

gaseous volume of the counter. In the Geiger-Müller counter a considerable contribution to the total ionization arises from photoelectrons ejected by photons which accompany the process of collision or recombination. Since the total number of ion pairs produced in an ionization chamber is proportional to the energy loss of the particle within the chamber, the time integral of the current pulse or total charge collected on one of the electrodes is a measure of this energy loss. This is also true of a proportional counter. In a Geiger-Müller counter, however, the time integral of the current pulse is almost entirely independent of the amount of primary ionization and no information on the energy loss of the primary particle can be obtained from the pulse size.

The most recently developed detector, the scintillation counter, makes use of the fluorescence radiation emitted when a charged particle passes through certain materials. It is interesting to note that the earliest detectors used in nuclear physics were based on this principle. The observation of the fluorescence was done visually. In the modern version of this instrument the fluorescence is recorded by photocells.

In the cloud chamber the presence of ions is recorded by direct observation. Condensation of a suitable vapor takes place preferentially on an electric charge, and this results in the formation of a visible drop of liquid around each ion present during the period of condensation.

The photographic plate method finally makes use of the fact that an ionizing particle passing through a photographic emulsion renders developable some of the silver halide grains located in the path of the particle. The photographic plate therefore registers, as the cloud chamber does, the path of the particle. From the records it is possible to determine not only its direction of propagation but to a certain extent also the energy and the nature of the particle. The great advantage of the photographic plate is its continuous sensitivity to particles, whereas the cloud chamber is sensitive only during a very small fraction of the observation time.<sup>1</sup>

## SECTION 2. FUNDAMENTAL PRINCIPLES OF PARTICLE DETECTION

### A. The Motion of Ions and Electrons in Gases

The majority of present-day detectors are based on the ionization produced by the passage of a charged particle through a gas. The number of ion pairs, i.e., positive gas ions and free electrons, depends on

<sup>1</sup> Editor's note: For monographic treatment of several of the subjects in this part recently added to the literature see (C6, W11, W12).

the loss of energy which the particle undergoes in the gaseous volume under consideration. Over a wide range the number of ion pairs is proportional to this energy loss, or, in other words, the average amount of energy  $I_0$  spent in the production of one ion pair depends only little on the velocity of the primary particle. Moreover, it does not depend very markedly on the nature (charge) of the primary. The quantity  $I_0$  varies somewhat for different gases but is generally around 30 ev. A number of values of  $I_0$  for various gases is given in Table 1. (See also Part II.)

TABLE 1  
ENERGY PER ION PAIR,  $I_0$

Gas	$I_0$ (ev)	Particle and Energy		
Air	32.0	electrons	0.3 Mev	(G4)
Air	36.0	protons	2.5-7.5 Mev	
Air	35.1	$\alpha$ -particles	7.8 Mev	
Air	35.6	$\alpha$ -particles	5.3 Mev	
Hydrogen	36.0	$\alpha$ -particles	5.3 Mev	(A3)
Helium	31.0	$\alpha$ -particles	5.3 Mev	
Nitrogen	36.3	$\alpha$ -particles	5.3 Mev	(S2)
Carbon monoxide	34.7	$\alpha$ -particles	5.3 Mev	
Carbon dioxide	34.6	$\alpha$ -particles	5.3 Mev	(B17)
Ethylene	27.6	$\alpha$ -particles	5.3 Mev	
Ethylene	28.2	$\alpha$ -particles	5.3 Mev	
Acetylene	27.6	$\alpha$ -particles	5.3 Mev	(S2)
Neon	27.8	$\alpha$ -particles	5.3 Mev	
Argon	24.9	$\alpha$ -particles	5.3 Mev	(N4)
Argon	26.9	electrons	17.4 kev	
Krypton	23.0	$\alpha$ -particles	5.3 Mev	(S2)
Xenon	21.4	$\alpha$ -particles	1.3 Mev	(G5)
Xenon	21.3	electrons	0.042 Mev	(W1)

Most of the electrons knocked out by the primary particle have comparatively little energy and will not travel over appreciable distances. Occasionally, however, high-energy electrons (delta-rays) are formed which have a range in air at normal temperature and pressure in excess of 1 mm. On the other hand, most of the primary-ionization electrons will still have sufficient energy to produce additional ionization. This additional ionization is called secondary ionization and might account for the larger fraction of the total ionization. The values of  $I_0$  given in Table 1 refer to the total ionization.

The total ionization produced by particles undergoing the same energy loss  $U$  in the gas will exhibit certain statistical fluctuations. The mean

square fluctuation  $\Delta n^2$  of the number of ion pairs would be

$$\Delta n^2 = n = \frac{U}{I_0}$$

if the number of ionization events were governed by Poisson's law. However, this is not the case, and consequently

$$\Delta n^2 = F \frac{U}{I_0}$$

where  $F$  is a numerical factor smaller than 1. As Fano (F1) has shown,  $F$  should be generally of the order of  $\frac{1}{3}$  to  $\frac{1}{2}$ .

After the ionization process has been completed, electrons and ions will move in a random fashion, and, unless they are separated by an external electric field, they will recombine. The originally free electrons often attach themselves to neutral gas molecules and thereby form negative heavy ions. The probability of attachment depends very strongly on the energy of the electron and the nature of the gas.

1. **Diffusion and Drift.** If an external field is applied to the gas, the motion of the charges will produce a current the density  $\mathbf{j}$  of which is given by

$$\begin{aligned} \mathbf{j} &= \mathbf{j}^+ + \mathbf{j}^- \\ \mathbf{j}^+ &= n^+ e \mathbf{w}^+ - D^+ e \text{grad } n^+ \\ \mathbf{j}^- &= -n^- e \mathbf{w}^- + D^- e \text{grad } n^- \end{aligned} \quad (1)$$

Here  $\mathbf{j}^+$  and  $\mathbf{j}^-$  represent the current densities of positive and negative particles of charge  $\pm e$ , respectively.  $n^+$  and  $n^-$  are their densities,  $\mathbf{w}^\pm$  their drift velocities, and  $D^\pm$  their coefficients of diffusion. The first term of the equation represents a current caused by the external electric field, the drift velocity being parallel to the electric field. The second term represents the diffusion current. The drift velocity should not be confused with the agitational velocity  $u$ , the direction of which is at random and causes the diffusion current, represented by the second term. In fact, the value  $w$  of  $|\mathbf{w}|$  is usually of orders of magnitude smaller than that of  $u$ . Moreover,  $w$  for free electrons is usually several orders of magnitude larger than for positive or negative ions. This is the reason why the operation of fast detectors often depends on the motion of free electrons alone.  $w$  and  $D$  depend, of course, on the velocity of agitation.

The particle densities  $n^+$  and  $n^-$  are given by the continuity relations

$$\begin{aligned} \frac{\partial n^+}{\partial t} &= D^+ \nabla^2 n^+ - \text{div}(n^+ \mathbf{w}^+) - \alpha n^+ n^- + n_0 \\ \frac{\partial n^-}{\partial t} &= D^- \nabla^2 n^- - \text{div}(n^- \mathbf{w}^-) - \alpha n^+ n^- + n_0 \end{aligned} \quad (2)$$

where  $n_0$  represents the time rate of production of ion pairs per unit volume, and the term  $\alpha n^+ n^-$  accounts for the loss due to recombination which is proportional to the product of the two densities.  $\alpha$  is the coefficient of recombination.

If it is assumed that at a time  $t = 0$  a distribution of ions  $n_0(x', y', z')$  exists in an unbounded volume and that  $\mathbf{w}$  and  $D$  are constants such that  $\mathbf{w}$  has always the direction of the  $+Z$  axis and that no additional ions are produced and no recombination takes place, the solution of the above equation giving the charge distribution at any subsequent time is

$$n^\pm(x, y, z, t) = \frac{1}{8(\pi t D^\pm)^{3/2}} \iiint_{-\infty}^{+\infty} n_0^\pm(x', y', z') \cdot e^{-\frac{(x-x')^2 + (y-y')^2 + (z-z'-w^\pm t)^2}{4D^\pm t}} \cdot dx' dy' dz' \quad (3)$$

2. **The Motion of Free Electrons.** If the ionization electrons do not form negative ions by attachment, in a uniform electric field they will usually acquire a constant average velocity of agitation and a constant drift velocity after a very short path involving a few collisions. The velocity of agitation is usually considerably higher than the value corresponding to temperature equilibrium in the gas. It depends on the ratio  $E/p$  of field strength to gas pressure. This is readily understood if one considers that electrons lose only a small fraction of their energy in a purely elastic collision with gas molecules and gain energy from the electric field between collisions. If, on the other hand, sufficient energy is gained so that frequent inelastic collisions between electron and gas molecules occur, the velocity of agitation will be determined by the energy of the level excited by inelastic collision.

If the average velocity of agitation of the electrons is defined as

$$\bar{u} = \frac{\int_0^\infty u f(u) du}{\int_0^\infty f(u) du} \quad (4)$$

where  $f(u) du$  is the number of electrons with velocity between  $u$  and  $u + du$ , the coefficient of diffusion  $D$  is given by

$$D = \frac{1}{3} \bar{l} \bar{u} \quad (5)$$

where  $\bar{l}$  is the mean free path assumed to vary only slowly with  $u$ .

From conservation of momentum and energy the following relations between the electric field strength  $E$  and the velocities  $u$  and  $w$  can be obtained. For simplicity's sake it will be assumed that the electrons have the same velocity of agitation  $u = \bar{u}$ , large compared to  $w$ , and that in every collision the velocity of the particle is completely "randomized," i.e., the directions of the velocities before and after the collision shall not be correlated. Under these conditions the average displacement  $s$  of the electron between two collisions in the direction of the field  $E$  is given by

$$s = \frac{2}{3} \frac{E}{em} \frac{\bar{l}^2}{u^2} \quad (H5)$$

where  $m$  is the mass of the electron and  $\bar{l}$  its mean free path. In deriving this expression one has to consider that

$$\overline{l^2} = 2(\bar{l})^2$$

Since the average number of collisions per unit time is

$$z = \frac{u}{\bar{l}}$$

the drift velocity  $w$  is given by

$$w = \frac{2}{3} \frac{E}{p} \frac{e}{m} L \cdot \frac{1}{u} \quad (6)$$

where  $L = \bar{l}p$  is the mean free path at unit gas pressure.

Denoting by  $\epsilon$  the average fraction of its own energy lost by the electron in one collision, and equating the energy gained between collisions to that transferred to the gas gives

$$eE \cdot w = eEw = \epsilon \frac{m}{2} \frac{u^3}{\bar{l}} = \epsilon \frac{m}{2} \frac{p}{L} u^3$$

When the relation between  $u$  and  $w$  is combined with Eq. (6), it becomes

$$w^2 = \frac{1}{3} \epsilon u^2 \quad (7)$$

Relations (6) and (7) are derived by assuming that the velocity  $u$  varies only little among the various electrons and between collisions. Actually

the electrons will have a certain velocity distribution, and, if  $u$  is identified with  $\bar{u}$  as defined in Eq. (4), a suitable numerical factor of the order of unity will enter in Eqs. (6) and (7). The value of this factor for different velocity distributions is found in (H5).

From the two relations, (6) and (7), it can be seen immediately how the drift velocity can be determined for a mixture of gases if the quantities  $\epsilon$  and  $L$  are known for the individual components. Since  $1/\bar{l}$  represents the average number of collisions per unit path, for the mixture

$$\frac{1}{\bar{l}} = \sum_i \frac{1}{\bar{l}_i} = \sum_i \frac{p_i}{L_i}$$

where  $\bar{l}_i$  and  $p_i$  are mean free path and partial pressure of the  $i$ th component. Similarly, the fractional loss of energy per unit path in the mixture is

$$\frac{\epsilon}{\bar{l}} \frac{m}{2} u^2 = \frac{m}{2} u^2 \sum_i \frac{\epsilon_i}{\bar{l}_i}$$

where  $\epsilon_i$  is the fractional loss of energy in a collision with a molecule of the  $i$ th component. Thus, for a gas mixture,

$$w = \frac{2E}{3} \frac{e}{p} \frac{1}{m} \frac{1}{\sum_i c_i/L_i} \cdot \frac{1}{u} \quad (8)$$

where  $c_i = p_i/p$  is the concentration of the  $i$ th component,  $p$  the total pressure, and

$$w^2 = \frac{1}{3} u^2 \frac{\sum_i \epsilon_i c_i/L_i}{\sum_i c_i/L_i} \quad (9)$$

In Table 2 the quantities  $u$ ,  $w$ ,  $L$ , and  $\epsilon$  are given for various gases as functions of  $E/p$ . In addition, the quantity  $h$ , the probability of attachment (see below), is given in the last column.

In Table 3a the drift velocity of electrons in a mixture of 95% argon and 5% carbon dioxide is given for various values of  $E/p$ . In Table 3b the values of the drift velocity are listed for boron trifluoride. The values of  $w$  in Table 3a are an excellent example of the way in which the drift velocity of electrons can be changed by a small admixture of a second gas (N1). For the same value of  $E/p$  the drift velocity is considerably larger in the mixture than in pure argon. As a consequence this mixture has found a wide application in fast ionization chambers. The increase of  $w$  is readily understood by considering Eqs. (6), (7), (8), and (9). At a value of  $E/p = 1$ , for example, the velocity of agitation is quite high ( $2 \times 10^8$  cm/sec) in pure argon because the first excitation potential of argon is at 11.5 volts. The mean free path  $L$  is

TABLE 2

The data presented in this table are taken from Healey and Reed (H5).

$E$  field strength, in volts per centimeter  
 $p$  gas pressure, in millimeters of mercury  
 $u, w$  the velocity of agitation and drift velocity, in centimeters per second  
 $L$  mean free path of electron at 1 mm pressure, in centimeters  
 $\epsilon$  average fraction of energy lost by electron in one collision  
 $h$  probability of attachment per collision

(a) *Hydrogen*: J. S. Townsend and V. A. Bailey, *Phil. Mag.*, **42**, 873 (1921)

$E/p$	$u \times 10^{-7}$	$w \times 10^{-6}$	$L \times 10^2$	$\epsilon \times 10^4$
0.25	2.02	0.65	3.64	26
0.5	2.62	0.90	3.25	29
1	3.5	1.19	2.86	28.5
2	4.3	1.60	2.39	34
5	5.9	2.55	2.14	46
10	7.62	3.8	2.05	62
20	10.15	7.0	2.5	117
40	13.1	16.0	3.67	368
50	14.0	21.7	4.2	590

(b) *Nitrogen*: J. S. Townsend and V. A. Bailey, *Phil. Mag.*, **42**, 873 (1921)

$E/p$	$u \times 10^{-7}$	$w \times 10^{-6}$	$L \times 10^2$	$\epsilon \times 10^4$
0.25	3.15	0.515	4.50	6.5
0.5	4.14	0.62	3.55	5.5
1	5.35	0.87	3.20	6.5
2	6.35	1.31	2.88	10.3
3	6.85	1.78	2.82	16.5
5	7.4	2.7	2.77	33
10	8.0	4.85	2.69	90
20	8.85	8.6	2.66	234
40	10.8	14.6	2.75	448
60	12.9	19.3	2.89	550

(c) *Oxygen*: R. H. Healey and C. B. Kirkpatrick, 1939

$E/p$	$u \times 10^{-7}$	$w \times 10^{-6}$	$L \times 10^2$	$\epsilon \times 10^4$	$h \times 10^5$
0.25	2.7	1.33	10.0	60	10.4
0.5	3.55	1.61	7.9	51	7.25
1	5.01	1.63	5.00	20.0	2.2
2	6.5	1.69	3.80	15.5	...
5	7.54	2.73	2.86	32.4	5.2
10	8.29	4.06	2.86	88	16.7
15	8.71	6.70	2.71	145	17.2
20	9.05	8.15	2.57	199	7.0
30	9.7	9.95	2.23	260	0
50	11.2	15.9	2.47	494	0

TABLE 2 (Continued)

(d) *Helium*: J. S. Townsend and V. A. Bailey, *Phil. Mag.*, **46**, 657 (1923)

$E/p$	$u \times 10^{-7}$	$w \times 10^{-6}$	$L \times 10^2$	$\epsilon \times 10^4$
0.013	1.53	0.111	9.14	1.30
0.02	1.68	0.133	7.8	1.56
0.05	2.12	0.214	6.6	2.3
0.1	2.87	0.296	5.95	2.6
0.2	3.87	0.393	5.3	2.5
0.5	5.06	0.574	4.6	2.3
1	8.4	0.825	4.85	2.4
2	11.8	1.27	5.25	2.85
3	13.5	1.75	5.5	4.15
4	14.2	2.35	5.85	6.75
5	15.1	3.02	6.4	9.8

(e) *Argon*: J. S. Townsend and V. A. Bailey, *Phil. Mag.*, **44**, 1033 (1922)

$E/p$	$u \times 10^{-7}$	$w \times 10^{-6}$	$L \times 10^2$	$\epsilon \times 10^4$
0.125	11.5	0.31	20	0.179
0.195	12.6	0.325	14.7	0.164
0.355	14.5	0.36	10.3	0.152
0.525	16.3	0.415	9.0	0.160
0.71	17.8	0.485	8.5	0.182
0.95	19.3	0.60	8.5	0.238
1.25	20.6	0.77	8.9	0.345
5	20.2	4.0	11.3	0.97
10	20.7	6.5	9.4	2.43
15	20.7	8.2	7.9	3.86

(f) *Carbon Dioxide*: J. B. Rudd

$E/p$	$u \times 10^{-7}$	$w \times 10^{-6}$	$L \times 10^2$	$\epsilon \times 10^4$
2.0	1.6	1.3	0.7	160
3.5	2.0	2.6	1.0	400
4.5	2.8	4.4	1.8	590
6.0	4.0	6.6	3.1	655
7.5	5.6	8.7	4.5	583
9.0	6.8	10.2	5.3	555
11.0	8.0	11.9	5.8	535
14.0	8.8	13.0	5.9	530
16.0	9.6	13.9	5.8	510

(g) *Water Vapor*: V. A. Bailey and W. E. Duncanson, *Phil. Mag.*, **10**, 145 (1930)

$E/p$	$u \times 10^{-7}$	$w \times 10^{-6}$	$L \times 10^2$	$\epsilon \times 10^4$	$h \times 10^5$
12	2.21	3.0	0.37	423	0.6
14	2.72	3.5	0.48	418	1.9
16	3.37	4.2	0.63	400	13
20	4.98	6.2	1.07	369	30
24	7.00	8.1	1.65	328	45
32	8.04	9.6	1.69	352	50

rather small ( $9 \times 10^{-2}$  cm), and consequently according to Eq. (6) the drift velocity is low ( $0.6 \times 10^6$  cm/sec). If now 5%  $\text{CO}_2$  is admixed, the collisions of the electrons with the carbon dioxide molecules will keep the value of  $u$  much lower, at about  $7 \times 10^7$  cm/sec, since carbon dioxide possesses excitation levels at low energies. The actual mean free path in the mixture for a collision with a carbon dioxide molecule is about 2.5 times larger than that for a collision with an argon

TABLE 3

Notations as in Table 2. The values presented in this table were measured by the Los Alamos Laboratory; see (N1).

## (a) 95% Argon plus 5% Carbon Dioxide

$E/p$	$w \times 10^{-6}$	$E/p$	$w \times 10^{-6}$
0.03	0.55	0.6	4.4
0.05	1.00	0.76	4.2
0.16	2.3	1.5	4.5
0.22	3.7	2.25	4.3
0.3	4.1	3.0	4.6
0.45	4.5		

(b) Boron Trifluoride Obtained from Thermal Decomposition of  $\text{C}_6\text{H}_5\text{N}_2\text{BF}_4$   
( $p = 379$  mm)

$E/p$	$w \times 10^{-6}$	$E/p$	$w \times 10^{-6}$
1.4	19	4.9	57
3.3	45	6.6	75

atom at this lower value of  $u$ . In pure argon at  $u = 7 \times 10^7$  cm/sec the mean free path is about  $40 \times 10^{-2}$  cm, the increase being caused by the Ramsauer effect (M7). The effective total mean free path  $L$  in the mixture is about  $30 \times 10^{-2}$  cm. As a consequence of the lower value of  $u$  and the increase in  $L$ , the drift velocity will be increased by a factor of about 9. The observed values in Table 3a are in substantial agreement with the values calculated from Eqs. (8) and (9).

In many gases the electrons will, after a certain number of collisions with neutral gas molecules, attach themselves and form negative ions, which show a behavior quite similar to that of the positive ions. In particular, their drift velocity is of course quite small compared to that of the free electrons. The rate of formation of negative ions is given by the attachment probability  $h$ , defined as the probability that an electron attaches itself to a molecule with which it collides. The quantity  $h$  depends quite markedly on the velocity of agitation of the electron and varies by orders of magnitude for different gases. Values of  $h$  are given

for various gases and velocities in Table 2. No finite attachment probability has been measured for the noble gases and for hydrogen, nitrogen, carbon dioxide.

The coefficient  $\alpha$  of recombination of free electrons and positive ions seems to be similar for most gases. For electrons of 0.4-eV energy in argon Kenty (K3) finds a value

$$\alpha = 2 \cdot 10^{-10} \text{ cm}^3 \text{ sec}^{-1}$$

**3. The Motion of Positive and Negative Ions.** The drift velocity of positive and negative ions differs from that of free electrons, not only by the different order of magnitude, but also in so far as the drift velocity is proportional to the field strength and inversely proportional to the pressure over a wide region. Thus, generally,

$$w = \frac{\mu E}{p} \quad (10)$$

where  $\mu$  is the ion mobility at standard (760 mm Hg and  $15^\circ\text{C}$ ) pressure and temperature. The proportionality of  $w$  with the field strength is caused by the fact that the ions will always have an agitational velocity which is essentially that of the gas molecules in thermal equilibrium. The values of  $\mu$  for positive and negative ions differ only little. For the gases commonly used in ionization chambers the values of  $\mu^+$  and  $\mu^-$  are given in Table 4.

TABLE 4

Values of mobilities  $\mu^+$  and  $\mu^-$  of positive and negative ions in  $\text{cm}^2 \text{ sec}^{-1} \text{ volt}^{-1}$  at 760 mm pressure and  $15^\circ\text{C}$ , coefficients of diffusion in  $\text{cm}^2 \text{ sec}^{-1}$ , and coefficient of recombination  $\alpha$  in  $\text{cm}^3 \text{ sec}^{-1}$ . Data are average values of those listed in *International Critical Tables*, Vol. VI.

Gas	$\mu^+$	$D^+ \times 10^2$	$\mu^-$	$D^- \times 10^2$	$\alpha \times 10^6$
Air	1.37	3.2	1.8	4.2	1.5
Hydrogen	5.7	...	8.6	...	1.5
Nitrogen	1.29	2.9	1.82	4.1	...
Oxygen	1.33	3.0	1.80	4.1	1.6
Irridium	5.1	...	6.3	...	...
Argon	1.37	...	1.7	...	...
Carbon dioxide	0.79	2.5	0.95	2.6	1.6
Water vapor	0.69	...	0.72	...	...
Sulfur dioxide	0.41	...	0.41	...	1.31
Acetylene	0.71	...	0.86	...	...
Benzene	0.18	...	0.21	...	...
Ethane	...	...	1.07	...	...
Ethylene	...	...	0.75	...	...
Methyl bromide	0.29	...	0.28	...	...
Methyl iodide	0.23	...	0.23	...	0.56

The coefficient of diffusion for ions is related to the mobility by Eq. (5):

$$D = \frac{1}{3} \bar{u} w$$

and  $w$  by a relation of the form of Eq. (6):

$$w = \frac{2Ee}{3pm} L \left( \frac{1}{u} \right)$$

Since for ions  $u$  will essentially show a Maxwellian distribution with

$$f(u) = Au^2 \exp(-\beta u^2)$$

$$\bar{u} = \frac{2}{\sqrt{\beta\pi}} \left( \frac{1}{u} \right) = 2 \sqrt{\frac{\beta}{\pi}} \quad \beta = \frac{m}{2kT}$$

the mobility is

$$\mu = \frac{e}{kT} D p \quad (11)$$

Direct measurements of  $D$  have shown that this relation is very closely satisfied.

For gas mixtures the mobility generally can be found according to a simple mixture rule (P4):

$$\frac{1}{\mu_{12}} = \frac{p_1}{p} \frac{1}{\mu_1} + \frac{p_2}{p} \frac{1}{\mu_2} \quad (12)$$

where  $p_1$  and  $p_2$  are the partial pressures of the two components,  $p = p_1 + p_2$  the total pressure,  $\mu_1, \mu_2$  the mobilities of the components.

The coefficients of recombination for positive and negative ions differ again only slightly for various gases. They are generally about  $10^4$  times larger than for electrons and positive ions. Some of the values are listed in Table 4.

**4. Recombination.** The recombination of electrons and positive ions or positive and negative ions is responsible for the so-called saturation phenomena in ionization chambers. For any given ionization the ionization current will increase with applied voltage and eventually reach a value which is solely determined by the amount of ionization present (see Section 2B). Saturation occurs as soon as no recombination takes place. The fields necessary to reach saturation depend entirely on the density of ionization at every point of the ionization chamber. If ionization occurs along densely ionizing particles, it is within a track that the densities are highest and consequently the chance for recombination largest. This type of recombination is called columnar recombination.

Its theoretical treatment has been given by Jaffé (11). In particular, it should be pointed out that the field strength required for saturation is very much higher for an ionized track in the direction of the electric field than for one perpendicular to it. The reason for this is that if the field is perpendicular to the track the ions of different sign are much more quickly removed from each other than in a track parallel to the field. It should also be pointed out that saturation is much more readily achieved if the negative particles are electrons, since even at very low fields, where diffusion is important, their high coefficient of diffusion separates them more readily from the positive ions and since, moreover, their coefficient of recombination is much smaller. Various observers (K6, J2, O1) have shown that the removal of gases apt to form negative ions results in a lowering of the saturation voltage by a large factor.

**5. Purification of Gases.** The requirements for purity of the gases in a detector are usually quite exacting in so far as contaminations by electronegative gases, forming negative ions, are concerned. As an example, let us consider an ionization chamber 1 cm in depth, filled with nitrogen at 1 atm contaminated by oxygen and water vapor and operating at 760 v/cm field strength. From Table 2,

$$u = 5.35 \times 10^7 \text{ cm/sec} \quad w = 0.87 \times 10^6 \text{ cm/sec}$$

The mean free path at this velocity at 1 mm pressure and the attachment probability for  $O_2$  and  $H_2O$  are

$$O_2: \quad L = 5 \times 10^{-2} \text{ cm} \quad h = 2 \times 10^{-5}$$

$$H_2O: \quad L = 1.3 \times 10^{-2} \text{ cm} \quad h = 35 \times 10^{-5}$$

If  $p$  is the total pressure,  $d$  the distance over which the electrons drift, the probability that an electron forms a negative ion is

$$P = \frac{udchp}{wL}$$

where  $c$  is the concentration of the impurity. If  $P$  should be not more than 1 percent, the concentration  $c$  for  $O_2$  and  $H_2O$  should be smaller than

$$O_2: \quad c < 0.5 \times 10^{-3}$$

$$H_2O: \quad c < 0.8 \times 10^{-5}$$

In order to obtain these very high purities it is usually necessary to employ various purification processes. For the noble gases the most efficient and simple procedure is the one used by Jentschke and Frankl

(J2). The gas is passed over metallic calcium at a temperature of approximately 150° to 250°C. Hot calcium removes all commonly present electronegative impurities and, in addition, nitrogen, hydrogen, and, to a lesser degree, carbon dioxide. Thus a mixture of argon and carbon dioxide should contain a surplus of carbon dioxide in order to

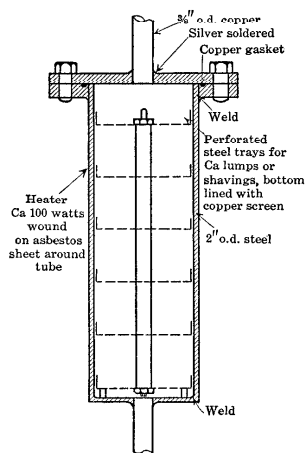


Fig. 1. Hot calcium purifier.

should subsequently be passed through liquid-air-cooled traps to remove the water vapor.

Nitrogen is most readily cleaned of oxygen by passing the gas over hot metallic copper.

Very often careful distillation of the liquefied gases leads to good results. Thus, for instance, boron trifluoride might be condensed at liquid-air temperature and then be distilled into the detector at the temperature of solid carbon dioxide. Although this procedure is often sufficient, it does not entirely remove impurities leading to negative-ion formation. If highest purity of boron trifluoride is desired, synthesis of the gas is advisable according to the following process (B1). Calcium fluoborate is formed by mixing calcium fluoride with a boron trifluoride-ether complex. The latter can be obtained by dissolving boron trifluoride in dimethyl or diethyl ether. The calcium fluoborate should be out-

account for the loss in the purification process. If noble gases without admixture are used, continuous purification, removing impurities released in the ionization chamber, is very convenient. A purifier of this type is shown in Fig. 1. It consists of a steel tube containing trays filled with metallic calcium permanently attached to the chamber. An electric heater brings the calcium to the appropriate temperature, and, since the purifying column is in a vertical position, the gas circulates continuously as a result of thermal convection.

For the purification of hydrogen, circulation of the gas over platinum asbestos at a temperature of about 300°C is suitable for the removal of oxygen by formation of water. The gas

gassed by heating it to 100°C in *vacuo* for about a day. Boron trifluoride is finally obtained by thermal decomposition of calcium fluoborate at a temperature of 180° to 250°C.

## B. Ionization Chambers

**1. Ionization Currents.** If the electric field across the gaseous volume of the detector is small enough that the ions and electrons do not gain sufficient energy between collisions to produce additional ionization, we are dealing with an ionization chamber. For very low fields electrons may form negative ions, and losses due to recombination, particularly within densely ionized tracks, might occur. Thus for a given ionization the ionization current flowing in the outer circuit of a chamber (Fig. 2) increases with increasing collecting voltage  $V_0$  but eventually shows saturation if recombination becomes negligible. The value of the field strength at which saturation is reached will depend markedly on the gas, its purity, and the density of the ionization. Even for a small average ionization, large fields might be required if the individual tracks show high ion density. If the field strength is sufficiently increased, further secondary ionization can occur. This might possibly happen even before saturation is reached. The production of secondary ionization by the motion of the electrons in the applied field is characteristic of proportional and Geiger counters and will be discussed subsequently.

The current densities caused by the motion of positive and negative ions or electrons are given by Eq. (1). For most practical cases the second term, which is due to diffusion, can be neglected at reasonably high fields. If, for instance, an ionization chamber is filled with argon at atmospheric pressure and a field of 760 v/cm is applied, according to Eq. (3) diffusion will cause, during the time  $t$ , an average displacement of the ions equal to

$$s_D = \sqrt{2Dt}$$

and the external field will displace them by

$$s_P = w \cdot t$$

The ratio of the two displacements is therefore

$$\frac{s_D}{s_P} = \sqrt{\frac{2D}{ws_P}}$$

Let us assume that the ions and electrons have to be swept over a path of 1 cm. For electrons we find from Table 2 that diffusion will produce a spread of 0.15 cm, whereas for ions we find, from Table 4, a spread of

0.008 cm. Thus for most practical cases diffusion might be neglected except in considerations of the finer details of the motion.

Besides neglecting diffusion we shall now also disregard recombination and moreover assume that the negative particles are either all electrons or negative ions. As drift velocities are always very small compared to light velocity, and if the ionization does not change materially within times comparable to the transit time of an electromagnetic wave through the detector, we can disregard any magnetic effect. Static magnetic fields can be taken into account easily. Then the power fed by the voltage supply (Fig. 2) to the chamber is equal to the sum of the power delivered to the gas, by the motion of the ions through collisions, and the rate of change in electrostatic energy of the chamber:

$$IV_0 = \int_{\text{vol}} \mathbf{E} \cdot \mathbf{j} \, d\tau + \frac{\partial}{\partial t} \int_{\text{vol}} \frac{E^2}{8\pi} \, d\tau$$

$I$  represents the total ionization current as measured on the external meter,  $\mathbf{E}$  the actual electric field strength (modified

by space charges), and  $\mathbf{j}$  the current density as given by Eq. (1). From this and Eq. (2) the charge density, neglecting diffusion, becomes

$$\frac{\partial \rho}{\partial t} = e \frac{\partial}{\partial t} (n^+ - n^-) = -\text{div } \mathbf{j} = -e \text{div} (n^+ \mathbf{w}^+ - n^- \mathbf{w}^-)$$

The field  $\mathbf{E}$  can be decomposed into two parts,  $\mathbf{E} = \mathbf{E}_0 + \mathbf{E}_1$ , where the first term is caused by the external source of emf and  $\mathbf{E}_1$  by the space charges. Introducing the potentials  $\phi_0$  and  $\phi_1$  gives

$$\text{div } \mathbf{E}_0 = -\nabla^2 \phi_0 = 0$$

$$\text{div } \mathbf{E}_1 = -\nabla^2 \phi_1 = 4\pi\rho = 4\pi e(n^+ - n^-)$$

The boundary conditions for an ideally closed chamber as shown in Fig. 2 are

$$\phi_1 = 0 \text{ at both electrodes, } \phi_0 = V_0 \text{ or } 0, \text{ respectively.}$$

$E_0$  is independent of  $t$ , and  $I$  becomes

$$I = \frac{1}{V_0} \left\{ e \int \mathbf{E}_0 \cdot (n^+ \mathbf{w}^+ - n^- \mathbf{w}^-) \, d\tau + \int \mathbf{E}_1 \cdot \mathbf{j} \, d\tau + \frac{1}{4\pi} \left[ \frac{\partial}{\partial t} \left( \int \text{grad } \phi_0 \cdot \text{grad } \phi_1 \, d\tau \right) + \int \text{grad } \phi_1 \cdot \frac{\partial}{\partial t} \text{grad } \phi_1 \, d\tau \right] \right\}$$

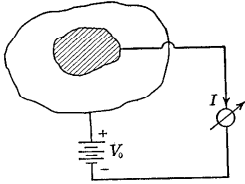


Fig. 2. Ionization chamber (schematic).

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Applying Green's theorem, considering boundary conditions and  $\nabla^2 \phi_0 = 0$  and  $\nabla^2 \phi_1 = -4\pi\rho$ , one finds that the third integral vanishes whereas the fourth one becomes

$$\frac{1}{4\pi} \int \text{grad } \phi_1 \cdot \frac{\partial}{\partial t} \text{grad } \phi_1 \, d\tau = \int \phi_1 \frac{\partial \rho}{\partial t} \, d\tau = - \int \phi_1 \text{div } \mathbf{j} \, d\tau$$

A second application of Green's theorem, again considering boundary conditions, yields

$$- \int \phi_1 \text{div } \mathbf{j} \, d\tau = \int \text{grad } \phi_1 \cdot \mathbf{j} \, d\tau = - \int \mathbf{E}_1 \cdot \mathbf{j} \, d\tau$$

The ionization current thus becomes

$$I = \frac{e}{V_0} \int \mathbf{E}_0 \cdot (n^+ \mathbf{w}^+ - n^- \mathbf{w}^-) \, d\tau \quad (13)$$

The current  $I$  can be interpreted as being caused partly by a positive current  $I^+$ , partly by a negative current  $I^-$  of magnitude

$$I^+ = \frac{e}{V_0} \int \mathbf{E}_0 \cdot (n^+ \mathbf{w}^+) \, d\tau$$

$$I^- = - \frac{e}{V_0} \int \mathbf{E}_0 \cdot (n^- \mathbf{w}^-) \, d\tau \quad (13a)$$

Although for a stationary state for which  $n_0$  is constant one cannot, of course, distinguish  $I^+$  and  $I^-$  in the outer circuit, the effect of the different drift velocities  $w^+$  and  $w^-$  becomes immediately apparent from the manner in which the current  $I$  follows a sudden variation of the ionization. If, for instance, the ionization suddenly ceases, the ionization current  $I$  will drop quickly if the motion of the electrons is the main contribution to the total current. It should be noted that  $I$  depends explicitly only on  $E_0/V_0$ , irrespective of space charges, and this would seem to contradict the dependence of the saturation current on  $V_0$ . However, it should be remembered that, since the drift velocities  $w$  depend strongly on the actual field strength, it is implicitly, through  $w$ , that the current  $I$  is affected by space charges. Recombination will manifest itself simply in a decrease of the ion densities  $n^+$  and  $n^-$ . Furthermore, it should be noted that practical ionization chambers as a plane parallel plate chamber do not exactly satisfy our assumptions even if fitted with guard rings, since at the lateral boundary, represented by the lines of force



projecting from the guard ring to the voltage electrode, neither  $\phi_1$  nor its normal derivative vanishes.

**2. Constant Ionization.** (a) *General Considerations.* Let us now consider an ion chamber irradiated at a constant intensity or an intensity which varies little during a time necessary to remove ions from the sensitive gas volume. Diffusion and recombination being neglected again, Green's theorem gives

$$I = -\frac{e}{V_0} \int \text{grad } \phi_0 \cdot (n^+ \mathbf{w}^+ - n^- \mathbf{w}^-) d\tau$$

$$= -\frac{e}{V_0} \left\{ \int \phi_0 (n^+ w_n^+ - n^- w_n^-) da - \int \phi_0 \text{div} (n^+ \mathbf{w}^+ - n^- \mathbf{w}^-) d\tau \right\}$$

For constant ionization, after equilibrium has been established,

$$\text{div} (n^+ \mathbf{w}^+) = \text{div} (n^- \mathbf{w}^-) = n_0$$

where  $n_0$  is the number of ion pairs produced per unit volume and time. For the surface integral which is to be taken over the two electrodes,  $\phi_0$  is equal to  $\phi_0^+$  and  $\phi_0^-$ , respectively, with  $V_0 = \phi_0^+ - \phi_0^-$ . Moreover, a necessary boundary condition for  $n^+$  and  $n^-$  is

$$n^+ = 0 \text{ at the positive electrode}$$

$$n^- = 0 \text{ at the negative electrode}$$

This is due to the fact that at the positive electrode, for instance, no positive ions enter the sensitive volume, and hence to satisfy the continuity equation  $n^+$  has to be zero at this electrode. Since the second integral vanishes,

$$I = -\frac{e}{V_0} \left\{ \phi_0^- \int_- n^+ w_n^+ da - \phi_0^+ \int_+ n^- w_n^- da \right\}$$

Furthermore,

$$\int n_0 d\tau = \int_- n^+ w_n^+ da = \int_+ n^- w_n^- da$$

and therefore

$$I = e \int n_0 d\tau$$

The expressions for the ion densities  $n^+$  and  $n^-$  can easily be found for simple geometries and simple assumptions concerning the dependence of  $w$  on the actual field modified by the space charges.

(b) *Plane Parallel Plate Chamber.* We shall now consider a plane parallel plate chamber of large area (Fig. 3). Let the  $x$  axis be perpendicular to the plates, the positive electrode being at  $x = 0$  and the negative at  $x = d$ . The chamber shall be uniformly irradiated so that  $n_0$  ion pairs are produced per unit time and volume. The problem is then one-dimensional, and, assuming no recombination or formation of heavy

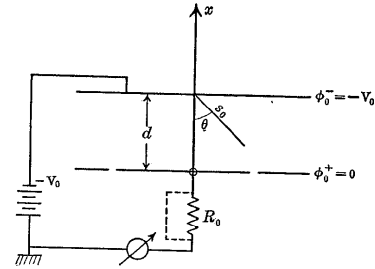


Fig. 3. Plane parallel plate ionization chamber.

negative ions taking place, we have, considering the boundary conditions for  $n^+$  and  $n^-$ ,

$$n^+ w_x^+ = n_0 x + c_1 = n_0 x$$

$$n^- w_x^- = n_0 x + c_2 = n_0 (x - d)$$

The drift velocity of the positive ions is proportional to the field:

$$w_x^+ = \frac{\mu}{p} E$$

whereas the drift velocity of the electrons can be assumed to be very large compared to that of the positive ions:

$$|w_x^-| \gg w_x^+$$

$$\text{div } \mathbf{E} = 4\pi e n_0 \left[ \frac{x}{(\mu/p)E} - \frac{x-d}{w_x^-} \right] \approx \frac{4\pi e n_0 x}{(\mu/p)E}$$

$$E = \sqrt{\frac{4\pi e n_0 x^2}{\mu/p} + c} = E_0 \sqrt{1 + \left( c' + \frac{4\pi e n_0 x^2}{\mu/p} \right) \frac{1}{E_0^2}}$$

where  $E_0$  is the field in the absence of ionization. If the field is only slightly modified by the space charge,

$$\int_0^d E dx - V_0 = V_0 + \frac{1}{2} \frac{c'd}{E_0} + \frac{2\pi en_0 d^3}{3(\mu/p)E_0}$$

and therefore

$$E = E_0 + \frac{2\pi en_0}{(\mu/p)E_0} \left( x^2 - \frac{d^2}{3} \right)$$

The contributions of negative and positive particles to the current  $I$  are equal, and, according to Eq. (13),

$$I^+ = \frac{e}{V_0} \int E_0 n^+ w_x^+ dr = \frac{I}{2} = - \frac{e}{V_0} \int E_0 n^- w_x^- dr$$

(c) *Cylindrical Chamber.* For a cylindrical chamber of which the outer negative electrode shall have a radius  $b$  and the inner positive one a radius  $a$ , the expression for  $n$  is quite simple, provided one assumes, in addition to the assumptions under (a), that the space charges are very small and do not materially affect the drift velocities. Then one has for uniform ionization:

$$\frac{d}{dr} (rn^+ w_r^+) = \frac{d}{dr} (rn^- w_r^-) = n_0 r$$

Since

$$n^+ = 0 \text{ at } r = a \quad \text{and} \quad n^- = 0 \text{ at } r = b$$

the density is

$$n^+ = \frac{n_0}{2w_r^+} \cdot \left( r - \frac{a^2}{r} \right) \quad n^- = \frac{n_0}{2w_r^-} \cdot \left( r - \frac{b^2}{r} \right)$$

With the above assumptions the field  $E$  is

$$E = E_0 = \frac{V_0}{r \log(b/a)}$$

Irrespective of space charges, however, the currents are

$$I^+ = \frac{eLn_0\pi}{\log(b/a)} \int_a^b \left( r - \frac{a^2}{r} \right) dr = I \left[ \frac{1}{2 \log(b/a)} - \frac{a^2}{b^2 - a^2} \right]$$

$$I^- = - \frac{eLn_0\pi}{\log(b/a)} \int_a^b \left( r - \frac{b^2}{r} \right) dr = I \left[ \frac{b^2}{b^2 - a^2} - \frac{1}{2 \log(b/a)} \right]$$

where  $L$  is the length of the chamber.

From these expressions it appears that for  $b \gg a$  most of the current is caused by the motion of the negative particles and very little is contributed by the positive ions. If the potential difference across the chamber were reversed, i.e., the outer electrode positive, most of the current would be carried by the positive ions. This is readily understood if it is realized that for uniform ionization the majority of the ions are produced close to the outer electrode. Since the contribution to the current by each ion is proportional to the field in which it finds itself during its motion in the chamber, the positive ions contribute little, for they move through regions of small fields. The fact that the current for such a chamber is primarily carried by electrons, if attachment is prevented, therefore allows the use of this chamber for the recording of relatively fast-varying ionization.

**3. Ionization Pulses.** (a) *General Considerations.* In this discussion we shall consider the current pulses induced in the outer circuit of an

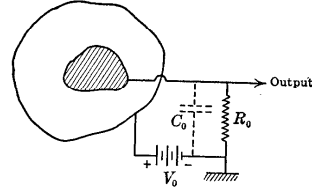


Fig. 4. Pulse ionization chamber (schematic).

ionization chamber by a single pulse of ionization at the time  $t = 0$ , giving rise to a density  $n_0(x, y, z)$  ion pairs per unit volume. Until all positive and negative ions have reached their respective electrodes a current  $I = I^+ + I^-$  will flow. We shall, however, now assume that the two electrodes are no longer connected by a current meter but rather by a resistor  $R_0$  so large that practically no charge induced at the collecting electrode (Fig. 4) can leak off during a pulse. If  $C_0$  is the total capacitance of the collecting electrode including accessory circuits like amplifier input, this requires

$$R_0 C_0 \gg T^+ \text{ and } T^-$$

where  $T^+$ ,  $T^-$ , "the collecting time," is the time required to sweep positive or negative ions or electrons from the sensitive volume of the chamber. The charge induced at the collector, which at  $t = 0$  shall have the potential zero, will raise or lower its potential  $V$ , but it will be

assumed that at any time  $V(t)$  is so small compared to the potential difference between the electrodes that the field  $E_0$  is not noticeably affected. Then the potential rise or drop of the collecting electrode is given, according to Eqs. (13) and (13a) by

$$V(t) = V^+(t) - V^-(t)$$

$$V^+(t) = \frac{1}{C_0} \int_0^t I^+(t) dt = \frac{e}{V_0 C_0} \int_0^t dt' \int n_0 \mathbf{E}(t') \cdot \mathbf{w}^+(t') d\tau$$

$$V^-(t) = + \frac{1}{C_0} \int_0^t I^-(t) dt = - \frac{e}{V_0 C_0} \int_0^t dt' \int n_0 \mathbf{E}(t') \cdot \mathbf{w}^-(t') d\tau$$

where  $E(t')$  is that value of the field which the ion experiences at the time  $t'$ . Similarly,  $w(t')$  is the drift velocity which the ion possesses at the time  $t'$ :

$$\mathbf{E}(t') = \mathbf{E}(\xi', \eta', \zeta') \quad \mathbf{w}(t') = \mathbf{w}(\xi', \eta', \zeta')$$

where

$$\xi' = x + \int_0^{t'} w_x dt' \quad \text{etc.}$$

Interchanging time and space integration gives

$$\begin{aligned} V^+(t) &= \frac{e}{V_0 C_0} \int n_0 d\tau \int_0^t \mathbf{E} \cdot (t') \cdot \mathbf{w}^+(t') dt' \\ &= \frac{e}{V_0 C_0} \int n_0 [\phi(xyz) - \phi^+(\xi, \eta, \zeta)] d\tau \\ V^-(t) &= - \frac{e}{V_0 C_0} \int n_0 d\tau \int_0^t \mathbf{E}(t') \cdot \mathbf{w}^-(t') dt' \\ &= - \frac{e}{V_0 C_0} \int n_0 [\phi(xyz) - \phi^-(\xi, \eta, \zeta)] d\tau \end{aligned} \quad (14)$$

$\phi(\xi, \eta, \zeta)$  is the value of the potential at the point at which that ion is found at the time  $t$  which was created at  $x, y, z$  at  $t = 0$ , where the potential had the value  $\phi(x, y, z)$ .  $\phi$  is, according to Eq. (13), the potential caused by the external field alone, unmodified by space charges. The relations show that the voltage induced at the collecting electrode by the motion of an ion is directly proportional to the potential difference through which it has dropped. The final value  $V_\infty$  to which the potential of the collector will rise is reached when all the positive particles have

reached the negative electrode and all negative particles the positive electrode, where the value of the potential is  $\phi_0^-$  and  $\phi_0^+$ , respectively.  $\phi_0^+ - \phi_0^- \sim \text{const} = V_0$ :

$$V_\infty^+ = \frac{e}{V_0 C_0} \int n_0 \phi(x, y, z) d\tau - \frac{e}{V_0 C_0} \phi_0^- \int n_0 d\tau$$

$$V_\infty^- = - \frac{e}{V_0 C_0} \int n_0 \phi(x, y, z) d\tau + \frac{e}{V_0 C_0} \phi_0^+ \int n_0 d\tau \quad (15)$$

$$V_\infty = V_\infty^+ + V_\infty^- = \frac{e}{V_0 C_0} (\phi_0^+ - \phi_0^-) \int n_0 d\tau = \frac{e}{C_0} \int n_0 d\tau$$

Thus the final potential rise of the collector is simply equal to the total number of ion pairs times the ion charge, divided by the total capacity. The manner in which this value is reached depends very strongly on the drift velocity. The rate of rise caused by each type of ion is directly proportional to the drift velocity and is therefore large for free electrons and small for heavy positive or negative ions. For free electrons the voltage rise  $V_\infty^-$  due to the negative particles is reached very quickly and is followed by a slow rise caused by the motion of the ions. The value  $V_\infty^-$ , however, depends not only on the total number of ion pairs but, through the first term in Eq. (15), also on where the ions were originally created. If  $w^+ \ll w^-$ , it is very easy to separate the effects of positive ions and electrons, for instance by reducing the value of the leakage resistor  $R_0$  to such a value that

$$T^- \ll R_0 C_0 \ll T^+$$

with the result that  $V_\infty^-$  is reached before any charge has leaked off, whereas the contribution by the positive ions is so small [ $\sim R_0 C_0 (dV^+/dt)$ ] that it may be neglected. In this case the voltage pulse obtained at the collector is almost exclusively caused by the motion of the electrons (electron collection). The short duration of the voltage pulses results in increased resolution. Moreover, it allows the amplifier to have a higher low-frequency cut-off. If this cut-off frequency is  $\nu_2$ , its order of magnitude is  $\nu_2 \sim 1/2\pi T^-$ . Since the electron collection time  $T^-$  at ordinary pressure, field strength, and chamber dimensions is of the order of microseconds, whereas the collection time for ions is of the order of milliseconds, amplifiers used in conjunction with such a chamber will have a low-frequency cut-off of  $10^4$  to  $10^5$  cps. Since most of the natural mechanical frequencies of the chamber and the amplifier system are in the audible range, it is immediately apparent that "electron collection" is largely free of microphonic disturbances. The same is true for dis

turbances caused by the alternating heater current of the tubes. The main disadvantage of pure electron collection is caused by the fact that the size of a pulse is no longer uniquely a function of the primary ionization but depends to a large extent on the spatial distribution of this ionization, as shown by Eq. (15).

The differentiation of the voltage pulse which suppresses the effects of the positive ions and which was assumed to be caused by a suitable value of  $R_0C_0$  can also be achieved at a later stage of the amplifier (see Section 3). As a matter of fact, it is preferable to make the  $R_0C_0$  value of the collecting electrode and amplifier input quite large and to differentiate, with exactly the same result, through one of the subsequent  $RC$  coupling circuits.

(b) *Plane Parallel Plate Chamber.* As an example, we shall consider a plane parallel plate chamber (Fig. 3) of plate separation  $d$ . The positive collecting electrode at  $x = 0$  will have the potential  $\phi_0^+ = 0$  at  $t = 0$ , whereas the voltage plate at  $x = d$  will be constantly kept at  $\phi_0^- = -V_0$ . Let us assume, furthermore, that an ionizing particle of energy  $U_0$  is emitted from the voltage electrode under an angle  $\theta$  with respect to the perpendicular to the plate. If we denote by  $s$  the distance from the point of emission along the straight path of the particle, the ionization at  $s$  is

$$n(s) = -\frac{1}{I_0} \frac{dU}{ds} \quad \text{ion pairs per unit path}$$

where  $U$  is the energy of the ionizing particle at  $s$  and  $I_0$  the average energy per formation of one ion pair. The range  $s_0$  of the particle is given by

$$U_0 = -\int_0^{s_0} \frac{dU}{ds} ds$$

If one assumes that  $s_0 < d$  and that  $w^+$  and  $w^-$  are not affected by the space charges, and if one considers that all the positive ions which have been swept from the chamber are at the potential of the negative electrode, from Eq. (14) one finds for the negative pulse at the collecting electrode

$$V^-(t) = -\frac{e}{C_0 d} \left\{ w^+ t \int_{w^+ t / \cos \theta}^{s_0} n(s) ds + \cos \theta \int_0^{w^+ t / \cos \theta} n(s) s ds \right\}$$

$$\text{for } 0 \leq t \leq \frac{s_0 \cos \theta}{w^+}$$

$$V^-(t) = -\frac{e}{C_0 d} \cos \theta \int_0^{s_0} n(s) s ds \quad \text{for } t > \frac{s_0 \cos \theta}{w^+}$$

$$V^-(t) = -\frac{e}{C_0 d} w^- t \int_0^{s_0} n(s) ds \quad \text{for } 0 < t < \frac{d - s_0 \cos \theta}{w^-}$$

$$V^-(t) = -\frac{e}{C_0 d} \left\{ w^- t \int_0^{(d-w^-t)/\cos \theta} n(s) ds + d \int_{(d-w^-t)/\cos \theta}^{s_0} n(s) \left( 1 - \frac{s}{d} \cos \theta \right) ds \right\}$$

$$\text{for } \frac{d - s_0 \cos \theta}{w^-} \leq t \leq \frac{d}{w^-}$$

$$V^-(t) = -\frac{e}{C_0} \int_0^{s_0} n(s) \left( 1 - \frac{s}{d} \cos \theta \right) ds \quad \text{for } t > \frac{d}{w^-}$$

The first integral of the first expression accounts for those positive ions which at the time  $t$  are still within the chamber, and the second integral is the contribution to  $V^+$  of those positive ions which have already reached the negative electrode. Similarly, the first integral of the fourth expression accounts for the negative particles still within the chamber whereas the other represents the contribution to  $V^-$  from those which have already reached the positive electrode. Since the current to the collecting electrode lowers its potential, the expressions are to be taken with the negative sign.

The initial voltage rise  $dV/dt$  at  $t = 0$  is

$$\frac{dV^+}{dt} = -\frac{e}{C_0} \frac{w^+ U_0}{d I_0}$$

and

$$\frac{dV^-}{dt} = -\frac{e}{C_0} \frac{w^- U_0}{d I_0}$$

If  $R_0$  is sufficiently large, the maximum voltage amplitudes are

$$V_{\infty}^+ = -\frac{e \cos \theta}{C_0 d} \int_0^{s_0} n(s) s ds$$

$$V_{\infty}^- = -\frac{e}{C_0} \left[ \frac{U_0}{I_0} - \frac{\cos \theta}{d} \int_0^{s_0} n(s) s ds \right] \quad (15a)$$

These relationships show clearly the dependence of the size of the voltage pulse on the position of the ionizing track. For  $\theta = 0$ ,  $|V_{\infty}^+|$  has a maximum and, correspondingly,  $|V_{\infty}^-|$  a minimum. For  $\theta = \pi/2$  the positive voltage pulse is zero, and the negative one has the value  $(e/C_0)$

$\times (I_0/I_0)$ , which is equal to the sum of  $V_{\infty}^+$  and  $V_{\infty}^-$  at any angle. The initial slope, on the other hand, which is due almost solely to the motion of the electrons, since  $w^- \gg w^+$ , does not depend on the orientation of the track at all. Sherr and Peterson (55) have used this fact to obtain from the initial slope and  $V_{\infty}^-$  the energy  $U_0$  and the value of  $\theta$  for a given pulse. For a complete determination a knowledge of the specific ionization (Bragg curve) of the particle under consideration is, of course, necessary. The value of the slope can be obtained by differentiating the observed voltage pulse by an  $RC$  circuit the time constant of which should be small compared to  $d/w^-$ . The amplitude of the pulse observed at the output of this network measures directly  $dV^-/dt$ , and thus the energy of the particle.

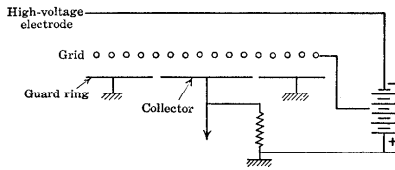


Fig. 5. Grid ionization chamber.

The dependence of  $V_{\infty}^-$  on the position of the ionizing track can be avoided by a simple device first proposed in another connection by Alfvén (A4). A third electrode consisting of a highly transparent grid of parallel fine wires is placed between the high-voltage and the collecting electrodes, as shown in Fig. 5. The screen electrode is kept at a constant negative potential  $V_s$  between zero and  $-V_0$  such that a relatively weak field exists between the screen and the high-voltage electrode. The screen will be at a distance from the high-voltage electrode which is larger than the range  $S_0$  of the particles, assumed again to be emitted from the negative electrode. The motion of the ions and electrons will at first contribute negligibly little to the voltage change of the collecting electrode, provided that the screen shields their field effectively from the collector. However, as soon as the electrons have passed through the screen, their motion will induce charges on the collector according to Eq. (14):

$$V^- = - \frac{e}{V_s C_0} \int n_0 [V_s - \phi(\xi, \eta, \zeta)] d\tau$$

where  $V_s$  is the potential difference between screen and collector and  $C_0$  the capacity of the collector (increased, of course, by the insertion

of the screen). The integration extends over the volume between screen and collecting electrode. The potential of the starting point of the electrons in this case is  $V_s$  for all electrons irrespective of their origin. The height of the pulse due to the motion of the electrons is, therefore,

$$V_{\infty}^- = - \frac{eU_0}{C_0 I_0}$$

and the contribution of the positive ions is zero, since they do not pass through the screen.

The choice of the mesh of the screen has to be made so that its transparency is as high as possible, in order to avoid electrons from being caught by the wires, but still sufficiently dense to shield the collecting electrode. The capture of the electrons by the wires is greatly reduced if the field between screen and collector is high. The field between screen and high-voltage electrode should be only sufficiently large to prevent the electrons from undergoing recombination or attachment.

(c) *Cylindrical Chamber.* As a second example we shall consider the voltage pulses caused by a momentary ionization in a cylindrical chamber. Let  $a$  be the radius of the inner,  $b$  the radius of the outer electrode, the latter being the voltage electrode kept constantly at a potential  $-V_0$ , while the positive collecting electrode is at a potential  $\phi_0^+ = 0$  at  $t = 0$ . If, at  $t = 0$ ,  $N_0$  ion pairs are produced at a distance  $r_0$  from the center, the final voltage pulses  $V_{\infty}^+$  and  $V_{\infty}^-$  are, according to Eq. (15),

$$\begin{aligned} V_{\infty}^+ &= - \frac{eN_0 \log(b/r_0)}{C_0 \log(b/a)} \\ V_{\infty}^- &= - \frac{eN_0 \log(r_0/a)}{C_0 \log(b/a)} \end{aligned} \quad (15b)$$

The actual rise of the voltage can be predicted only if the dependence of  $w^+$  and  $w^-$  on the field is known. From the above expressions it follows that there is a certain distance  $r_0$  for which  $V_{\infty}^+ = V_{\infty}^-$ , and it is given by

$$r_0 = \sqrt{ab}$$

The fraction of the volume of the ionization chamber in which the  $N_0$  ion pairs can originate, so that more than one-half of the ensuing voltage pulse is caused by the motion of the electrons, is equal to

$$F = \frac{b^2 - r_0^2}{b^2 - a^2} = \frac{b}{b+a}$$

Thus it appears that, in a cylindrical chamber in which equally ionizing tracks are uniformly distributed, most pulses caused by the motion of electrons alone have almost their full size as determined by the ionization. If the voltage were reversed, this would of course hold for the pulses caused by the motion of the positive ions. The reason for this fact is immediately clear, if it is realized that the electrons of most of the pulses move through the same region of high field strength close to the inner electrode, provided the outer electrode is negative.

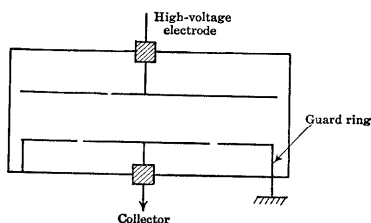


Fig. 6. Guard ring for ionization chamber.

**4. Guard Rings.** In practice most ionization chambers are of the guard-ring type. In its simplest form the guard ring consists of a metal ring separating the insulators for the collecting and high-voltage electrode. It is kept at a fixed potential, approximately equal to the potential of the collecting electrode. If no guard ring is used, a high electric field exists across the insulator and, since the resistance of the insulator is finite, a small current will flow to the collecting electrode. This current often exhibits large fluctuations which in pulse chambers lead to spurious pulses. A guard ring can also be used to define the active volume of the chamber without introducing distortions of the field. Finally, the guard ring might be extended to enclose both high-voltage and collecting electrodes and thus, if kept at ground potential, serve as a very effective electrostatic shield for the chamber. Such an arrangement, serving this three-fold purpose for a plane parallel plate chamber, is schematically shown in Fig. 6. The lateral boundary of the counting volume is represented by the electric lines of force from the high-voltage electrode to the interspace between the collector and the guard ring and is therefore, for a sufficiently wide guard ring, a straight cylindrical surface. If both ions and electrons are collected, an ion pair produced at a point through which the line of force leads to the collecting electrode will produce a pulse of full size. The guard ring acts therefore like a complete screen.

If the pulses are caused by the motion of the electrons alone (electron collection), this is not so. Suppose that a positive ion and an electron are initially formed in the vicinity of the lateral boundary. If the electron is removed to the collecting electrode, assumed to be positive, a charge will be induced on the positive electrode which, according to Eq. (15), is equal to

$$q_{\infty}^{-} = -\frac{\phi_1}{V_0} e$$

where  $\phi_1$  is the potential at the point of origin of the ion pair.  $|q_{\infty}^{-}|$  is smaller than  $e$  because the remaining positive ion induces a positive charge  $q^+$ , given by

$$4\pi q^+ = \int E_n^+ da$$

where  $E_n^+$  is the normal component of the field due to the positive ion, and the integration extends over the area of the collecting electrode. If the active volume is limited by a guard ring, only a fraction of all the lines of force leading from the positive ion to the positive electrode end on the collecting electrode proper. It is therefore apparent that the electron pulse from an ion pair close to the boundary, but inside the active volume, will be larger than that caused by an ion pair originating far away from the guard ring. An ion pair originating outside the active volume will induce a finite electron pulse of opposite sign. For the case of two infinite parallel plate electrodes, one of which is split into a guard ring and a collecting electrode, the electrostatic problem can be solved. The resultant expression and its graphical representation are given in (N1).

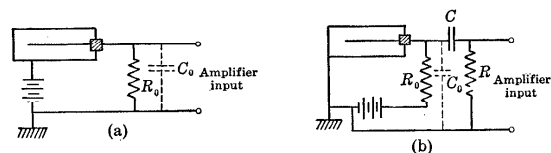


Fig. 7. Coupling methods: (a) grounded collecting electrode; (b) grounded shell.

**5. Coupling Methods.** The first grid of the amplifier used in connection with a pulse ionization chamber is usually kept close to ground potential. Direct coupling of the collecting electrode to this grid is therefore possible if, likewise, the collecting electrode is near ground potential as in Fig. 7a. A different way of coupling, in which the "voltage electrode" is grounded and the collecting electrode is kept at a high potential, is shown in Fig. 7b. No guard ring is used here, but a large

potential difference appears across the coupling condenser  $C$ . Unless this condenser is made with a very high-grade insulating material, spurious pulses will occur; in any event, this type of coupling should be used only if the ionization pulses are quite large and the collecting voltages low.

### C. Proportional Counters

**1. Introduction.** If the electric field in an ionization chamber is sufficiently raised and the electrons do not recombine or form negative ions, an increase of the ionization current above its saturation value is observed. This increase sets in as soon as the electrons gain sufficient energy between collisions to ionize neutral gas molecules. The electrons resulting from this secondary ionization may in turn ionize, and every primary ionizing event will thus cause an avalanche of secondary ionization. This type of secondary ionization, which occurs only in sufficiently high fields, has to be distinguished from the secondary ionization proper, which is caused by energetic electrons from the primary ionization and is independent of the applied field (cf. Section 2A). In the process of formation of this avalanche light quanta are emitted by molecules excited by electron impact or as a result of recombination. These quanta can, under suitable conditions, release photoelectrons at the negative electrode or in components of the gas having a lower ionization potential than the component which emitted the quanta. The light quanta might therefore contribute to the secondary ionization, and spread the discharge over the whole counter volume. Whether they contribute essentially to the discharge depends on the probability that an electron produces a tertiary photoelectron. If this probability is  $\gamma$  and if the number of secondary electrons formed through impact by a single electron is  $n$ ,  $n\gamma$  photoelectrons are formed by the  $n$  secondary electrons. They will in turn multiply by collision to  $n^2\gamma$  tertiaries, giving rise to a new set of  $n^2\gamma^2$  photoelectrons, provided that each photoelectron originates at a sufficient distance from the anode to produce the same  $n$ -fold multiplication by collision. The total number of electrons, the multiplication factor, will therefore be

$$M = \frac{n}{1 - n\gamma} \quad (10)$$

**2. Gas Multiplication.** As long as  $n\gamma \ll 1$ , the multiplication is due entirely to secondary ionization by collision and the contribution of photons might therefore be neglected for small multiplication numbers  $M \approx n$ . Then the detector is called a multiplication or proportional counter, since the total number of secondaries is proportional to the

number of primary ion pairs if every primary electron actually multiplies by the same number. This will be correct as long as space charges due to the secondary positive ions do not materially change the electric field and the primary ionization does not occur close to the positive

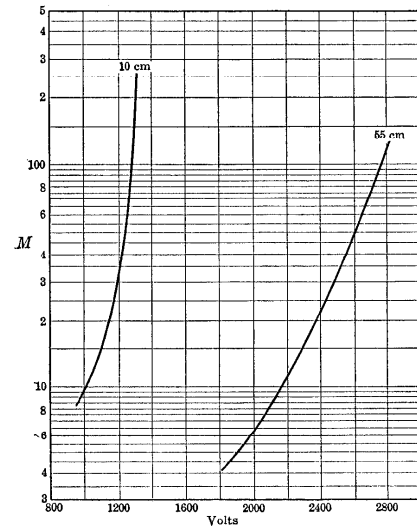


Fig. 8a. Multiplication factor for hydrogen:  $p = 10$  cm and  $p = 55$  cm Hg;  $a = 0.005$  in.,  $b = 0.435$  in. (Data from N1.)

electrode. We shall, moreover, assume that no recombination or formation of negative ions by attachment takes place and, furthermore, restrict our considerations to cylindrical chambers with the outer electrode of radius  $b$  being at a potential  $V_0$  and an inner electrode of radius  $a$  at potential 0 before the ionizing event occurs. With this geometry, multiplication will take place in a narrow region around the central electrode. It will set in if  $V_0$  is larger than a certain threshold value  $V_t$ :

$$V_t = aE_c \log \frac{b}{a} \quad (17)$$

where  $E_c$  is the critical field strength for multiplication characteristic for the gas under consideration. For a given potential difference  $V_0$ , there will be a critical radius  $r_c$  at which multiplicative collisions begin.

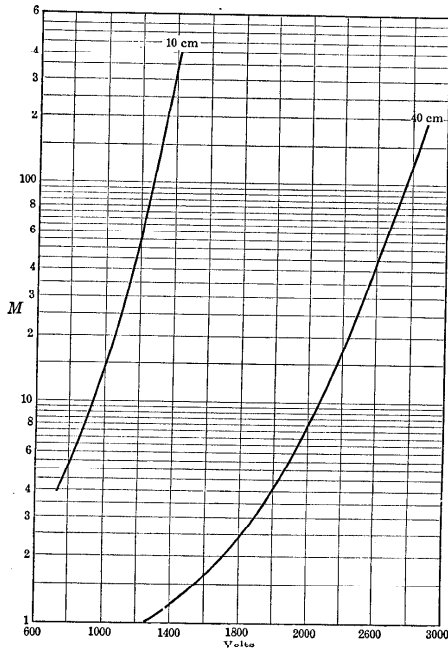


Fig. 8b. Multiplication factor for methane:  $p = 10$  cm and  $p = 40$  cm Hg;  $a = 0.005$  in.;  $b = 0.435$  in. (Data from N1.)

Rose and Korff (R4) have given an expression for  $M$  under the assumptions made above. Moreover, they assume that the ionization cross section of the electrons increases linearly with energy and that the majority of the electrons have an energy about equal to the ionization energy of the gas. With these assumptions  $M$  is given by the expression

$$M = \exp \left\{ k \sqrt{\frac{V_0 a p}{\log(b/a)}} \left( \sqrt{\frac{V_0}{V_t}} - 1 \right) \right\} \quad (18)$$

In this expression  $p$  is the gas pressure and  $k$  a constant characteristic

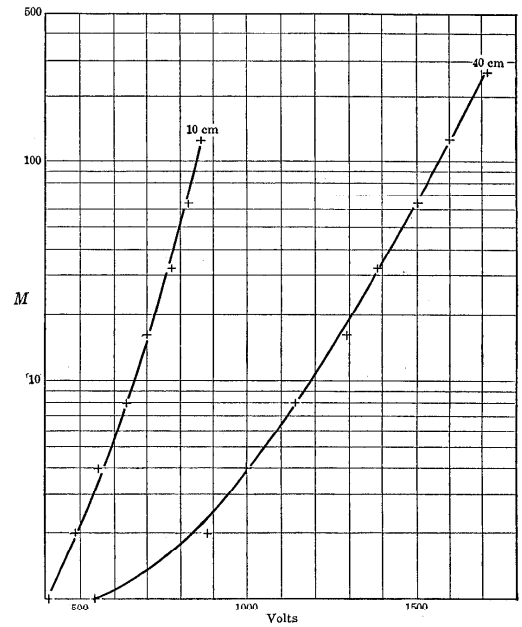


Fig. 8c. Multiplication factor for argon:  $p = 10$  cm and  $p = 40$  cm Hg;  $a = 0.005$  in.;  $b = 0.435$  in. (Data from N1.)

for the gas. It should be noted that, for a given gas,  $M$  shows a dependence on  $V_0$ ,  $p$ ,  $b$ , and  $a$  which is of the general form

$$M = f \left[ \frac{V_0}{\log(b/a)}, ap \right] \quad (19)$$



as one can easily see by substituting  $V_t$  from Eq. (17) and considering that  $E_c \sim p$ , which follows from the fact that, in order to multiply, an electron has to gain sufficient energy between two collisions.

Rose and Korf's expression has been tested for various gases, and it was found that for moderate values of  $M$  between 10 and  $10^3$  good

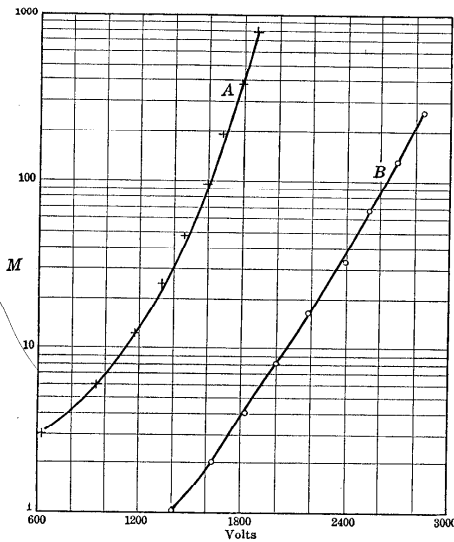


Fig. 8d. Multiplication factor for boron trifluoride. Curve A:  $p = 10$  cm Hg;  $a = 0.005$  in.;  $b = 0.75$  in. Curve B:  $p = 80.4$  cm Hg;  $a = 0.0005$  in.;  $b = 0.78$  in. (Data from N1.)

agreement with expression (18) is obtained. Figure 8 shows the values of the multiplication factor as a function of voltage for various gases commonly used. Together with the more general relation, Eq. (19), they can serve for finding  $M$  for different geometries and pressures. It should be noted that the addition of a polyatomic gas to argon, hydrogen, or nitrogen tends to make  $M$  less critically dependent on the voltage at low pressure and thus tends to stabilize the operation of the counter.

**3. Shape of Pulses.** The pulse shape of a proportional counter is quite different from that observed when the counter is operated as an ionization chamber. For a reasonably high multiplication factor the voltage pulses caused by an ionizing event will be of the same size, irrespective of the position of the ionizing track, unless this track is located within a few mean free paths of the electrons from the central electrode. The contribution to the pulse due to the motion of the primary electrons and ions will be negligible if  $M$  is sufficiently large. The size of the pulse will be proportional to the number of primary ions as long as the assumptions made above are correct. Since multiplication takes place within a few mean free paths from the positive electrode, the contribution of the electrons to the pulse is very small. A simple estimate shows that for large values of  $M$  and  $(\bar{l}_i/a) \log M \ll 1$  the fraction of the pulse height due to the motion of the electrons is of the order

$$\frac{V_{\infty}^-}{V_{\infty}^+} = \frac{\bar{l}_i}{a \log(b/a)}$$

where  $\bar{l}_i$  is the mean free path of the electrons for ionization; cf. Eq. (15b). Thus, for a counter with  $b = 1$  cm,  $a = 0.01$  cm,  $p = \frac{1}{2}$  atmos,  $\bar{l}_i \approx 5 \times 10^{-3}$  cm,  $V_{\infty}^-/V_{\infty}^+$  becomes about 0.10. The pulse will therefore be almost entirely due to the motion of the positive ions which form, at  $t = 0$ , a thin layer at the surface of the central electrode. If it is assumed that the positive ions left after complete removal of the electrons do not appreciably alter the field, the voltage pulse caused by positive ion movement is, Eq. (14),

$$V^+(t) = \frac{eMn_0}{V_0C_0} [0 - V(r)] = \frac{eMn_0 \log(r/a)}{C_0 \log(b/a)}$$

$$\frac{dr}{dt} = \frac{\mu^+}{p} E(r) = \frac{\mu^+}{p} \frac{V_0}{r \log(b/a)}$$

where  $Mn_0$  is the total number of ions located originally at  $r = a$  and  $\mu^+$  the positive ion mobility. Combining the two relations gives

$$V^+(t) = \frac{eMn_0}{2C_0 \log(b/a)} \log \left( 1 + \frac{2\mu^+V_0}{pa^2 \log(b/a)} t \right)$$

The voltage will therefore at first increase linearly with time and later only logarithmically, until the positive ions are completely removed at a time

$$T = \frac{(b^2 - a^2)p \log(b/a)}{2\mu^+V_0}$$

At this time the pulse has risen to its full value,  $V = eMu_0/C_0$ . Figure 9 shows the shape of the pulse  $V^+(t)/V_\infty^+$  for a typical case:  $b = 1$  cm;  $a = 0.01$  cm;  $p = \frac{1}{2}$  atmos of argon.

$$\frac{\mu^+}{p} = 2.7 \text{ cm}^2 \text{ sec}^{-1} \text{ volt}^{-1} \quad V_0 = 1500 \text{ volts}$$

The total collection time  $T$  is

$$T = 590 \text{ } \mu\text{sec}$$

The pulse rises to about one-half of its value in 5  $\mu\text{sec}$ , but the remaining half takes a very long time. In order to obtain high resolution it is

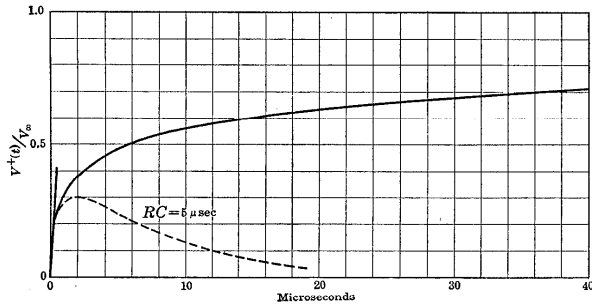


Fig. 9. Shape of pulse of a proportional counter.  $a = 0.01$  cm,  $b = 1$  cm,  $p = 380$  cm Hg, argon,  $V_0 = 1500$  volts. Dotted curve shows shape of pulse after passage through an  $RC$  coupling circuit with a time constant of 5  $\mu\text{sec}$ .

therefore necessary to clip the pulses in the amplifier by a short time-constant  $RC$  circuit or a delay line (see Section 3).

According to Eq. (27),

$$V_2 = \int_0^\infty V_1(t-t') \frac{dr}{dt'} dt' = \int_0^t \frac{dV_1}{dt'} r(t-t') dt'$$

since

$$V_1(t) = 0 \quad \text{for } t \leq 0$$

For the  $RC$  circuit the response function is

$$r(t) = e^{-t/RC}$$

By the  $RC$  differentiation the pulse height is considerably reduced, as the dotted curve in Fig. 9 shows. This curve is computed according to the above expression for an  $RC$  clipping time of 5  $\mu\text{sec}$ . It should be

borne in mind, however, that by this procedure all pulses are reduced by the same factor, since the shape of the pulse is the same, regardless of where the primary ionization took place. Consequently the resultant clipped pulse has still an amplitude proportional to the primary ionization.

**4. Variations of Pulse Size and Time Lags.** In practice it will be noticed that the height of the pulses caused by the same primary ionization will show a certain spread. This spread has various causes. In the first place, the number of ion pairs produced by the primary particle shows a certain fluctuation and, similarly, the subsequent multiplication adds additional statistical variations. If these fluctuations were governed by a Poisson distribution, the resultant fluctuation  $\Delta N$  of the total number  $N = Mn_0$  of ion pairs produced by an average multiplication of  $n_0$  ion pairs would be (S7):

$$\frac{\Delta N}{N} = \sqrt{\frac{2}{n_0}}$$

However, here again, as in non-multiplicative ionization (cf. Section 2A), the actual fluctuation is considerably smaller, as observed by Hanna, Kirkwood, and Pontecorvo (111, K5).

An additional spread of the pulse height is encountered if the electrons undergo capture on their way to the central electrode. Since the probability for formation of a negative ion depends on the number of collisions which the electron undergoes, the pulse size will vary according to the location of the primary ionization.

Another cause of pulse height spread is non-uniform or non-circular cross section of the central electrode or eccentricity of this electrode. Finally, the ends of the central electrode will cause a spread. The termination of the active volume will in any case result in tracks being partly located inside or outside the active volume. In addition, the multiplication factor will vary in the neighborhood of the end of the electrode in an arrangement like that in Figs. 10a and 10b, since the field becomes weaker close to the ends. The variation of the field can be avoided by a guard ring arrangement as shown in Fig. 10c.

For coincidence experiments it should be kept in mind that the pulses of a proportional counter show a time lag the magnitude of which depends on the position of the primary ionization. This time lag is simply the time which the primary electrons need to reach the central electrode where secondary ionization takes place. It is of the order of magnitude

$$\delta = \frac{b}{w}$$

For a counter 1 cm in radius and an assumed drift velocity  $w^-$  of the electrons of about  $10^6$  cm/sec, as in pure argon, the delay might be as large as 1  $\mu$ sec.

After the occurrence of an ionizing event the region through which the positive ions pass will be partially paralyzed, since the positive space charge will decrease the field in the neighborhood of the central electrode.

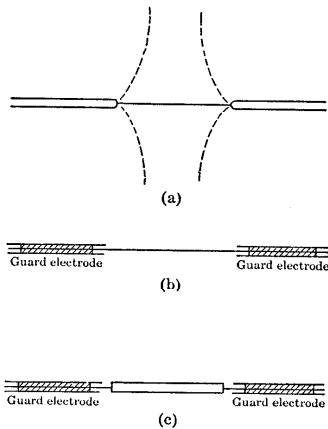


Fig. 10. Methods of supporting the central electrode in proportional counters (N1): (a) without guard; (b) with ordinary guard electrode; (c) guard electrode without field distortion. Hatched areas represent insulators.

This "regional" dead time will be of the order of magnitude of the collection time of the positive ions. In contrast to the Geiger counter, only a small region of the total sensitive volume will be paralyzed, and thus this effect will generally be quite small.

**5. Extremely Small Primary Ionization.** The application of proportional counters to the detection and energy determination of extremely low energetic electrons has been described recently (K5, H1, H2, P2, C7). Kirkwood, Pontecorvo, and Hanna used counters filled with argon or argon and xenon with an addition of methane at a total pressure of 500 to 600 mm Hg with multiplication factors up to 10,000. They showed that such counters, if carefully constructed, possess a very uniform multiplication. Electrons were liberated in the gas by mono-

chromatic x-rays, either by exposing the counter to characteristic x-rays (Mo  $K\alpha$ ,  $h\nu = 17.4$  kev) or by addition of  $A^{37}$  which, as a  $K$ -captor, emits characteristic chlorine  $K$ - and  $L$ -radiation (2.8 kev and 0.25 kev, respectively). The secondaries produced by these x-rays are predominantly photoelectrons, and, since the yield of Auger electrons is extremely high, practically the whole quantum energy is eventually transferred to electrons and only a small fraction is lost in radiation absorbed in the walls of the counter. Consequently the pulses of such a counter should be very uniform in size. The observations of Hanna, Kirkwood, and Pontecorvo and of Curran, Angus, and Cockroft show indeed remarkably uniform pulse groups. Counters of this type find their application in the measurement of low-energy beta-spectra of gaseous materials, as for instance tritium.

#### D. Geiger-Müller Counters

**1. General Characteristics.** If the negative potential of the outer electrode of a cylindrical proportional counter is raised so that the multiplication factor becomes very large, it is observed that the pulses are now

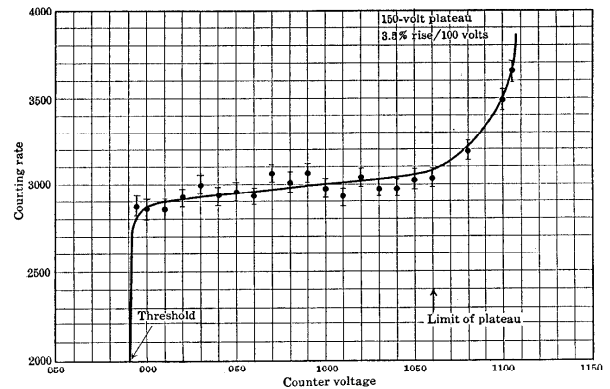


Fig. 11. Dependence of counting rate of a Geiger counter on applied voltage.

longer proportional to the primary ionization (limited proportionality). If the voltage is raised still further, the pulses will eventually become independent of the magnitude of the primary ionization. Their size,