for four fixed pressures, each subplot corresponding to one pressure. Each of figures 12

Figure 12. Experimental Gas Gain Data as a Function of Electric Field, for gas mixtures of Argon with Methane.

Figure 13 Experimental Gas Gain Data as a Function of Electric Field, for gas mixtures of Argon with Carbon Dioxide.

and 13 display data for one minority gas type, with four different mixtures shown per plot. Figure 12 contains data for mixtures of argon with a methane minority component for concentrations of methane varying from 30% down to 5%, with the precise breakdown given in table 2-iv. The equivalent data for argon based mixtures with a carbon dioxide component is given in figure 13.

Each of the four gain curves, on each of the eight subplots, show the same general trends. The first is that gas amplification increases with increasing electric field on the anode wire, corresponding to increasing high voltage. The second feature is that the gas gain increases with increasing concentration of argon.

For each of these gain curves at fixed pressure and gas mixture, the natural logarithm of the gain can be fit with a quadratic polynomial of the electric field. This allows interpolation, or a limited extrapolation of the data. Such fits enable one to exhibit the dependence of the gas amplification on gas pressure at fixed electric field. In figure 14, this has been done for three of the four methane gas mixtures at a fixed anode electric field of 200,000 volts/cm. Figure 14 shows that the gas gain falls off rapidly with increasing pressure at fixed applied voltage.

Figure 14. Fitted Gas Gain Values as a Function of Pressure, for fixed electric field, for three gas mixtures.

The gain for any other pressure could be determined by a quadratic fit to each of the curves in figure 14.

In light of this analysis, requiring 12 quadratic fits to obtain the data for figure 14, and a further 3 quadratic fits to determine the gain as a function of pressure, it appears desirable to attempt to reduce the parameterization of the gain data to a more compact and accessible form. The following section gives a considerably more compact although less transparent method of describing the gas amplification dependence on the variables.

As an aside, it should be noted that for pressures of two and three atmospheres (1500 and 2250 torr), it was impossible to accumulate useful Fe55 spectra at gas gains of less than about 2×10^3 , for the mixture of Argon +20% carbon dioxide, and for gas gains less than 10×10^3 for the mixture of Argon +30% carbon dioxide. The reason for this was unclear. However the further observation was made that the Fe55 photopeak in the spectrum was very broad for the data that was obtained for these two gases, and the escape peak was not discernable. These last remarks also hold for the triplet mixture of Argon +10% carbon dioxide +10% methane.

3.3 a) Parameterizing the gas gain.

From the previous plots, it becomes obvious that to display all the data in such a format would prove cumbersome at best. The data sample contains some 1200 Fe55 spectra. Two wire radii were used involving at least ten different pressures for each of the ten gases. For each pressure and gas mixture some 10 to 15 spectra were recorded.

In section 1.5 the formalism which describes the electron avalanche gain mechanism was presented. In particular it was shown that the gain depends only on the variables k and S , where $k = E_a \cdot R_a$ and $S_a = P \cdot R_a$. Furthermore, the gas gain is expected to reduce to a dependence on the single parameter $X_a = k/S_a = E/P$, for low to moderate values of X .

To investigate this expected dependence experimentally, plots of $Y = \ln G/k$ versus $X_a = k/S_a$ have been made and are shown in figure 15. The full data samples for the gas mixtures, argon + 10% methane, and argon + 10% carbon dioxide, are included (all voltages, pressures, and both wire radii). A second advantage of this method of presenting the data is that the onset of the non-proportional aspects of the gas gain mechanism become clearly visible.

Figures 15a) and b) are in agreement with the discussion of section 1.5. The dependence of $\ln G/k$ on the variable X

D

Figure 15 a) Experimental values of $\ln G/k$ plotted as a function of X for a sample gas mixture of Argon +10% Methane. This plot contains all of the data for both wires, all pressures, and voltages.

Figure 15 b) Experimental values of $\ln G/k$ plotted as a function of X for a sample gas mixture of Argon +10% Carbon dioxide.

is only valid for the proportional region of gas amplification. Any additional non-proportional phenomena should exhibit marked departure from this curve. This is visible as the various "tails" on these two figures, occurring at different values of X , for each data set at fixed wire radius and pressure.

Constraining the data to be in a region free of space charge amounts to applying a gain cut to the data. This has been done in figures 16 a) and b), where a cut, $\text{gain} < 2 \times 10^4$, has been applied. In the region of low X on this curve, i.e. for $X < 200$ volts/cm-torr, $\ln G/k$ appears to be a function of the single variable X_a alone. At higher $X > 200$ volts/cm-torr there still seems to be some scatter of the data, which suggests that $\ln G/k$ also depends on k and S_a separately, and not only on their ratio.

There are numerous ways to empirically parameterize the gain data for a given gas. To begin, consider a parameterization for $Y = \ln G/k$ as a function of $X = k/S$. The simplest solution is a polynomial in X . Least squares fits have been done for each of these gases with third, fourth, and fifth order polynomials. The root mean square (RMS) deviation of the deviations of the experimental data from the fits has been calculated for each case, and the results entered in table 3-i.

Figure 16 (a) Experimental values of $\ln G/k$ are plotted as a function of X , for the gas mixture Argon 10% Methane, where the data have been subjected to gain cut of 20,000.

Figure 16 b) Experimental values of $\ln G/k$ are plotted as a function of X , for the gas mixture of Argon + 10% Carbon dioxide, where a gaincut of 20,000 has been applied to the data

Table 3-i) Average RMS deviation of the deviations of the data from the fits to polynomials, and breakdown of the deviation into regions of X, for the fourth order polynomial.

Argon plus	Average RMS Deviation from fit to polynomial with last term:			Average RMS deviation for polynomial to fourth order with:	
	X ³	X ⁴	X ⁵	X < 200 volt/cm-torr	X > 200 volt/cm-torr
10%CH ₄	13.3%	11.9%	12.0%	6.5%	17.4%
10%CO ₂	12.3%	11.3%	10.3%	9.4%	11.7%

For both gases there is a significant improvement in going from a third order polynomial to a fourth order polynomial. For the methane mixture there is no improvement in going from a fourth order to a fifth order polynomial; however, an improvement is seen to occur for the carbon dioxide mixture. For the moment, the fourth order polynomial is selected since in the end analysis, it is desirable to use the least number of parameters possible to describe the gas gain.

The fourth and fifth columns of table 3-i) are of interest since, as has been seen in figures 17 a) and b), the largest deviation from a polynomial occurs at high X. These columns demonstrate, that a break down is occurring in the ability of a polynomial in $X=k/S$ to adequately describe the gas gain at large X. Figures 17a) and b) give the deviation, $\ln G/k(\text{fit}) - \ln G/k(\text{experimental})$, as a function of X, which clearly shows evidence for increasing deviations at large X.

Figure 17 The plots show the deviation of the experimental data from a fit for each of two gas mixtures. The fit was to Townsend terms only.

3-3b) k/S Symmetry

The discussion of the previous section indicates that for $X > 200$ volts/cm-torr an additional functional dependence of $\ln G/K$ on the two variables k and S is required. Figures 16 a) and b) have been plotted with two different symbols, one for each wire radii. Clearly at high X the gas amplification data for the 100 micron wire fail to overlap with that of the 10 micron wire. At low X however, the overlap is very good. For this reason, the new fit was chosen to begin with a fourth order polynomial in $X=k/S$, as above, but one or two extra terms have been added to investigate a more general k, S dependence.

A general function fitting package called Minuit [14] made available by CERN was used to perform this task. Table 3-ii gives the RMS deviation of the deviations from the various fits. The diagonal entries in the table give the results for the fourth order polynomial plus one term, indicated by the column row label, while the off-diagonal entries give the results for the polynomials plus two additional non-Townsend terms.

Table 3-ii Average RMS deviation of the experimental data to a fit to a fourth order polynomial plus: (values in percent)

For Argon +10% methane

	1/K	1/S	X/S	X/S^2	X^2/S	X^2/S^2
1/K	9.7	9.8	9.7	9.7	9.9	9.8
1/S		9.7	9.7	9.5	9.9	9.7
X/S			9.6	9.7	9.8	9.6
X/S^2				9.7	8.8	9.6
X^2/S					9.7	8.9
X^2/S^2						9.7

For Argon +10% carbon dioxide

	1/K	1/S	X/S	X/S^2	X^2/S	X^2/S^2
1/K	10.9	11.0	10.9	11.0	11.1	11.0
1/S		11.0	11.0	11.0	11.1	11.0
X/S			10.9	11.0	11.0	11.0
X/S^2				11.0	10.9	11.1
X^2/S					11.0	9.6
X^2/S^2						11.0

The best fit, or lowest average RMS deviation of the deviations of the data from a fit occurs, for the polynomial to fourth order, plus two terms of the form X^2/S , and X^2/S^2 , for both gases. In the interest of simplicity, the X/S term is selected, since it has a slightly lower RMS deviation than the rest of the single terms, and is similar to most of the combinations of terms. It is also consistent with that used by Beingsner [15]. Table 3-iii summarizes the parameter values for these two gases for the six parameter fit to the function:

$$\ln G(K, S) = \sum_{i=0}^4 a_i X^i + bX/S$$

Table 3-iii: Summary of the coefficients for a six parameter fit to the gas gain data for two gas mixtures.

Coefficient of:

	1 $\times 10^{-2}$	X $\times 10^{-2}$	X^2 $\times 10^{-5}$	X^3 $\times 10^{-8}$	X^4 $\times 10^{-12}$	X/S $\times 10^{-3}$	RMS devia- tion
Argon plus 10% CH ₄	-.736	.386	-.118	.212	-.143	-.060	9.6
10% CO ₂	-.667	.378	-.109	.175	-.105	-.289	10.9

The experimental deviation from these fits ($\ln G/k(\text{fit}) - \ln G/k(\text{experimental})$) has been plotted in figures 18a) and b). Note that they have the same scales as figures 17a) and b) to allow comparison. The fact that the improvement is only slight is most probably due to the lack of high statistics at high values of X . Now that a standard parameterization has been selected, it is possible to compare the various gas mixtures.

3.4 Comparison of the gain for ten gas mixtures.

The experimental gain data in figures 12 and 13 together with the subsequent analysis appear to indicate that the gas amplification might be only a function of the concentration of argon, and not dependent on the type of minority gas. Thus formally the gain could be considered a function of four variables:

Figure 18 The plots show the deviation of the experimental data from the fit to Townsend terms plus one non-Townsend term, for each of two gas mixtures.

$$G = G(V, P, r, \% \text{argon})$$

or in the preferred set of variables:

$G = G(K, S, r, \% \text{argon})$ which reduces in the proportional region to a dependence on three variables

$$G = G(K, S, \% \text{argon}).$$

The goal of this section is to ascertain whether such a functional dependence may be shown to exist.

We begin by extending the analysis of the previous section to include all ten gases. Figures 19, 20 and 21 show the gain measurements presented as a plot of $\ln G/k$ versus $X=k/S$, where each graph includes only a single minority gas type. For instance, figure 19, shows all of the data for mixtures of argon with methane alone. The data in these figures has been subjected to a gain cut of $G < 2 \times 10^4$. It is evident that a few of the gas mixtures display non-proportional behaviour even at low gains. These are the mixtures of argon +20% carbon dioxide, argon +30% carbon dioxide and argon +10% carbon dioxide +10% methane. Several of the data points for these mixtures show some departure, from the main curve at moderate values of X .

The ten gases have each been fitted with the same six parameter function fits outlined in the previous section. The coefficients of the fit parameters for each of the ten

Figure 19 The gas gain data for four gas mixtures, subject to a gain cut of 20,000. Notice that LNG/K increases as a function of increasing argon concentration.

Figure 20 The gas gain data for four gas mixtures, subject to a gain cut of 20,000.

Figure 21 The gas gain data for triple component gas mixtures, subject to a gain cut of 20,000.

gases are summarized in table 3-iv. The last two columns of this table give the RMS deviation of the deviations of the experimental data from the fit as well as the chi-squares for each of the fits. The large chi-square and RMS deviation for the three problem cases are due to the inclusion of some non-proportional data points in these data sets under study originally defined by the gain cut $G < 2 \times 10^4$.

Table 3-iv: Summary table of the coefficients for the six parameter fits, to each of ten gases. The last two columns give the RMS deviation of the experimental data from the fit, and the chi-square for each of the fits.

Gas	Coefficient of:							RMS deviation	chi square	number of points
Argon+	1	X	X ²	X ³	X ⁴	X/s				
	$\times 10^{-2}$	$\times 10^{-3}$	$\times 10^{-5}$	$\times 10^{-8}$	$\times 10^{-11}$	$\times 10^{-4}$				
30% CH4	-.720	.252	-.052	.061	-.027	-.036	6.6	21.0	45	
20% CH4	-.774	.312	-.082	.128	-.078	-.042	8.8	42.5	50	
10% CH4	-.736	.386	-.118	.212	-.143	-.060	9.6	48.9	49	
5% CH4	-.561	.400	-.122	.225	-.148	-.100	11.0	61.6	47	
30% CO2	-1.03	.323	-.092	.144	-.085	-.212	16.4	109.4	39	
20% CO2	-.656	.306	-.082	.128	-.079	-.101	28.7	579.0	63	
10% CO2	-.667	.378	-.109	.175	-.105	-.289	10.9	62.6	49	
5% CO2	-.630	.411	-.129	.235	-.161	-.663	12.0	74.6	48	
10%+10%	-.715	.323	-.099	.183	-.128	-.293	33.7	533.6	44	
5% + 5%	-.577	.361	-.101	.172	-.107	-.594	9.4	44.9	47	

It is now possible to examine the differences in gas gain between the gas mixtures. We begin by examining the gas amplification as a function of the concentration of argon in the gas, for a single minority gas type, at fixed $X=k/S$. Figure 22 shows this dependence for mixtures of argon with the single additional component, methane. The result is a

very linear dependence of $\ln G/k$ on the concentration of argon except at the largest values of X . This is a very good indication that the gain might be parameterized as a function of the percentage of argon in a given gas mixture. The equivalent plot has been made for mixture of argon with the single additional component carbon dioxide in figure 23. Both plots have been made with the same scales for ease of comparison. They appear to be in agreement, to within the uncertainty of the experimental measurements.

It would be fortunate if all ten gas mixtures could be characterized by a single fit which depends only on the concentration of argon and not on the minority gas type. The agreement between figure 22 and figure 23 suggests that this might be possible. However the coefficients of the six parameter fits in table 3-iv although similar do not show complete agreement between gases of approximately the same concentration. For this reason, we begin by performing an 18 parameter fit to all of the argon-methane gas gain data. The basis of the fit is the same six parameter function as above but each of these parameters is modified to be a quadratic function of the concentration of argon in the gas mixtures. The results of this fit, and the same fit made to the argon-carbon dioxide data, are summarized in table 3-v.

Figure 22 LNG/k as a function of argon concentration for fixed $X=K/S$, for minority gas component, methane.

Figure 23 LNG/k as a function of argon concentration for fixed $X=K/S$, with minority gas component: carbon dioxide.

2 OF/DE 2

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Table 3-v Summary table of the 18 parameter fits to a) argon-methane mixtures, b) argon-carbon dioxide mixtures.

a) Argon-methane

multiply by:	1	X^{-1}	X^{-2}	X^{-3}	X^{-4}	X/s
	$\times 10^{-1}$	$\times 10^{-3}$	$\times 10^{-5}$	$\times 10^{-8}$	$\times 10^{-11}$	$\times 10^{-3}$
1	.287	.320	-.121	.707	-.634	-.167
A_2	-.945	-.629	.398	-.215	1.93	.427
A^2	.612	.773	-.433	.177	-1.53	-.278

RMS deviation = 10.0%, Chi-square = 212.0
Number of points=195

b) Argon-carbon dioxide

multiply by:	1	X^{-1}	X^{-2}	X^{-3}	X^{-4}	X/s
	$\times 10^{-1}$	$\times 10^{-2}$	$\times 10^{-5}$	$\times 10^{-8}$	$\times 10^{-11}$	$\times 10^{-3}$
1	-.544	.125	-.446	.795	-.417	-.109
A_2	1.02	-.262	1.00	-1.88	1.01	.278
A^2	-.545	.182	-.698	1.33	.758	-1.79

RMS deviation = 19.6%, Chi-square = 855.2
Number of points=192

The carbon dioxide data has a fairly large RMS deviation which as stated earlier is due to the lack of proportionality of some of the experimental data at moderate values of gas amplification. The methane data has an RMS deviation, substantially in agreement with the deviation for the six parameter fits to each of the gases separately.

Using these new fits it is a simple matter to do a comparison of the gases with varying minority gas component, but with the same concentration of argon. Beginning with the triplet mixture of argon +10% methane +10% carbon dioxide, the argon-methane and argon-carbon dioxide 80/20 mixtures are

scaled to the same argon concentration, as the triplet mixture. At each value of K and S where experimental gain measurements were made, the gains are calculated from the fits. Figure 24 presents the comparison of these gains for the 80% argon mixtures with the argon-methane mixture used as a reference gas. Figure 26 presents the corresponding results for mixtures of 90% argon. By way of comparison, recall figures 18a) and b) where the experimental deviations from the fit were displayed. The typical deviation is 8-10%. The differences between the fits presented in figures 24 and 25, are of the same magnitude or less since the vertical scales are the same. The immediate conclusion is that the gas amplification dependence on the minority gas type is insignificant at the level of the experimental error of this experiment.

This indicates that a single global fit to the data for all ten gases should be possible. Before proceeding with the fit, it is necessary to consider whether or not all 18 parameters are needed. Recalling figures 22 and 23, there appeared to be a fairly linear dependence of the gas amplification on the concentration of argon in the gas. This remark is certainly true at values of $X < 300$ volts/cm-torr.

Figure 24 Plot of $\ln G/k_i - \ln G/k_{ref.}$ as a function of $X=k/S$, where experimental values of k and S have been used to determine fitted values of $\ln G/k$.

Figure 25 Plot of $\ln G/k_i - \ln G/k_{\text{ref.}}$ as a function of $y=k/S$.

At higher values of X , there appears to be a small non-linear correction needed. Table 3-vi summarizes the results of an 18 parameter fit, and of a 14 parameter fit, where four of the coefficients have an assumed linear dependence on the concentration, while the first and last terms which are of most importance at large X are fitted with quadratics.

Table 3-vi Summary of the coefficients of the 18 parameter fit, and a similar summary of the 14 parameter fit coefficients.

a) 18 parameter global fit to ten gases.

	multiply by:	1	X^{-1}	X^{-3}	X^{-5}	X^{-8}	X^{-11}	X/s^{-3}
		$\times 10^{-1}$	$\times 10^{-3}$	$\times 10^{-5}$	$\times 10^{-8}$	$\times 10^{-11}$	$\times 10^{-14}$	$\times 10^{-17}$
1		-.125	.660	-.151	.414	-.254	-.163	
A_1		.0033	-1.25	.336	-.109	.736	.413	
A_2		.670	.105	-.329	.955	-.672	-.263	

RMS deviation = 20.7%, Chi-square = 2457.
Number of points = 485

b) 14 parameter global fit to ten gases.

	multiply by:	1	X^{-1}	X^{-3}	X^{-5}	X^{-8}	X^{-11}	X/s^{-4}
		$\times 10^{-1}$	$\times 10^{-3}$	$\times 10^{-5}$	$\times 10^{-8}$	$\times 10^{-11}$	$\times 10^{-14}$	$\times 10^{-17}$
1		.367	-.131	.144	-.434	.366	.283	
A_1		-1.17	.584	-.294	.722	-.562	-.561	
A_2		.758	0	0	0	0	.164	

RMS deviation = 21.1%, Chi-square = 2586.
Number of points = 485

It is clear that the 14 parameter fit is adequate to describe the entire data set. This fit is therefore sufficient to describe the gain behaviour of any mixture for

Argon with carbon dioxide or methane, or both for the proportional gain region. The large deviation is due to the presence of a few non-proportional data points in the carbon dioxide mixtures. The next chapter looks at the onset of this non-proportional region of operation of the proportional counter.

Chapter 4

The onset of non-proportional behavior.

4.1 Introduction

Recall from section 1-6 that most of the gas amplification occurs within a few wire radii of the central anode wire. Since the electrons drift towards the anode wire much faster than the positive ions towards the cathode, a sheath of positive ions collects around the anode wire. If the density of the positive ions is sufficient (ie. for higher gains, larger numbers of positive ions are produced around the anode wire), a local reduction of the field around the anode wire occurs. Thus the gain is actually reduced. The expectation is that the 10 micron wire would yield a higher positive ion density around the wire for the same expected gas amplification, this larger density would reduce the electric field, and thus the expected gain relative to that measured with the 100 micron wire.

Some evidence was cited in the previous chapter of a dependence of non-proportional gas amplification on minority gas type, namely that the onset of space charge seemed to occur at lower gains for mixtures of argon with carbon

dioxide. In this chapter further examination is made of the data to determine the exact nature of this dependence. In particular, the upper limit of proportional gas amplification, is investigated as a function of pressure, minority gas type, and minority gas concentration.

4.2 The effect of a Gain cut on the goodness of fit.

In the previous chapter, an 18 parameter fit, and a 14 parameter fit were made to the full data set of all ten gases subject to the constraint that the gas amplification be less than 20000. We begin by repeating these fits, but now varying the gaincuts for the 10 micron and 100 micron wire separately. In table 4-i, the RMS deviation, chisquare, number of points, and the gain cuts for each of the wires is given. In each case at least one of the wires has the gain cut maintained at the nominal 2×10^4 value used throughout chapter 3.

Table 4-i: Summary of the RMS deviation of the deviation for 14 parameter fits to the full data sets. Chi-squareds are also included.

10 micron wire Gain cut	100 micron wire Gain cut	RMS deviation	Chi- Square	number of points
2×10^4	2×10^4	21.1%	2586	485
1×10^5	2×10^4	31.5%	7336	613
2×10^4	1×10^5	24.0%	4682	674
2×10^2	2×10^4	16.8%	1211	363
2×10^4	2×10^2	21.3%	1643	307

It becomes clear from this type of analysis that space charge effects do occur at lower gains for the 10 micron wire than for the 100 micron wire. This analysis, however, does not yield any insight into the dependence on gas type. The following section considers this aspect of the analysis using a slightly different approach.

4.3 The dependence of space charge on pressure.

As demonstrated, in the previous section, the onset of the non-proportional gas gain region occurs at lower gains for thin wires than for thicker wires. In this section, we exploit this fact to study space charge effects as a function of pressure.

Recall from chapter 2, the data was taken at four different values of $S=P \cdot r$ for each of the wires. The values

of S for each of the wires were similar but not identical. To solve this problem, four standard values of S were selected and the data were scaled to these values. These were 0.325 cm-torr, 0.65 cm-torr, 1.30 cm-torr, and 1.95 cm-torr. These correspond approximately to pressures of 0.5, 1.0, 2.0, and 3.0 atmospheres, for data taken on the 10 micron wire. The data were scaled to these values of S using a Taylor series expansion of the gain. To first order:

$$\ln G = \ln G_0 + \left. \frac{\partial(\ln G)}{\partial S} \right|_{S_0, G_0} \times (S - S_0) \quad 4.1$$

The six parameter fits of section 3-4 were used to obtain the derivatives. Figures 26 a), b), c), and d) present the gas gain data as a function of $X = K/S$, with each subframe of a plot corresponding to a single value of S , for four sample gas mixtures.

It appears that the onset of space charge (non-proportional gas gain) occurs at lower values of gas gain for the gas mixtures with carbon dioxide particularly at higher pressures. The onset of space charge can be taken to be the point where the gain data for the 10 micron wire shows marked departure (attenuation) from the 100 Micron wire data. The two methane mixtures shown are quite similar to each other,

Figure 26a) Comparison of the gas gains for the 10 and 100 micron wires for the gas mixture Ar+20% methane. The actual data has been scaled to the quoted values of 8 in each subplot using equation 4.1.

Figure 26b) Comparison of the gas gain for the 10 and 100 micron wires for the gas mixture Ar+10% methane.

Figure 26 c) Comparison of the gas gain for the 10 and 100 micron wires for the gas mixture Ar+20% carbon dioxide.

Figure 26 d) Comparison of the gas gain for the 10 and 100 micron wires for the gas mixture Ar 10% carbon dioxide.

with the onset of space charge occurring at gain values well above the 20000 gaincut used for the fits in the previous chapter. The carbon dioxide data on the other hand shows a stronger dependence of space charge on pressure, with the limit of proportionality falling off with increasing pressure, especially for the argon +20% carbon dioxide data.

In order to determine a quantitative measure of the onset of space charge, the natural logarithm of the gain for each wire has been separately fit with fourth order polynomials in X . This has allowed the calculation of the point, where the gain on the 10 micron wire was attenuated by a fixed factor relative to the gain for the 100 micron wire. This allows the systematic comparison of the onset of space charge. In the previous chapter, the six parameter fits gave a root mean square(RMS) deviation of the average deviation from the fits of approximately 10% for most of the gases. In this section, the point where the gains differ by three standard deviations is selected as the point where the onset of space charge occurs. This corresponds to an attenuation factor of 0.7 between the gain for the 10 micron wire and that for the 100 micron wire.

Table 4-ii summarizes the results for each of the four values of S , for each of the ten gases. The value of gain

given is the average of the values for each of the wires or 0.85 of the value for the 100 micron wire. The values of gain in the table for $S=0.325$ cm-torr are subject to larger systematic errors than the other values of S due to a lack of data where the two wire deviate significantly at high X .

Table 4-ii: Summary of the gas gain values where the 10 micron wire gain is equal to 0.7 times the 100 micron wire gain.

		$S=P \times R$ (cm-torr)			
Gas		0.325	0.65	1.3	1.95
argon +					
30% CH ₄		25,800	103,000	80,400	34,900
20% CH ₄		52,700	74,600	89,800	40,600
10% CH ₄		65,500	75,000	84,800	67,800
5% CH ₄		20,000	26,800	60,600	55,200
argon +					
30% CO ₂		54,500	17,700	<1000	<1000
20% CO ₂		114,000	30,800	1,210	<1000
10% CO ₂		76,400	55,000	30,600	12,300
5% CO ₂		68,000	35,400	27,200	13,100
argon +					
10% CH ₄ + 10% CO ₂		108,000	21,500	<1000	<1000
5% CH ₄ + 5% CO ₂		23,200	29,700	28,400	18,300

In order to treat space charge in a consistent manner for all of the gas mixtures, it is necessary to look at the gain measurements for argon + 20% carbon dioxide mixture, shown in figure 26c) more carefully. For the gas pressures above 750 torr, the gas amplification for the 10 micron wire is attenuated relative to that of the 100 micron wire at all values of the gas gain. We have attributed this systematic shift of the 10 micron wire to some as yet undetermined secondary process other than space charge since it breaks the

scaling of the gain data between the two wires, even at low gain. In order to obtain a better estimate of the value of gas amplification where the onset of space charge occurs an alternate method has been considered. The low values of $X=E/p$ are fit to a linear function of $\ln G$ for the 10 micron wire alone. A polynomial fit in X is then made to all of the 10 micron wire data for fixed values of S . A comparison between these two fits is then used is then used to estimate the point where the onset of space charge occurs. These new values have been used for the 2 and 3 atm. 20% and 30% CO₂ gases in the discussion and plots that follow.

Figures 27, 28, and 29 present the data from table 4-ii) in graphical form. The values of gain for the six smallest entries in the table have been replaced using the alternative method discussed above. The gains have been plotted as a function of pressure (for the 10 micron wire), with each figure containing the data for a separate minority gas type. A lower limit on the gas amplification has been applied to the graphs so that only valid experimentally measured regions are portrayed. Curves have been included on each of the graphs but they have no explicit functional form, they are intended merely as a guide for the reader. The scales on all 3 graphs are the same for comparison.

Figure 27 The gas gain has been determined above the onset of space charge is said to occur. These values are plotted as a function of pressure for mixtures of Argon with methane. The errors are given by 0.15 G.

Figure 10. The gas gain is plotted against pressure, for the point where the onset of space charge occurs. The points have been staggered at the various pressures so that the error bars are visible.

Figure 20 The points where the onset of space charge effects occur. The lines on these graphs are only for guidance.

In figure 27, it appears that for the 0.5 atm. pressure data the onset of space charge occurs at lower gain than at higher pressures. This is not a reliable assumption. In reference to figures 26 b) and c), the point at which the onset of space charge occurs, for $S=0.325$ cm-torr, is subject to a large amount of uncertainty due to the lack of data at high X and high gain.

The results presented in figures 27 and 28 seem to favor carbon dioxide mixtures over methane mixtures at low pressure. However at high pressures carbon dioxide mixtures lose their attractiveness. Recall that in the operation of drift chambers two major constraints were applied. The first was large proportional gain for energy loss measurements, and the second was low electron diffusion which improves with increasing pressure.

These results indicate that mixture of argon with carbon dioxide are inferior to mixtures of argon with methane, if high gas amplification with proportional operation are desired. This is most certainly the case if dE/dX measurements are to be made.

The triplet mixtures of figure 29 seem to indicate, that the Ar:CH₄:CO₂ 80:10:10 mixture behaves like the 80:20 mixture of argon with carbon dioxide, while the 90:5:5

mixture behaves like a cross between 90:10 mixtures of argon with methane and argon with carbon dioxide.

Chapter 5

Epilogue

The general nature of the gas gain mechanism is well understood and has been put to use for many years in chamber design for particle detectors. We have carried out an experimental study of the gas amplification as a function of the voltage applied to the proportional counter, the anode wire radius, and the pressure of the gas in the counter.

A χ^2 parameter fit was developed which described all the gas gain measurements within the proportional region of operation of the counter. For example, it was found that a given mixture of Argon with methane could be parameterized with a root mean square deviation of the experimental data from the fit of between 6% and 10% when the data was subject to a gain cut of 20000. Mixtures of argon with carbon dioxide yielded slightly worse values for the RMS deviations, especially for the higher concentrations of carbon dioxide.

We have extended the analysis from parameterizing the gas gain for a single gas mixture to examining the dependence of the gas gain on ten separate gas mixtures. Experimental evidence was given showing that the gas gain depends mainly

(1)

on the concentration of the argon component in the gas for a single type of minority gas component. The 18 parameter fits made to all of the gas gain data for (i) mixtures of argon with methane and (ii) argon with carbon dioxide yielded RMS deviations which were no worse than for the separate fits to single gases. The analysis was then extended to a combined fit to all ten gases with a only slight deterioration in the goodness of fit. It was determined that at the level of the error on a single gain data point that for a fixed concentration of argon there was no variation in the gain between the different minority components.

The final chapter of the thesis examines the onset of non-proportional (space charge) phenomena. The 18 parameter fits of chapter 3 were recalculated using various limits on the maximum gas gain in the data sample, treating ten and one hundred micron wire separately. The results demonstrated that the ten micron wire experiences the effects of space charge at lower gains than the thicker wire as expected. The analysis was then continued to see how the effect varies with the type of gas mixture. It was found that the gas mixtures of argon with methane maintain proportionality up to higher gains and at higher pressures. In addition, a secondary process was discovered but remains unexplained, in the

measurements of gas gain for gas mixtures of argon with large concentrations of carbon dioxide.

The overall result can best be summarized as follows: in the operation of gas gain cells where strict proportionality is required such as for energy loss measurements the designer should choose either a mixture of argon with methane or use a larger wire with a mixture of argon with carbon dioxide.

Appendix

This appendix considers the effects of uncertainties in the measurement of pressure or voltage on the uncertainty in the gain.

First we consider the pressure letting the real pressure be P , and the measured pressure $P + \Delta P$. The gain has been parameterized in chapter 3 using the six parameter fit:

$$\ln G/k = \sum_{i=0}^4 a_i X^i + b X/s.$$

Using a first order Taylor expansion:

$$\ln G = \ln G_0 + K \partial \ln G / \partial P(E, P) \Delta P$$

becomes the expression giving the resulting uncertainty in the gain.

As a typical example we use the six parameter fit developed for the gas mixture Ar+20% methane. If we measure the pressure to be $P=1515$ torr, which is 1% higher than the actual value 1500 torr, and $E=340,000$ volts/cm, on the ten micron wire, the measured gain is 19900 and $\Delta P=+15$ torr.

$$\partial \ln G / \partial P = \sum_{i=1}^4 a_i X^i / P - 2X / (S \cdot P)$$

$$\text{and } \Delta \ln G = .165$$

or $G=0.938$ times the measured Gain, i.e. there is a 6.2% change in the gain.

A similar calculation is required for the effect of an error in the voltage k . The Taylor series expansion for the change in $\ln G$ is:

$$\ln G = \ln G_0 + \partial \ln G / \partial k(E, P) \Delta k$$

using $P=1500$ torr, $E=340,000$ volts/cm, $k=297.5$ volts, and $G=19900$. We take the actual value of k to be 294.5 volts.

This gives $G=1.18$ times the measured gain.

Thus the change in the gain corresponding to a 1% error in the measurement of the voltage is 18%.

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