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PROPERTIES OF ARGON-ETHANE/METHANE MIXTURES FOR USE IN
PROPORTIONAL COUNTERS

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Abstract

Properties of Argon/Ethane and Argon/Methane mixtures for use in proportional counters have been investigated. Multiplication and resolution are reported as a function of gas mixture and pressure for X-rays and charged particles. It is found that filtered industrial natural gas can be used as a substitute for pure methane gas in the operation of proportional counters.

I. INTRODUCTION

I.1 Scope and apparatus

Present experiments in high energy physics make extensive use of gas-filled particle detectors. While the basic processes related to the operation of such detectors are well understood, further examination is often warranted for special applications. The results reported here were obtained as part of a search of suitable gas mixtures for the operation of large arrays of planar multi-wire drift chambers. These chambers form the muon detector of the CLEO experiment at the Cornell Electron Storage Rings (CESR). The chambers are presently operated with a 50/50 Argon/Ethane mixture at atmospheric pressure.

In general, the gas must be free of avalanche-quenching electronegative elements, the most common one being oxygen. For this reason purified gases are used, and continuous flow is maintained. For the muon detector alone the gas consumption is of the order of 30 cu.ft./hour, which over long periods of operation represents a substantial cost. Since the cost is dominated by the ethane component we examined the performance of filtered natural gas as a substitute for the ethane. The results of this study are reported in Section IV.

The test apparatus was a cylindrical single-wire proportional counter as shown in Fig. 1. An 8-inch long, 1-5/8 inch inner diameter brass tube was sealed with brass endcaps containing ceramic feed-throughs which held a 20 μ m gold-plated tungsten wire. Openings for the insertion of X-ray or β -ray sources were provided at the center of the counter. Data at atmospheric pressure were obtained with a flowrate of ~ 1 l/min whereas for the high pressure data static conditions were maintained.

The cylinder was held at negative high voltage and the signal was taken directly across the discharge resistor R_c to a preamplifier, using a short length (~ 5 cm) of RG 58/U cable. The preamplifier output was fed to a LECROY 3001 QVT multichannel analyzer operated in the peak sensing (V) mode. Pulse height spectra were displayed on a scope or printed out.

The majority of the data were obtained with a 5.6 μ curie Fe^{55} source which emits 5.9 keV monochromatic X-rays. A Ru^{106} source was used to provide 3.54 MeV electrons from Rh^{106} decay; however the geometry of the counter is not optimal for the study of the traversal of charged particles.

I.2 Calibration

In order to achieve an absolute determination of the charge induced on the anode the preamplifier gain must be known. This can be determined by injecting a known charge and we found it convenient to use the counter as a calibrated source in the following manner: For given operating conditions (i.e. H.V. gas mix, etc.) we examined the anode pulses directly on a Tektronix 465 scope where the equivalent circuit is as shown in Fig. 2. The effective resistance and capacitance are

$$R_{eff} = \frac{R_i R_c R_s}{R_i R_c + (R_i + R_c) R_s} \quad (1a)$$

$$C_{eff} = C_i + C_c + C_s \quad (1b)$$

where

R_i, C_i	Input impedance, capacitance of scope
R_c, C_c	Discharge resistor, capacitance of counter
R_s	Variable shunt resistor
C_s	The distributed capacitance of the cabling from counter to scope.

If V is the peak-height of the observed voltage pulses then the charge delivered by the counter is

$$Q = V C_{\text{eff}} \quad (2)$$

The value of C_{eff} can be calculated from Eq. (1b) but can also be determined experimentally from the decay time of the signal since

$$\tau = R_{\text{eff}} C_{\text{eff}} \quad (3)$$

R_{eff} is given by Eq. (1a) and could be varied by changing the shunt resistor R_s . Pulses corresponding to different values of R_s are shown in Fig. 3a and a plot of τ vs R_s in Fig. 3b. The solid curve is obtained using Eq. (1a) with $R_i = 1 \text{ M}\Omega$, $R_c = 1 \text{ M}\Omega$ and R_s as indicated in the abscissa; matching to the data one finds

$$C_{\text{eff}} = 170$$

in good agreement with the value calculated from Eq. (1). The corresponding values were $C_i = 20 \text{ pf}$, $C_s = 113 \text{ pf}$ and $C_c = 37 \text{ pf}$ as measured on a bridge (this includes the capacitance of the feed-throughs and connections).

Having established the induced charge for given operating conditions, the counter was connected to the preamp and its output voltage directly calibrated in pC. For instance for a 50/50 A/Ethane mix at 1 atm. and at 2.6 KV the peak voltage on the scope was 8 mV, and therefore $Q = 1.36 \text{ pC}$. We used two different commercial preamplifiers and determined the following gain

ORTEC 124	177 mV/pC
LECROY TRA 510	409 mV/pC

This agrees with the nominal gain of the LECROY TRA 510 chip which is given by the manufacturer as 333 mV/pC. In spite of its lower gain the ORTEC preamp had much better sensitivity and was used in the region of low multiplication. The response of both preamplifiers is linear over a range of several decades (see Fig. 5).

I.3 Typical Results

Representative pulse height spectra from the X-ray and β -ray sources are shown in Figs. 4a,b. These were obtained at atmospheric pressure with a 50/50 A/Ethane mix. The X-ray spectrum exhibits the primary peak corresponding to complete absorption of the 5.9 keV photon and an "escape peak". The latter results when Argon captures a free electron to fill a vacancy in the K-shell and emits a 3.2 KeV photon which escapes the volume of the counter. Therefore the position of the escape peak is at

$$E_{\text{esc.}} = 5.9 - 3.2 = 2.7 \text{ KeV}$$

as observed in Fig. 4a. The area under the escape peak is 14% of all counts in agreement with the known rate for K-shell absorption from the continuum. As expected the escape peak is slightly skewed at the high energy side. The data were taken at a multiplication $M \sim 400$.

The β -ray spectrum was obtained at a higher multiplication ($M \sim 7200$) and exhibits the well known shape of the Landau distribution. A detailed discussion of the pulse height spectra and comparison with theoretical predictions is given in Section III.

In the proportional region the output signal depends exponentially on the applied H.V. This can be seen in Fig. 5 where the multiplication is plotted vs. H.V.; the right hand side scale gives the induced charge on the anode. We note that results obtained with either of the two preamplifiers

agree and we take this as evidence for linear response.

The pulse induced at the anode is due to the motion of the positive ions (produced in the avalanche) toward the cathode and for our geometry the ion drift-time is of the order of ~ 1000 μsec . The discharge resistor R_c shunts the anode to ground and thus differentiates the signal increasing the rate capability of the counter. Since the induced signal has a fast rise time it is possible to differentiate without loss of charge, as also shown in Fig. 3a. Changing the time-constant from 50 μsec to 5 μsec had no effect on the output. A further decrease to $\tau = 5$ nsec resulted in reduction of the output signal by a factor of 1.35.

Both sources were partially collimated and resulted in a rate of 5-7 KHz spread over a length of ~ 2.5 cm of the cathode wire. This rate is below the limit where space charge effects may be expected (500 Hz/mm). Reducing the rate by a factor of 100 showed no change in output confirming that no rate dependent effects were present.

II. MULTIPLICATION

II.1 Ionization and avalanche formation

The ionization of a gaseous medium when traversed by charged particles or photons is described in several texts⁽¹⁾ and many articles. For the particular application to proportional counters we recommend the excellent monograph by Sauli⁽²⁾ and refrain here from a detailed discussion of the processes involved.

When a charged particle traverses a gaseous volume it undergoes collisions with the atomic electrons and transfers energy to them. Similarly a photon may interact with one of the atoms and transfer energy to one or more electrons. The electrons liberated in this primary ionization process may,

and in general do, have sufficient energy to produce further ionizations. The energy required to produce one ion-pair is labelled w_i and typical values of w_i for gaseous materials are of the order of 20-40 eV. Thus for an energy deposition ΔE the total number of ion pairs produced is

$$n_T = \frac{\Delta E}{w_i}$$

Of course n_T is larger than n_p , the number of primary ion pairs.

In a proportional counter the electrons liberated in the ionization process drift toward the anode under the influence of the attractive electric field. At large distances from the anode wire the energy gained between collisions is too small to produce further ion pairs. However for distances smaller than a critical radius r_c the electric field is strong enough so that the electrons gain sufficient energy (between collisions) to produce further ion pairs. In this region the number of ion pairs grows rapidly and an "avalanche" takes place. As long as the gas does not become fully ionized and no discharge occurs the number of ion pairs in the avalanche is proportional to the number of initial ion pairs n_T .

We define the multiplication of a proportional counter as the ratio of the electrons reaching the anode to the number of ion pairs that initiate the avalanche. Thus if Q is the total charge induced at the anode and e the electron charge

$$M = \frac{Q/e}{n_T} \quad (4)$$

For Argon the energy required to produce one ion pair is $w_i = 26$ eV, so that for the 5.9 KeV X-ray

$$n_T = \frac{5.9}{0.026} = 227 \quad (5)$$

Since Ethane has the same Z as Argon the corresponding values of w_i will be nearly equal; Therefore we will use the result of Eq. (5) for all A/Ethane mixtures.

The simplest model for a regenerative phenomenon (the avalanche) is to assume that the increase in ion pairs dn , in an interval dx , is proportional to dx and to the number of ion pairs, n

$$dn = \alpha n dx \quad (6a)$$

The proportionality constant α has a direct physical interpretation and equals the inverse of the mean free path λ , if one additional pair is produced in every collision: thus

$$dn = \alpha n dx = n \frac{dx}{\lambda} \quad (6b)$$

Since ionizing collisions occur only for $x < r_c$ and since x must be larger than the radius, a , of the wire, Eq. (6b) must be integrated between these limits. In the avalanche region the mean free path depends strongly on the electric field so that

$$\begin{aligned} \text{or} \quad \int \frac{dn}{n} &= \int_a^{r_c} \alpha(x) dx \\ n &= n_0 e^{\int_a^{r_c} \alpha(x) dx} \end{aligned} \quad (7)$$

The critical radius r_c is proportional to the applied high voltage V and therefore the multiplication $M = n/n_T$ will depend exponentially on V as also indicated in Fig. 5. In the region $10 < M < 10^4$ we can parametrize M by the simple expression

$$M = e^{\gamma(V-V_0)} \quad (8)$$

where V_0 is some threshold voltage and γ the slope. At large values of M we expect saturation as the counter enters the semi-proportional and eventually the Geiger mode; at very low values of M we expect deviations from the simple form of Eq. (8). A more detailed parametrization is discussed in Section II.3.

II.2 Experimental results

The results reported in this section were all obtained using the X-ray source. Note that the mean free path of a 5.9 KeV photon in Argon at atmospheric pressure is $\lambda \sim 20$ mm (and $\lambda \sim 50$ mm for a 50/50 A/Ethane mix) so that the conversion efficiency in our counter is high. Using n_T as given by Eq. (5) and the measured preamplifier gain (Section I.2) the observed pulse height spectra yield directly the multiplication M . The multiplication was measured as a function of applied HV for different A/Ethane mixtures and for different pressures.

Typical results are shown in Fig. 6a for $p = 1$ atm for different gas mixtures and in Fig. 6b for a 50/50 mix for different pressures. The curves are the predictions of the parametrization discussed in the following section and are in good agreement with the data. From Fig. 6a we note that the slope of the curves is not sensitive to the gas mix, the difference in multiplication at fixed HV being due mainly to a different intercept V_0 [see Eq. (8)]. That V_0 increases at higher Ethane concentrations is due to the strong quenching properties of complex molecules such as Ethane. A similar tendency is observed as a function of pressure as shown in Fig. 6b: there is some change in slope and the intercept increases with increasing

pressure. Again this behavior is expected since for the reduced m.f.p. higher fields are required before multiplication can occur.

Our results are summarized in terms of the intercept V_0 and slope γ , defined by Eq. (8), in Tables I, II.

Table I. V_0 in (kV) for Argon/Ethane

Mix A/E (%)	Pressure (atm)			
	1	2	3	4
65/35	.86	1.19	1.60	1.99
50/50	.98	1.31	1.72	2.10
35/65	1.06			
15/85	1.19	1.79	2.22	2.76

Table II. γ in (kV)⁻¹ for Argon/Ethane

Mix A/E (%)	Pressure (atm)			
	1	2	3	4
65/35	7.26	6.12	5.64	5.17
50/50	7.05	5.41	4.62	4.21
35/65	6.82			
15/85	6.26	5.44	4.50	4.13

Finally, we can define an e-folding voltage as the H.V. increment necessary to increase the multiplication by a factor of e. Of course $\Delta V_e = 1/\gamma$ and can be read off from Table II; for instance at 1 atm. for

a 50/50 mix $\Delta V_e = 140$ V. Similarly we can define an e-folding pressure where

$$(\Delta p_e)^{-1} \approx \frac{\partial \gamma}{\partial p} (V - V_o) - \gamma \frac{\partial V_o}{\partial p}$$

Using the data in Tables I, II we find, for example, that at 1 atm, a 50/50 mix and $M = 10^4$

$$\Delta p_e \approx - 0.222 \text{ atm}$$

Thus for an increase in atmospheric pressure by 50 mbars the gain will decrease by $\exp(50/222) = 1.25$.

II.3 Parametrization

An analytic expression for the multiplication in gaseous materials has been given by Rose and Korff⁽³⁾ where

$$M = \exp \left[\sqrt{\frac{4kN}{V_T} \left(\frac{C/\ell}{2\pi\epsilon_o} \right) a} \left(V - \sqrt{VV_T} \right) \right] \quad (9)$$

The constants in Eq. (9) are defined as follows:

a anode radius (cm)

C/ℓ chamber capacitance per unit length (pF/m)

$\epsilon_o = 8.85$ pF/m

N = number of molecules per unit volume (cm^{-3})

k = Korff's coefficient in units of cm^2/kV

V_T = Threshold voltage

The threshold voltage V_T is defined as the voltage above which avalanche multiplication begins and can be related to the critical electric field, E_c , for the onset of avalanche multiplication or to the critical radius, r_c , through

$$E_c = \left(\frac{C/\ell}{2\pi\epsilon_0} \right) \frac{V_T}{a} \quad \text{or} \quad \frac{r_c}{a} = \frac{V}{V_T} \quad (10)$$

In general V_T is determined empirically from the data. Korff's coefficient is related to the collision m.f.p. through

$$\frac{1}{\lambda} = \alpha = kN \frac{\epsilon}{e}$$

where ϵ is the electron energy, e the electron charge and N the molecule density. For Argon at atmospheric pressure

$$k = 1.81 \times 10^{-14} \text{ cm}^2/\text{kV}$$

In the case of a gas mixture

$$(kN)_{\text{eff}} = \sum_i k_i N_i$$

where the effects of different pressure are accounted for by the variation of N_i .

Equation (9) was developed from a study of multiplication at low pressure and therefore is not directly applicable to our data.* Instead we used Eq. (9) to determine V_T as a function of gas mix** and pressure and obtained the results shown in Table III.

*Eq. (9) does not fit the data given in Rossi and Staub⁽¹⁾ either.

**We used $k(\text{Ethane}) = 3.2 \times 10^{-14} \text{ cm}^2/\text{kV}$; $a = 10^{-3} \text{ cm}$ and $C/\ell = 2.3 \text{ pF/m}$.

Table III. V_T (in kV) for Argon/Ethane

Mix	Pressure (atm)			
A/E (%)	1	2	3	4
65/35	.77	1.07	1.39	1.70
50/50	.89	1.28	1.69	2.06
15/85	1.14	1.64	2.13	2.64

The above values of V_T agree to within $\sim 10\%$ with the values of V_0 obtained from the simpler relation of Eq. (8) and given in Table I. The values of V_T are plotted in Fig. 7a as a function of (k_{eff}) and in Fig. 7b as a function of pressure. From these graphs V_T can be expressed as follows

$$V_T(\text{kV}) = 1.18 - \frac{1.5}{k_{\text{eff}}} + \left[1.14 - \frac{1.91}{k_{\text{eff}}} \right] p(\text{atm}) \quad (11)$$

where

$$k_{\text{eff}} = \frac{\sum k_i N_i}{\sum N_i} \times 10^{14}$$

and p is the pressure in atmospheres. Using V_T as given by Eq. (11) in Eq. (9) provides a good parametrization of our data for the region $10^1 < M < 10^4$ as indicated by the curves in Figs. 6a,b. The value of $k_{\text{ethane}} = 3.2 \times 10^{-14} \text{ cm}^2/\text{kV}$ was used.

III. RESOLUTION

III.1 X-rays

Since the Fe^{55} source emits monochromatic X-rays the width of the direct peak of the pulse-height spectrum provides a quantitative measure of the resolution of the system. In particular the separation between the escape and direct peaks is an excellent indicator of resolution.

In Fig. 8 we show a pulse-height spectrum obtained at atmospheric pressure with a 50/50 mix of A/Ethane at a multiplication $M = 400$. The width of the peak is governed mainly by the statistical fluctuations in the number of ion pairs produced and only to a lesser degree by the multiplication process. Since n_T is large, the fluctuations can be treated as Gaussian and the curve in Fig. 8 is a Gaussian corresponding to $n_T = 130$. The best value of FWHM/(peak position) that we achieved was 0.192 which is still 23% broader than expected from $n_T = 230$ as given by Eq. (5). The escape peak is clearly separated.

Figure 9a shows oscilloscope traces of the pulse height spectrum for different multiplication (at 1 atm and 50/50 mix). We note a very marked deterioration of the resolution with increasing multiplication. The ratio of the FWHM over the position of the direct peak is plotted in Fig. 9b as a function of multiplication for different gas mixtures; all the data are at atmospheric pressure. The poor resolution at low multiplication can be attributed in part to fluctuations in the multiplication process. Assuming a Gaussian distribution for M and combining it in quadrature with the fluctuations in n_T gives the dashed curve in Fig. 9b. Apart from the intrinsic resolution of the counter the stability of the preamplifier gain also contributes to the broadening of the peak, especially at low signal levels.

The deterioration of the resolution at high multiplication is clearly correlated with the Ethane content of the gas as shown in Fig. 9b. Argon rich mixtures have systematically poorer resolution at high multiplication. The polyatomic quencher is introduced to absorb low energy secondary photons which can photoemit electrons when reaching the cathode (the work function of copper is 7 eV). We believe that the observed effect is due to such secondary emission where at high multiplication the quenching ability of the

Ethane begins to saturate. It is also possible that local discharges contribute to a broadening of the signal. These effects are even more pronounced at high pressure as discussed in Section III.4.

III.2 β -rays

The average energy loss per unit path when a charged particle traverses matter is given by the well known Bethe-Bloch equation

$$-\frac{dE}{dx} = \frac{2\pi N_0 z^2 e^4}{mc^2} \frac{Z}{A} \frac{\rho}{\beta^2} \left[\ln \left(\frac{2mc^2 \beta^2}{I^2} \gamma^2 E_M \right) - 2\beta^2 \right] \quad (12)$$

with the usual definitions

N_0 Avogadro's number

ρ Density of medium

Z, A Nuclear charge and atomic number of the medium (for mixtures an appropriate average is used)

e, m Electron charge and mass

z Charge of incident particle in units of the electron charge

β, γ v/c and $1/\sqrt{1-\beta^2}$ of incident particle

The symbol I stands for the effective ionization potential of the medium and is often quoted at $I = I_0 Z$ where $I_0 \approx 12$ eV; better values for I_0 for different gases can be found in ref. (2). E_M is the maximum energy that can be transferred in a collision

$$E_M = 2mc^2 \frac{E^2 - M^2}{M^2 + 2Em + m^2}$$

where E, M are the energy and mass of the incident particle. For heavy

particles ($M^2 \gg 2Em$) $E_M = 2mc^2 \beta^2 \gamma^2$ whereas for electrons (where $m^2 \ll 2Em$), $E_M = mc^2 \gamma$.

For a path length x through a gas at pressure p it is convenient to introduce an energy scale through the variable ξ

$$\xi = \left(\frac{2\pi N z e^4}{mc^2} \right) \frac{Z}{A} \frac{\rho}{\beta^2} (xp) \quad (13)$$

Then the average energy loss for fast electrons is

$$\overline{\Delta E} = \xi \left[\ln \left(\frac{2(mc^2)^2 \gamma^3}{I^2} \right) - 2 \right] \quad (14a)$$

Numerically for Argon gas ($\rho = 1.782 \times 10^{-3} \text{ g/cm}^3$, $Z = 18$, $A = 40$)

$$\xi_A = 0.123(xp) \text{ keV} \quad (xp) \text{ in cm.atm.}$$

Since Ethane has the same Z as Argon we use the same value of ξ for all A/Ethane mixtures. For the ionization potential we take $I(\text{Argon}) = I(\text{Ethane}) = 284 \text{ eV}$ so that for the 3.54 MeV β -rays we find

$$\overline{\Delta E} = 2.48(xp) \text{ keV} \quad (14b)$$

Since small angle collisions (and therefore small energy transfers) are much more probable than large angle collisions the most probable energy loss is less than $\overline{\Delta E}$, provided $\overline{\Delta E} \ll E$. The distribution of the energy loss in thin samples was first studied by Landau⁽⁴⁾ who defines the most probable energy loss $\Delta E_{m.p.}$ through

$$\Delta E_{m.p.} = \xi \left[\ln \left(\frac{\xi}{\epsilon'} \right) + 1 - C \right]$$

Here C is Euler's constant, $C = 0.577$ and ϵ' is the minimum energy transfer given by

$$\ln \epsilon' = \frac{I^2}{2mc^2 \gamma^2 \beta^2} + \beta^2$$

Therefore

$$\Delta E_{m.p.} = \xi \left[\ln \left(\frac{2mc^2 \gamma^2 \beta^2}{I^2} \xi \right) - \beta^2 + 0.423 \right] \quad (15)$$

The distribution of the energy loss ΔE is given in terms of the reduced energy variable

$$\lambda = \frac{\Delta E - \Delta E_{m.p.}}{\xi} \quad (16a)$$

A good approximation⁽⁵⁾ to the Landau distribution is

$$f(\lambda) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(\lambda + e^{-\lambda})} \quad (16b)$$

which peaks at $\lambda = 0$ and the median is at $\lambda \approx +1.0$. Equation (16b) does not describe correctly the distribution of energy loss in very thin samples. For instance, for Argon gas, Talman⁽⁶⁾ has shown that the Landau limit is approached only when $(xp) \gtrsim 20$ cm.atm. Furthermore, the Talman distribution peaks at $\lambda \approx -1/3$.

In Fig. 10 we show the pulse height spectrum for β -rays* for a 50/50

*The β -rays were selected with a small scintillator to ascertain equal path lengths through the counter volume.

mix at atmospheric pressure. The abscissa is labeled in terms of energy deposition in keV as well as by the reduced energy variable λ defined in Eq. (16a). The absolute value of the energy deposition was determined by calibrating the system using the X-ray source under identical operating conditions. For the 50/50 mix at atmospheric pressure and for $x=(x_p)=4.13$ cm one obtains $\xi = 0.525$ keV. We use $I(\text{Argon}) = I(\text{Ethane}) = 284$ keV to find

$$\Delta E_{m.p.} = 6.345 \text{ keV}$$

and therefore the peak of the distribution is expected at $\Delta E_{\text{peak}} = \Delta E_{m.p.} - (\xi/3) = 6.17$ keV to be compared with the observed value $\Delta E_{\text{peak}} = 6.11$ keV. The average energy loss is $\overline{\Delta E} = 10.22$ keV. Good agreement is also observed at higher pressures and different gas mixtures. For instance for a 50/50 mix

P	ΔE_{peak} (calculated)	ΔE_{peak} (observed)
1 (atm)	6.17 (keV)	6.11 (keV)
2.5	16.62	13.92
4.0	27.59	27.98

The distributions shown in Fig. 10 (1 atm. 50/50 mix) has

$$\frac{\text{FWHM}}{\text{peak}} = 0.67$$

which is much broader than the Landau distribution shown by the dashed curve. The solid curve is a best fit to the data using the distributions calculated by Talman and corresponds to $x_p \approx 2.0$ as compared ^{*} to the actual value of $x_p = 4.13$ cm-atm. The data are broader than the prediction by 16% which is similar to the 23% discrepancy observed for the X-ray source (see Fig. 9);

*Only the widths of the distributions are compared; the peak value corresponds to $x_p = 4.13$ as previously discussed.

analogous effects have been reported in other investigations⁽⁷⁾. The contribution of instrumental resolution to this broadening cannot be completely excluded but is considered to be small.

III.3 Linearity and saturation

The presence of two distinct peaks, direct and escape, in the X-ray pulse height spectrum makes possible an immediate check of the linearity of the counter system. In Fig. 11a we show the collected charge for the direct and escape peaks as a function of H.V. (or multiplication) for a 15/85 mix at 1 atm. The ratio of the two peaks remains constant up to $M \approx 10^3$ and then decreases indicating the onset of saturation, as shown in more detail in Fig. 11b. The expected ratio is $E_{\text{esc}}/E_{\text{direct}} = 0.46$, 6% smaller than observed.

The approach to complete saturation for a 50/50 mix at 1 atm. is shown in Fig. 12 which includes both X-ray and β -ray data. The counter did not enter the Geiger mode even at 3.5 kV; signals were typically 20-50 mV. Occasional discharges with amplitudes of ~ 5 V were observed when the counter was operated at 3.7 kV.

III.4 Pressure broadening

At high pressure the resolution deteriorates both for the X-ray and β -ray spectra. Figures 13a,b give the ratio of FWHM/(peak position) for the X-ray source for 65/35 and 15/85 mixtures of A/Ethane as a function of multiplication for different pressures. For the Argon-rich mixtures the resolution deteriorates with increasing multiplication as also noted in section III.1 for the case of atmospheric pressure. Even at optimum multiplication pressure broadening is clearly evident.

Results for the best resolution achieved are summarized in Table IV where we give the ratio of the observed FWHM/(peak position) divided by the expected FWHM/(peak position). For the X-rays the expected FWHM is calculated as the variance of n_T whereas for the β -rays we use the curves of Talman at the corresponding value of (xp) .

Table IV Ratio of observed to expected FWHM/(peak position)

Gas mix (A/E)	65/35	15/85	50/50
p(atm)	X-rays		β -rays
1	1.23	1.38	1.14
2.5	1.67	2.06	2.01
4.0	2.02	2.80	2.70

A possible explanation for this pressure broadening effect is recombination of the primary electrons.

In Fig. 14 we show oscilloscope traces for the pulse height spectrum of the X-ray source at 4 atm. for a 50/50 mixture. These can be compared to the traces shown in Fig. 9a for the same mix at 1 atm. The broadening of the peak with increasing multiplication is evident and for $M \gtrsim 10^4$ the spectra exhibit a depletion at their central value. As the multiplication is further increased the spectrum separates into two apparent peaks. At the low energy side the peak is saturated and its position is not affected by the applied H.V.; it is not related to the escape peak. The position of the apparent peak at the high energy side continues to grow exponentially with H.V. until complete saturation sets in. This effect is not observed with β -rays and thus cannot be attributed to instrumental effects.

IV. INDUSTRIAL NATURAL GAS

IV.1 Pure Methane Calibration

Commercial gas consists mainly of methane and ethane with 5% higher hydrocarbons by volume. A mercapton compound is added to produce the characteristic odor. The methane/ethane ratio is likely to vary from ~99/1 to ~85/15. We have therefore first examined the performance of the test counter with Argon/Methane mixtures.

In Fig. 15(a) we show the multiplication obtained with a 50/50 mixture of A/Ethane (triangles) and compare it with the yield from a 50/50 mix of A/Methane (solid circles). The counter was operated at 1 atm using the Fe^{55} X-ray source. The Methane mixture has a gain approximately 2.5 times smaller than the Ethane mix. A fit to Eq. (9) yields $k_{\text{ethane}} = 2.8 \times 10^{-14} \text{ cm}^2/\text{kV}$

The resolution of the A/Methane mixture as obtained with the Fe^{55} X-rays is shown in Fig. 15(b) as a function of multiplication. The optimal resolution is similar to that obtained with A/Ethane mixtures. However the deterioration of resolution with increasing multiplication is much less pronounced for the methane mixtures than for ethane. We conclude that CH_4 is a better quenching agent than C_2H_6 contrary to the prediction of the composition law based on photon mean-free-path arguments⁽⁸⁾.

IV.2 Natural gas

To avoid gain fluctuations due to variations in the methane/ethane content of the natural gas a purification column was built; it held ~1 liter of Linde (Union Carbide) Type 3A Molecular Sieve designed to exclude molecules of effective diameter $>3\text{\AA}$. This excludes all but the methane component. The natural gas was introduced at a rate of $200 \text{ cm}^3/\text{min}$ and the

filter remained effective after passing 50 liters of natural gas. Even after 150 liters of gas flow no mercapton could be detected after the filter.

The gain and resolution using the filtered gas was identical to that obtained with pure methane and showed no change after 10 days of operation. This corresponds to approximately 5×10^9 counts, and a collection of ~ 0.01 Coul. of charge on the anode. The pulse height spectrum on the first and tenth day of operation are shown in Figs. 16(a,b). To test the unfiltered gas a new wire was strung and the pulse height spectra for the first and tenth day of operation are shown in Figs. 16(c,d). Some deterioration in resolution can be observed in Fig. 16(d) after operating for 10 days with unfiltered gas.

A possible cause for the deterioration of the resolution when using unfiltered gas is the deposition of organic compounds on the anode wire. However, examination of the wire under 100X magnification failed to reveal such deposits. We conclude that filtered industrial natural gas is an adequate substitute for pure gas in the operation of proportional chambers and counters.

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References and Notes

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2. F. Sauli, Principles of Operation of Multiwire Proportional and Drift Chambers, CERN report 77-09 (1977).
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5. Given by J. E. Moyal, Phil. Mag. 7th Series 46, 263 (1955).
6. R. Talman, Nucl. Instr. and Methods 159, 189 (1979).
7. See for instance S. Csorna et al., "Electron beam test of dE/dx detector" Cornell University, unpublished report, Wilson Synchrotron Laboratory CBX 79-33. These authors find FWHM/(peak position) ≈ 0.82 for a single gap distribution at $x_p = 2.0$.
8. F. Sauli, op. cit., page 13.

Figure Captions

1. Sketch of the test counter.
2. Circuit used for absolute calibration of gain.
3. (a) Oscilloscope traces of the output signal for different discharge resistors; horizontal scale 20 $\mu\text{sec/div}$; vertical scale 3 mV/div for 10 M Ω and 100 k Ω and 2 mV/div for 9.1 k Ω . (b) Decay time vs. shunt resistor.
4. Oscilloscope traces from the X-ray and β -ray sources, at 1 atm. for a 50/50 mix.
5. Multiplication (and induced charge) as a function of H.V. for a 50/50 mix at 1 atm. Triangles: ORTEC preamplifier; solid points: LECROY preamplifier.
6. Multiplication as a function of H.V. (a) for different gas mixtures at 1 atm; solid lines are fits to the Rose and Korff expression (b) for a 50/50 mixture at different pressures; solid lines are fits to Eq. (9) of the text.
7. Values of the threshold voltage V_T used in Eq. (9) of the text as deduced from the data (a) as a function of pressure for different mixtures (b) as a function of gas mix for different pressures.
8. Pulse height spectrum of the 5.9 KeV Fe^{55} X-ray source for a 50/50 mixture at 1 atm and $M = 400$. The curve is a Gaussian with $\sigma(E)/E=0.089$. The escape peak is clearly separated.
9. (a) Oscilloscope traces of the X-ray source p.h. spectrum for a 50/50 mixture at 1 atm. for different multiplications (b) FWHM/(direct peak) for the X-ray source as a function of multiplication for different gas mixtures at 1 atm.
10. Landau spectrum of the energy loss of 3.54 MeV β -rays for a 50/50 mixture at 1 atm. The abscissa is calibrated in eV and also in terms of the reduced energy variable λ (see Eq. (16a)). The dashed curve is

Eq. (16b) of the text; the solid curve is obtained from Ref. 6 and is fit to the data as discussed in the text.

11. (a) Pulse height of the direct and escape peaks produced by 5.9 KeV X-rays as a function of H.V. for a 15/85 mixture at 1 atm.
(b) The ratio of the escape peak over the direct peak as a function of H.V.
12. Saturation of the multiplication for X-rays and β -rays for a 50/50 mix at 1 atm.
13. (a) FWHM/(direct peak) for X-rays as a function of multiplication for different pressures for a 65/35 gas mixture (b) as in (a) for a 15/85 mixture.
14. Oscilloscope traces of the X-ray source spectrum for a 50/50 mix at 4 atm., for different multiplications. At high multiplication the spectrum appears "depleted" at its central value.
15. Comparison of A/Ethane and A/Methane, 50/50 mixtures at 1 atm.
(a) Multiplication; triangles Ethane, solid circles Methane.
(b) Resolution for A/Methane mix at 1 atm.
16. Pulse height spectra for filtered and unfiltered A/(Natural gas) 50/50 mixture on the first day and after 10 days of operation at 1 atm.

Fig. 1

Fig. 2

$$R_s = 9.1 \text{ K}\Omega$$

$$R_s = 100 \text{ K}\Omega$$

$$R_s = 10 \text{ M}\Omega$$

Fig. 3(a)

$20 \mu\text{s}/\text{div.}$

Fig. 3(b)

X-rays
 $M \approx 400$

(a)

β -rays
 $M \approx 7200$

(b)

Fig. 4

Fig. 5

Fig. 6(a)

Fig. 6(b)

Fig. 7(a)

Fig. 7 (b)

Fig. 8

50/50; 1 atm X-rays

$M \approx 160$

$M \approx 2600$

$M \approx 10500$

$M \approx 44000$

Fig. 9(a)

Fig. 9(b)

Fig. 10

Fig. 11

Fig.12

Fig. 13

50/50; 4 atm X-rays

$M \approx 1800$

$M \approx 4500$

$M \approx 10000$

$M \approx 30000$

Fig. 14

Fig. 15(a)

Fig. 15(b)

Filtered Gas

Unfiltered Gas

Day 1

(a)

(b)

Day 10

(c)

(d)

Fig.16