CHAPTER I

ELECTRICAL CONDUCTIVITY OF GASES IN A NORMAL STATE

1. A GAS in the normal state conducts electricity to a slight, but only to a very slight, extent, however small the electric force acting on the gas may be. So small however is the conductivity of a gas when in this state, and so difficult is it to eliminate spurious effects, that there have been several changes of opinion among physicists as to the cause of the leakage of electricity which undoubtedly occurs when a charged body is surrounded by gas. It was thought at first that this leakage took place through the gas; later, as the result of further experiments, it was attributed to defective insulation of the rods or threads used to support the body, and to the dust present in the gas; more recently however it has been shown that there is a true leak through the gas which is not due to the dust or moisture the gas may happen to contain.

2. The escape of electricity from an insulated charged body has attracted the attention of many physicists. Coulomb[1], whose experiments were published in 1785, came to the conclusion from his investigations on the loss of electricity from a charged body suspended by insulating strings, that after allowing for the leakage along the strings there was a balance over, which he attributed to a leakage through the air. He explained this by supposing that the molecules of air when they come into contact with a charged body receive a charge of electricity of the same sign as that on the body and are then repelled from it, carrying off some of its charge. We shall see later on that this explanation is not tenable.

Matteucci[2] experimenting on the same subject in 1850 also came to the conclusion that there was a leakage of electricity through the gas; he was the first to prove that the rate at which this leak takes place is less when the pressure of the gas is low

[1] Coulomb, *Mémoires de l'Académie des Sciences*, 1785, p. 612.
[2] Matteucci, *Annales de Chimie et de Physique*, xxviii. p. 390, 1850.

than when it is high. He found also that the rate of leak was the same in air, carbonic acid and hydrogen. On the other hand Warburg[1] found that the rate of leak through hydrogen was only about half of that through air and carbonic acid; he agreed with Matteucci with regard to the equality of the rate of leak through these gases and could detect no difference between the leaks through dry and moist air; he confirmed Matteucci's observations on the effect of pressure on the rate of leak. Warburg seemed inclined to suspect that the leak was due to dust in the gases. The belief in dust being the carrier of the electricity was strengthened by an experiment made by Hittorf[2] in which a small carefully insulated gold-leaf electroscope was placed in a glass vessel filled with filtered gas; the electroscope was found to have retained a charge even after the lapse of four days. We know now from recent experiments that the smallness of the leak observed in this case was due to the smallness of the vessel in which the charged body was placed rather than to the absence of dust.

Further experiments on this subject were made by Nahrwold[3] and by Narr[4] who showed that the rate of leak from a charged hollow sphere was not increased when the temperature of the sphere was raised by filling it with hot water. Boys[5] made an experiment which showed very clearly that, whatever the cause of the leak might be, it was not wholly due to want of insulation in the supports of the charged body; in this experiment he attached the gold leaves of an electroscope first to a short and thick quartz rod and then to a long and thin one, and found that the rate of leak of electricity from the gold leaves was the same in the two cases; if the leak had been along the supports it would have been much greater in the first case than in the second. Boys also confirmed Warburg's observation that the rate of leak was the same in dry as in moist air.

1 Warburg, *Pogg. Ann.* cxlv. p. 578, 1872.
2 Hittorf, *Wied. Ann.* vii. p. 595, 1879.
3 Nahrwold, *Wied. Ann.* v. p. 460, 1878; xxxi. p. 448, 1887.
4 Narr, *Wied. Ann.* v. p. 145, 1878; viii. p. 266, 1879; xi. p. 155, 1880; xvi. p. 558, 1882; xxii. p. 550, 1884; xliv. p. 133, 1892.
5 Boys, *Phil Mag.* xxviii. p. 14, 1889.

3. The subject of the electric conduction through air is evidently of considerable importance in relation to Meteorology and Atmospheric Electricity. Experiments especially bearing on this point were made by Linss[1] on the loss of electricity from charged bodies placed in the open air; he found there was an appreciable loss of charge which, as control experiments showed, was not due to leakage along the supports of the charged body.

An extensive series of open air measurements were made by Elster and Geitel[2] in many different localities and in different states of the weather. They found that the rate of leak varied much from time to time and from place to place, that it was very much smaller in mist or fog than when the weather was bright and clear, that it was greater at high altitudes than at low ones, and that on the tops of mountains the rate of escape of negative electricity was much greater than that of positive. This is doubtless due to the negative charge on the earth's surface, a mountain top being analogous to a sharp point on a conductor, and thus a place where the earth's electric force tending to move away any negatively electrified body is much greater than it is on the flat. In plains they found the rate of leak to be the same for plus and minus charges.

4. Further experiments on the rates of leak from a charged body placed in a closed vessel filled with air were made almost simultaneously by Geitel[3] and by C. T. R. Wilson[4]. The apparatus used by Wilson for this purpose is represented in Fig. 1. Since the quantity of electricity which escapes from the charged body is very small it is necessary that the capacity of the instrument used to measure it should be small; this condition makes it advisable to use a small gold-leaf electroscope rather than a quadrant electrometer. To prevent the leakage from the supports of the gold leaves vitiating the experiments, the brass strip which carries the gold leaf is attached to and insulated from a metal

[1] Linss, *Meteorol. Zeitschr.* iv. p. 352, 1887; *Elektrotechn. Zeitschr.* i. 11, p. 506, 1890.

[2] Elster and Geitel, *Ann. d. Phys.* ii. p. 425, 1900.

[3] Geitel, *Phys. Zeits.* ii. p. 116, 1900.

[4] C. T. R. Wilson, *Proc. Camb. Phil. Soc.* xi. p. 32, 1900; *Proc. Roy. Soc.* lxviii. p. 151, 1901.

rod *A* by a piece of sulphur *B*, *A* being insulated by a plug of sulphur from the vessel containing the gas under examination, and connected with a condenser *C* formed of parallel plates of metal imbedded in a block of sulphur. The brass strip and gold leaf are initially charged to the same potential as the rod by making momentary contact between the rod and the strip by means of a moveable wire; the rod being connected with a large capacity remains at almost constant potential, and thus if there is any leakage of electricity along the sulphur supporting the brass strip and gold leaf, it will tend to keep them charged and not to

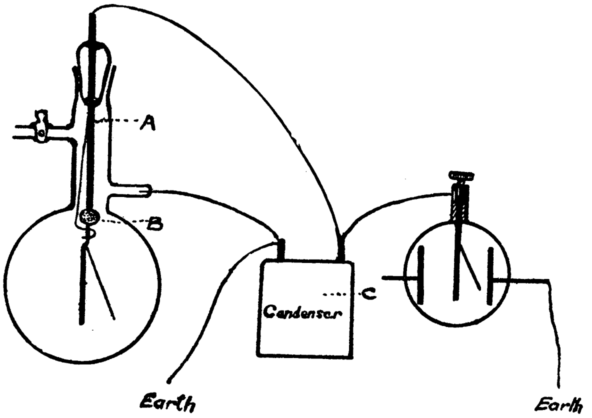

Fig. 1.

discharge them. The position of the gold leaf is read by means of a microscope provided with an eye-piece micrometer scale. The brass strip and gold leaf are used as the charged body and the rate at which the image of the gold leaf moves across the micrometer scale is a measure of the rate of leak through the gas. The following results were obtained by both Geitel and Wilson—the rate of escape of electricity in a closed vessel is much smaller than in the open and the larger the vessel the greater is the rate of leak. The rate of leak does not increase in proportion to the difference of potential between the gold leaves and the walls of the vessel; the rate soon reaches a limit beyond which it does not increase however much the potential difference is increased; provided of course that this is not great enough to cause sparks to pass.

Assuming that the maximum leak is proportional to the volume of the vessel, Wilson's experiments, which were made with vessels less than 1 litre in volume, showed that in dust-free air at atmospheric pressure the maximum quantity of electricity which can escape in one second from a charged body in a closed space whose volume is V cubic centimetres is about $10^{-8}\ V$ electrostatic units. Rutherford and Allen[1] working in Montreal obtained results in close agreement with this.

As the result of a series of experiments made at pressures ranging from 43 to 743 millimetres of mercury, Wilson came to the conclusion that the maximum rate of leak is very approximately proportional to the pressure, thus at low pressures the rate of leak is exceedingly small: this result is illustrated in a striking way by an observation of Crookes[2] that a pair of gold leaves could retain an electric charge for months in a very high vacuum. More recent experiments have shown that it is only in small vessels that the maximum rate of leak is proportional to the volume and to the pressure. With large vessels the rate of leak per unit volume is considerably less than in small vessels. The rate of leak also depends upon the nature of the walls of the vessel. The rate of leak is about the same in the dark as it is in the light, it is thus not due to light, and that it can be wholly due to some invisible form of radiation coming from outside is rendered improbable by the observations of Rutherford and Cooke[3], Cooke[4], McLennan and Burton[5] that though the leak inside a closed vessel can be reduced by about 30 per cent. by surrounding the vessel with thick lead, yet the diminution reaches a limit when the lead is about 2 inches thick, after this no diminution in the leak is produced by increasing the thickness of the lead. The rate of leak in a closed vessel is the same when the vessel is inside a railway tunnel as when it is outside; in the former case any radiation reaching the gas from outside must have travelled through many feet of solid rocks (see however § 6·1).

1 Rutherford and Allen, *Phys. Zeits.* iii. p. 225, 1902.
2 Crookes, *Proc. Roy. Soc.* xxviii. p. 347, 1879.
3 Rutherford and Cooke, *Phys. Rev.* xvi. p. 183, 1903.
4 Cooke, *Phil. Mag.* vi, 6. p. 403, 1903.
5 McLennan and Burton, *Phys. Rev.* xvi. p. 184, 1903.

5. Geitel (*loc. cit.*) made the very interesting observation that the rate of leak in a closed vessel increases, after the refilling of the vessel with fresh air, for some days, when it reaches a constant value at which it remains for an indefinitely long time. The most obvious explanation of this result is that it is due to the settling down of the dust, as Elster and Geitel (*loc. cit.*) have shown that the presence of dust, fog, or mist diminishes the rate of leak. This explanation is however rendered untenable by some later experiments[1] made by the same physicists, in which they found that the period required for the gas to attain its maximum conductivity was not appreciably diminished by filtering the dust out of the air by sending it through water, or by extracting the moisture from the gas: thus if the increase in the rate of leak is due to the settling down of some foreign matter from the gas, this matter must be something which cannot be got rid of by filtering the gas through water-traps or plugs of glass-wool.

6. Another aspect of this phenomenon is the very interesting fact discovered by Elster and Geitel[1] that the rate of leak in caves, and cellars where the air is stagnant and only renewed slowly, is very much greater than in the open air: thus in some experiments they made in a cave—the Baumannshöhle in the Harz Mountains—they found that in the cave the electricity escaped at seven times the rate it did in the air outside, even when this was clear and free from mist. They found too that in a cellar whose windows had been shut for eight days the rate of leak was very considerably greater than it was in the air outside. These experiments suggest that something producing abnormally great conductivity slowly diffuses from the walls surrounding the gas, and that this diffusion goes on so slowly that when fresh gas is introduced it takes a considerable time for the substance from the walls to again diffuse through the volume.

This explanation is in accordance with modern knowledge of radioactivity. The minute traces of radium and thorium products in the soil give rise to 'emanations,' radioactive gases which can diffuse out from porous substances. These emanations themselves produce conductivity in any gas with which they are mixed, and by their decay give rise to a series of secondary solid products

[1] Elster and Geitel, *Phys. Zeits.* ii. p. 560, 1901.

which decaying in their turn also give rise to conductivity in the gas near them. As these substances have very different rates of decay and vary in their power of making a gas conducting, the variation of conductivity with time may be very complicated.

The experiments we have described show that the rate of leak of electricity through gas in a normal state is influenced by a great variety of circumstances, such as the pressure of the gas, the volume of gas in the electric field, the thickness of the walls of the vessel containing the gas, and the amount of dust or fog held in suspension by it; all these effects receive a ready explanation on the view to which we are led by the study of the effects shown on a larger scale by gases whose conductivity has been increased by artificial means, namely that the conductivity is due to the presence of charged particles, or "ions." We may at once point out that the increase of the rate of leak with the size of the vessel containing the charged body shows that the conduction is not due, as Coulomb thought, to particles of gas originally uncharged striking against the charged body and receiving a charge which they deliver up to the sides of the vessel; if this were the method by which the electricity escaped the rate of leak would not increase with the size of the vessel. For the sake of completeness we add here an account of recent work on the subject, though this involves reference to the ionic theory to be developed in the next chapter.

6·1. The leakage of electricity through air under normal conditions has attracted a great deal of attention during the last few years and has a very important bearing on theories relating to the constitution of the stars and the transformation of matter into radiant energy.

There are several sources of the conductivity of normal air: part of it may be due to the presence of radioactive substances in the walls of the vessel in which the gas is contained or of a little radioactive emanation in the gas itself. The conductivity we are considering is so small that the presence of a mere trace of a radioactive substance or a trace of radioactive property in ordinary substances would be sufficient to account for it. The metal of which the containing vessel is made has certainly a considerable effect on the conductivity of the gas; this may however be due not to any intrinsic radiation from the metal, but to an excited radiation produced by the passage through the metal of a very penetrating radiation, for the existence of which we shall see that there is very strong evidence. The intrinsic radiation of the metal cannot be the only source of the conductivity of the gas; for, if it were, the conductivity of the gas in a closed vessel would be independent of the surroundings of the vessel. Now McLennan[1] measured the conductivity in a hermetically sealed vessel on land at Toronto in Canada, Cambridge, England, and Bowland, Scotland, and also on board the S.S. *Grampian* while crossing the Atlantic. He found that the rate of leak of electricity through the gas was very much the same at all the land stations, and could be represented by the production in the gas of ions at the rate of 9 ions per c.c. of the gas per second; the leak over the sea was however considerably less than this and could be represented by the production of only 6 ions per c.c. per second in the gas. McLennan and Wright[2] had previously found that the leak over the ice in Toronto Bay was considerably less than that on the shore. Pacini[3] also found a diminution in the rate of leak out at sea compared with that on shore. These experiments indicate that some of the leak is produced by radiation coming from the land and that this radiation is cut off by the ocean. Rocks and soil are known to be radioactive, as is also the water in many rivers and streams. Confirmation of the existence of this terrestrial radiation was obtained by measurements of the leak at different heights above the surface of the earth. McLennan and McCallum[4] measured the rate of leak at the top of a tower 64 metres high, Wulf[5] at the top of the Eiffel Tower 300 metres high, and Bergwitz[6] at the top of a tower 100 metres high, and found a marked diminution as compared with that at the base of the towers; this is what we should expect from the absorption of the radiation by the atmosphere.

1 McLennan, *Phil. Mag.* vi. 24, p. 520, 1912.
2 McLennan and Wright, *Phil. Mag.* vi. 17, p. 310, 1909.
3 Pacini, *Annali dell' Ufficio Centrale Meteor. e Geod. Italiano*, 27, pt. 1, 1910.
4 McLennan and McCallum, *Phil. Mag.* vi. 22, p. 629, 1911.
5 Wulf, *Phys. Zeits.* xi. p. 811, 1910.
6 Bergwitz, *Habilitationschrift*, Brunswick, 1910.

Observations in balloons at greater heights have brought to light the existence of another radiation coming from the sky and not from the earth, which also makes the gas a conductor of electricity.

Goekel[1] found from balloon observations that the diminution of the rate of leak with height got very small at altitudes of from 1 to 2 kilometres, while Hess[2] at similar altitudes found the rate of leak was actually greater than at sea level.

Kolhörster[3] made a very detailed study of the variation in the rate of leak at high altitudes, and observed very decided increases in the rate of leak with the altitude. The results are given below; the figures in the second column represent the difference in the number of ions produced per second per c.c. of the gas at the altitude given and at the surface of the earth.

Height in kilometres	Relative number of ions per c.c. per sec.
1·0	− 1·5
2·0	+ 1·2
3·0	+ 4·0
4·0	+ 8·3
5·0	+ 16·5
6·0	+ 28·7
7·0	+ 44·2
8·0	+ 61·3
9·0	+ 80·4

Millikan and Bowen sent up self-registering instruments in balloons which were afterwards retrieved; these also registered an increase in the rate of leak with the height, though considerably less than that obtained by Kolhörster.

The variation of the leak with the height is what would occur if the leak were produced by radiation of two types: (1) a radiation coming from the ground, and (2) another coming from the sky. The effect due to (1) would diminish as the height increased, while that due to (2) would increase.

Estimates of the leak due to the second type of radiation at the surface of the earth have been made by various experimenters.

1 Goekel, *Phys. Zeits.* x. p. 845, 1909; xii. p. 595, 1911.
2 Hess, *Phys. Zeits.* xii. p. 998, 1911.
3 Kolhörster, *Phys. Zeits.* xiv. pp. 1066, 1153, 1913; *Deutsch. Phys. Gesell. Verh.* xvi. 14, p. 719, 1914.

Their results are given in the following table; the amount of the leak is expressed as the number of ions produced per c.c. per second.

Kolhörster	1·4; 1·05; 1·70; 2·0
Pacini	2·1
v. Schweidler	1·6
Hess	2·7; 2·3
Goekel	1·6; 2·4
Millikan and Bowen ...	1·4

As the total leak at the earth's surface would generally correspond to the production of between 10 and 20 ions per c.c. per second, the rays of type (2) at sea level are only responsible for a small fraction of the leak. The greater part seems to be due to radiation of type (1), for Bergwitz found that in a cavern in a rock-salt mine where both radiations were presumably cut off the rate of leak sank to ·8 ions per c.c. per second.

Millikan and Bowen[1] give the following numbers as representing the number of ions per c.c. per second produced by radiation of type (2):

1·4 at sea level,
2·6 at 1600 metres,
4·8 at 3600 metres,
5·9 at 4300 metres.

Kolhörster[2] made observations at the top and at some distance below the surface of glaciers on the Jungfrau, and deduced the absorption of these rays by ice. He found values for μ, the coefficient of absorption for ice, ranging from $1{\cdot}6 \times 10^{-3}$ cm.$^{-1}$ to $2{\cdot}7 \times 10^{-3}$ cm.$^{-1}$, values which are much smaller than that for the γ radiation from any known radioactive substance. He found a diurnal variation in the amount of this radiation and suggested that it might be connected with the Milky Way. A description of apparatus suitable for these measurements is given by Kolhörster in the *Zeits. Instrumentenk.* xliv. p. 333, 1924.

6·2. A very complete investigation of the absorption of these rays by water has been made by Millikan and Bowen[3], who made

1 Millikan and Bowen, *Phys. Rev.* xxvii. p. 353, 1925.
2 Kolhörster, *Berlin. Berichte*, 1923, p. 366.
3 Millikan and Bowen, *Phys. Rev.* xxvii. p. 353, 1925; xxviii. p. 851, 1926.