# UNIVERSITY OF TORONTO STUDIES

## PAPERS FROM THE PHYSICAL LABORATORIES

No. 47: ON THE MOBILITIES OF IONS IN AIR AT HIGH PRESSURES, by Professor J. C. McLennan and David A. Keys

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# *On the Mobilities of Ions in Air at High Pressures.*

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(Read May Meeting, 1915.)

## I. INTRODUCTION.

In a paper by the writers, "On the electrical conductivity imparted to Liquid Air by alpha rays," attention was called to the exceedingly high insulating properties possessed by liquid air. The paper also included some measurements on the saturation currents in liquid air and in air at high pressures, when these were ionised by alpha rays. In the discussion of some phenomena connected with these currents, attention was drawn to the necessity of making measurements on the mobilities of ions both in liquid air and in air at very high pressures. Since the publication of that paper we have on several occasions made attempts to measure the mobilities of ions produced in liquid air; but up to the present have not succeeded in getting any trustworthy results. Convection currents due to the motion of air bubbles formed in the liquid air and the contamination of the liquid air by ice crystals formed from condensed atmospheric water vapour, have been two disturbing factors which we have not as yet been able to satisfactorily eliminate. It has been difficult, too, to reduce the size of the ionisation chamber of the measuring apparatus to dimensions small enough to permit of its use in a mass of liquid air small enough to be jacketted and kept at a low temperature by an outside vessel of liquid air maintained at a low temperature by rapid evaporation.

With regard to measurements on the mobilities of ions in air at high pressures, however, it has been quite different, for it has been found easy to make measurements on the mobilities at all pressures up to as high as approximately one hundred and ninety atmospheres, for such high pressures were obtained quite readily by the use of a liquid air compressor.

The only experiments which have been made hitherto on the mobilities of ions in air at high pressures appear to be the ones made by Dempster[1] and those made by Kovarik[2].

In his work Dempster used pressures to as high as 100 atmospheres and he found that over the range from one atmosphere to this limit the mobility of the positive ion made in air by alpha rays varied inversely as the pressure. He found, however, that the mobility of the negative ion at the higher part of the range did not appear to vary inversely as the pressure; but it decreased less rapidly with the pressure than it should have done if the inverse pressure law had been valid. Kovarik in his experiments, on the other hand, worked with pressures from 13·3 to 74·6 atmospheres and over the whole of this range he found that the mobilities of both positive and negative ions made in air by alpha rays followed the inverse pressure law.

In the present investigation the mobilities of the two kinds of ions were measured in air over a range of pressures commencing at 66·86 atmospheres and extending to 181·5 atmospheres. At the lower pressures of this range the mobilities obtained agreed with the results of Kovarik; but at the higher pressures it was found that the mobilities of the two kinds of ions began to approach each other in value and both decreased less rapidly with increases in pressure than they should according to the inverse pressure law.

## II. Apparatus.

In making the measurements the apparatus shown in Fig. 1. was used. AB was a thick circular plate of brass about 8 cms. in diameter, into which a polonium-coated copper plate CD was inserted. GH was a circular plate of brass 2 cm. in diameter and EFKL was a circular guard plate surrounding GH. The plate GH was held firmly in position with ebonite supports, with its lower face flush with that of the guard plate EL. The upper face of CD, which was the one coated with polonium, was also flush with the upper face of the plate AB, into which it was inserted. The plate CD was square and has an area of 16 sq. cm. The plates GH and EL were kept at a distance of 1 cm. from the upper face of AB by means of ebonite supports. The clearance between GH and the guard plate EL was less than one-half a millimetre.

When this ionisation chamber was in use, it was placed in a strong steel cylinder which had a capacity of about 1·5 litres. The guard plate was electrically connected to the steel chamber, which was itself kept joined to earth. One terminal of a battery of small cells

[1]Dempster. Phys. Review, Vol. XXIV. No. 1. Jan. 1912, p. 53.
[2]Kovarik. Proc. Roy. Soc. A. Vol. 86, 1912. p. 154.

was joined to earth and the other terminal was joined by a wire, which passed through an insulating plug of ebonite in the walls of the steel cylinder, to the plate AB. An insulated wire PR also passed out

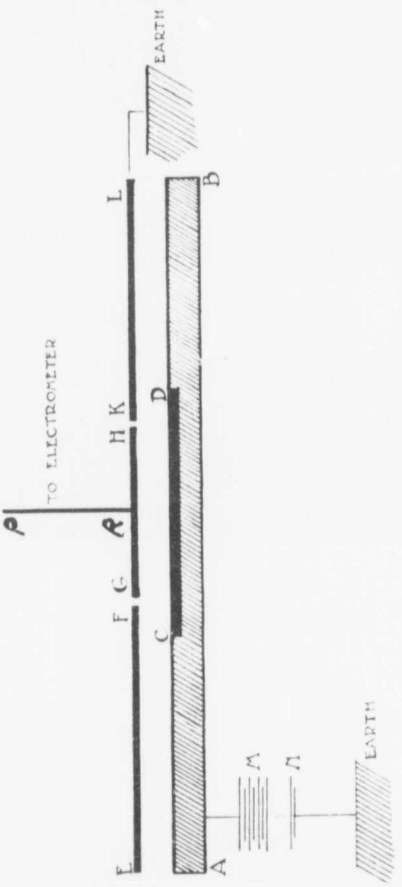



Fig. 1.

through the walls of the steel cylinder and was joined up to a pair of quadrants of a Dolazalek electrometer. With this arrangement any desired uniform electric field, positive or negative, could be established and maintained between the polonium-coated copper plate CD and the electrode EH. As the range of the alpha rays from polonium is only about 3·8 cm. in air at atmospheric pressure, it will be seen that at a pressure of about 70 atmospheres and higher the ionized portion of the air between GH and CD was confined to a very thin layer close to the latter plate.

The experiment consisted in measuring the current between CD and GH with various positive and negative voltages applied to AB at the different pressures. The formula for determining the mobilities which is applicable to the present case is that given by Rutherford[1] and Child.[2]

Expressed in electrostatic units the mobility of an ion is given by:

$$K = \frac{32.\pi.d^3.i}{9V^2} \text{ cm. a second per 300 volts a cm} \qquad (1)$$

where i is the current between CD and GH in e.s.u. per square cm. cross section, d the distance in cm. between GH and CD and V the potential difference between them in electrostatic units.

Expressed in practical electromagnetic units:

$$K = \frac{3200.\pi.d^3.i}{3V^2} \text{ cm. a second per volt a cm} \qquad (2)$$

where d is in cm., V is in volts, and i is in electrostatic units and is the current per square cm. cross-section between CD and GH.

As d was 1 cm. in the apparatus used by us the relation (2) reduces to:

$$K = \frac{3200.\pi.i}{3V^2} \qquad (3)$$

From equation (3) it will be seen that for a selected pressure the current i should be proportional to $V^2$.

*Table I.*

Air

Pressure = 145·35 atmospheres.

| P.D. in Volts, V. | Square of P.D. | Current in e.s.u. per cm.$^2$ |
|---|---|---|
| *Positive* | | |
| 4·11 | 16·89 | $4{\cdot}51 \times 10^{-5}$ |
| 6·16 | 37·95 | 11·51 |
| 8·21 | 67·3 | 21·51 |
| 10·26 | 105·27 | 33·87 |
| 12·3 | 150·69 | 48·71 |
| 14·35 | 206·27 | 67·24 |
| 16·4 | 268·0 | 84·89 |
| *Negative* | | |
| 4·1 | 16·8 | $7{\cdot}09 \times 10^{-5}$ |
| 6·16 | 37·95 | 16·42 |
| 8·2 | 67·0 | 29·83 |
| 10·26 | 105·27 | 45·32 |
| 12·3 | 150·69 | 66·25 |
| 14·36 | 206·2 | 91·56 |
| 16·4 | 268·0 | 122·9 |

[1]Rutherford, Phys. Rev., Vol. XIII (6), p. 321, 1901.
[2]Child, Phys. Rev., Vol. XII (3) p. 137, 1901.

*Table II.*

Mobilities of ions at various pressures in air.

| Pressure in Atmospheres | Mobility in cm/sec per volt/cm. | | Mobility × Pressure | | Ratio of mobilities $k_2/k_1$ |
|---|---|---|---|---|---|
| | Positive = $k_1$ | Negative = $k_2$ | Positive | Negative | |
| Experimental Results. | | | | | |
| 66·86 | $19·70 \times 10^{-3}$ | $28·30 \times 10^{-3}$ | 1·32 | 1·89 | 1·43 |
| 87·21 | 16·13 | 21·37 | 1·41 | 1·86 | 1·33 |
| 96·9 | 14·92 | 19·46 | 1·46 | 1·89 | 1·30 |
| 108·53 | 13·65 | 18·83 | 1·48 | 2·04 | 1·38 |
| 116·28 | 12·87 | 17·83 | 1·50 | 2·07 | 1·39 |
| 123·1 | 12·31 | 16·69 | 1·52 | 2·05 | 1·36 |
| 132·75 | 12·03 | 15·36 | 1·60 | 2·04 | 1·28 |
| 145·35 | 10·98 | 15·20 | 1·60 | 2·21 | 1·38 |
| 155·04 | 10·82 | 14·24 | 1·68 | 2·21 | 1·32 |
| 164·73 | 10·36 | 14·08 | 1·71 | 2·32 | 1·36 |
| 175·4 | 9·19 | 12·46 | 1·61 | 2·19 | 1·36 |
| 181·5 | 9·11 | 11·97 | 1·65 | 2·17 | 1·31 |
| Calculated on basis of $p \times k$ = constant. | | | | | |
| 20 | $67·3 \times 10^{-3}$ | $94·5 \times 10^{-3}$ | 1·34 | 1·89 | 1·41 |
| 30 | 44·9 | 63·0 | " | " | " |
| 40 | 33·5 | 47·3 | " | " | " |
| 60 | 22·4 | 31·5 | " | " | " |
| 80 | 16·8 | 23·6 | " | " | " |
| 100 | 13·4 | 18·9 | " | " | " |
| 120 | 11·2 | 15·8 | " | " | " |
| 140 | 9·6 | 13·5 | " | " | " |
| 160 | 8·4 | 11·8 | " | " | " |
| 180 | 7·5 | 10·5 | " | " | " |
| 200 | 6·7 | 9·5 | " | " | " |

At all the pressures used this law of proportionality between i and $V^2$ was tested by giving different values to V and in all cases it was found to hold. One of the different sets of readings obtained at a pressure of 145·35 atmospheres will serve to illustrate this point. The voltages applied, together with their squares and the corresponding currents per square cm. cross section, are given in Table I. They are represented graphically in Fig. 2 and it is clear from the diagram that the relation between i and $V^2$ is a linear one.

## III. Results.

Diagrams similar to that in Fig. 2 were plotted from the readings taken with different voltages at all the pressures selected. From them values for $i/V^2$ were calculated for each of the pressures and on substituting these values in the relation given by the equation (3) the mobilities for both positive and negative ions were deduced for the corresponding pressures. These mobilities are all collected in Table II and they are plotted in Fig. 3 against the pressures as abscissae.

Mobilities calculated according to the inverse pressure law on the basis of the mobilities for positive and negative ions at atmospheric pressure being respectively 1·34 and 1·89 cm. a second per volt a cm. are also given in Table II. The dotted curves represent the calculated mobilities and the smooth curves the mobilities determined in the present investigation. As both the table and the figure show, the mobilities did not decrease as the pressure rose so rapidly as was demanded by the inverse pressure law. Moreover, it will also be seen from the table and the diagram that the mobility of the positive ion approached that of the negative ion as the higher pressures were reached, the ratio of the mobility of the negative ion to the positive ion dropping from 1·43 at 66·86 atmospheres to 1·31 at 181·5 atmospheres. The departure from the inverse pressure law, however, was not very great.

It will be recalled that Greinacher[1], in his experiments on the ionisation of paraffin oil and of petrol ether by alpha rays, found that the mobilities of the positive and negative ions produced in these liquids were practically identical. In this connection it is interesting to see that our results indicate that very probably the same equality would apply to the mobilities of positive and negative ions in liquid air. Measurements on the mobilities of ions in air at pressures still higher than those used in this investigation would be required, however, to show whether this surmise were correct or not.

In closing we desire to express our appreciation of the services of Mr. P. Blackman, who assisted us in taking many of the readings in this investigation.

The Physical Laboratory,
University of Toronto,
May 1st, 1915.

[1]Greinacher. Phys. Zeit., 10 Jahr., No. 25, p. 986.

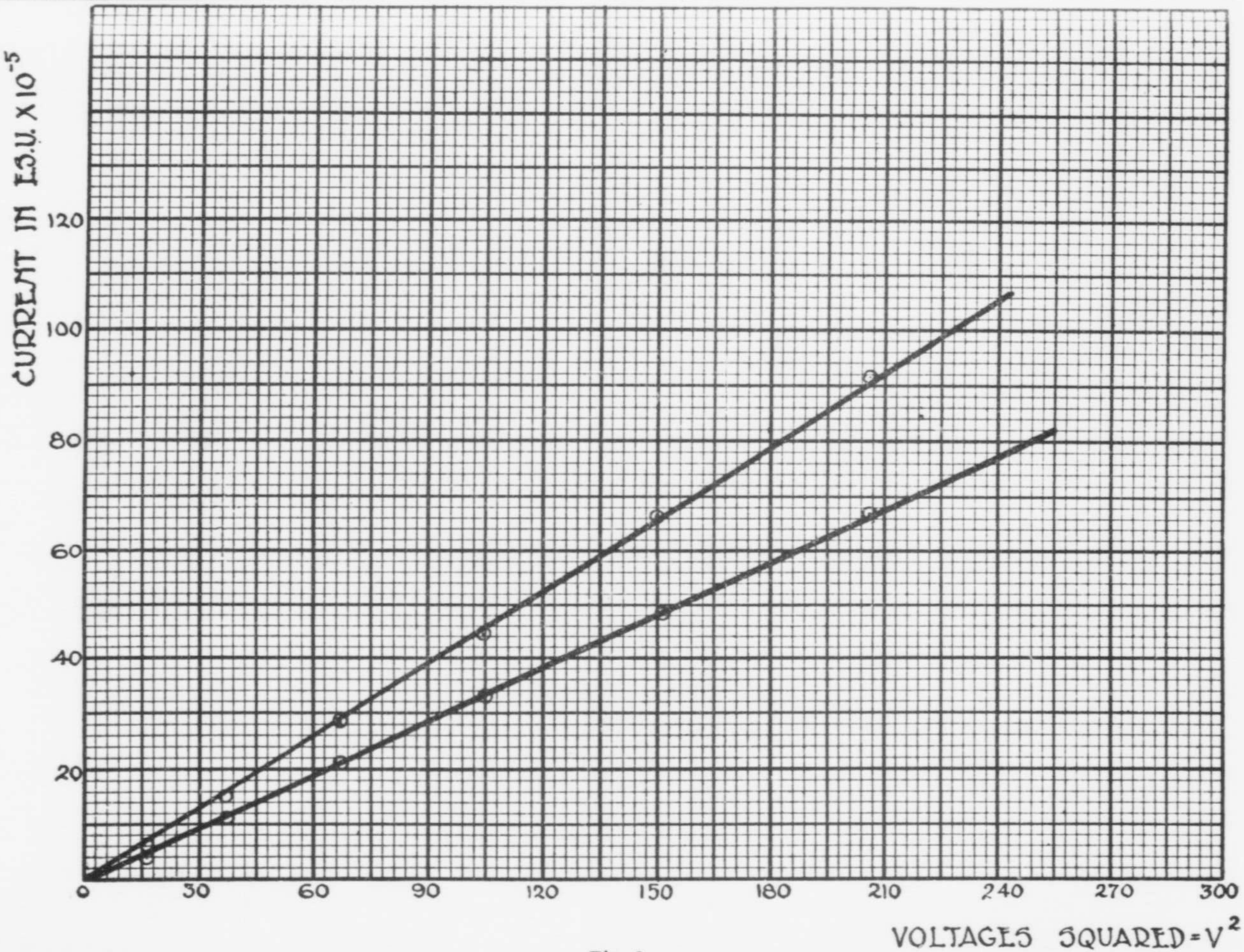
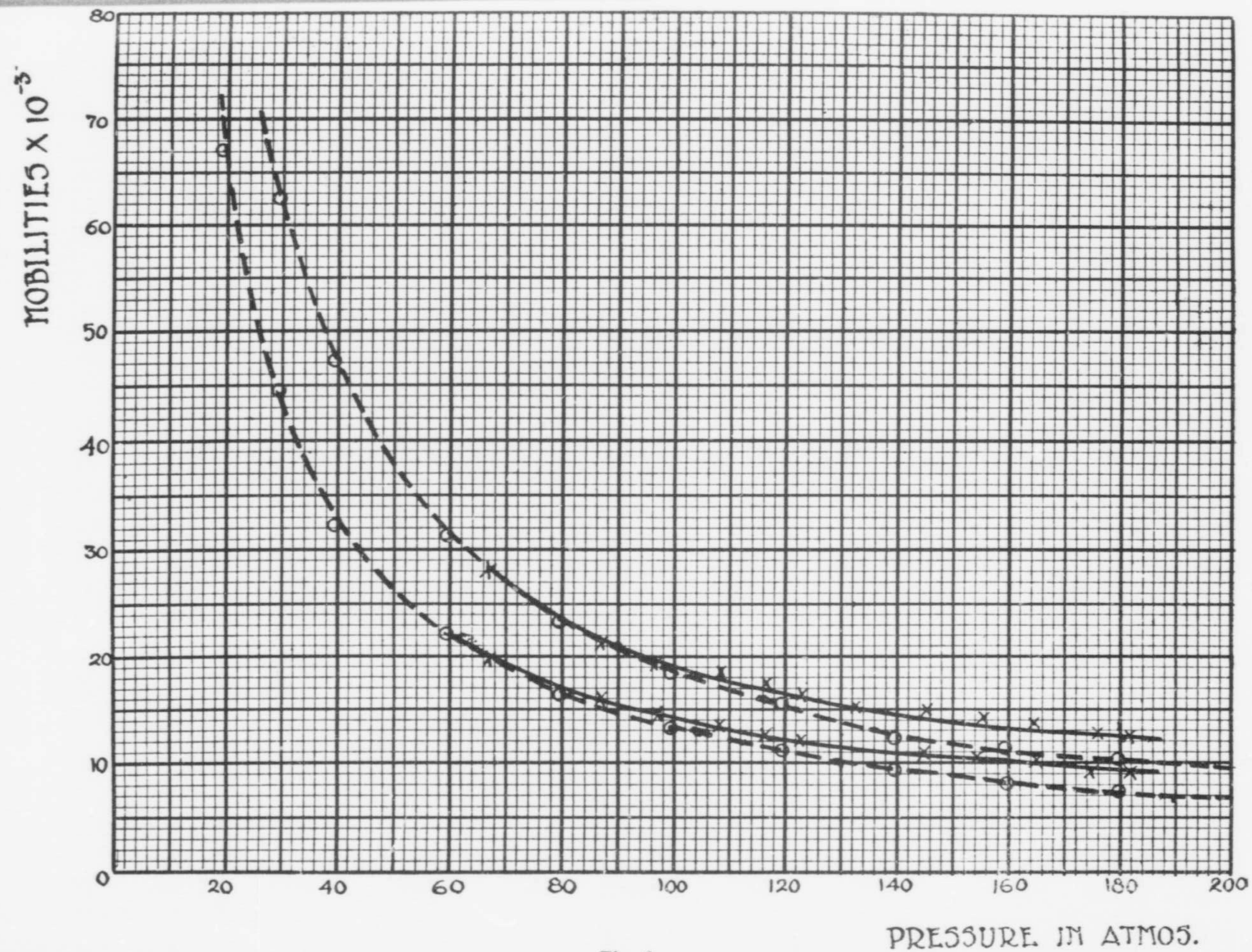

CURRENT IN E.S.U. X 10^-5
120
100
80
60
40
20
0
30
60
90
120
150
180
210
240
270
300
VOLTAGES SQUARED = V^2

Fig. 2.



MOBILITIES X 10^-3
80
70
60
50
40
30
20
10
0
20
40
60
80
100
120
140
160
180
200
PRESSURE IN ATMOS.


Fig. 3.