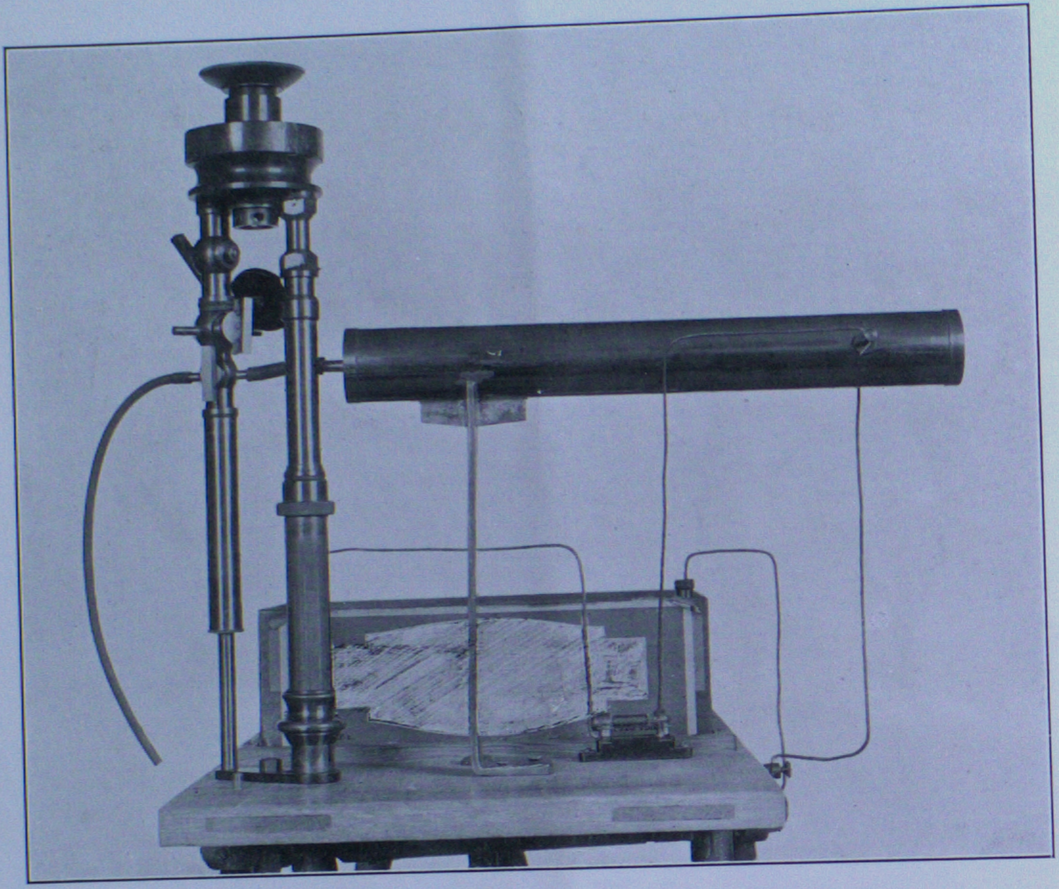

FIG. 1.—"PORTABLE" AITKEN NUCLEUS COUNTER WITH CONDENSER ATTACHED.

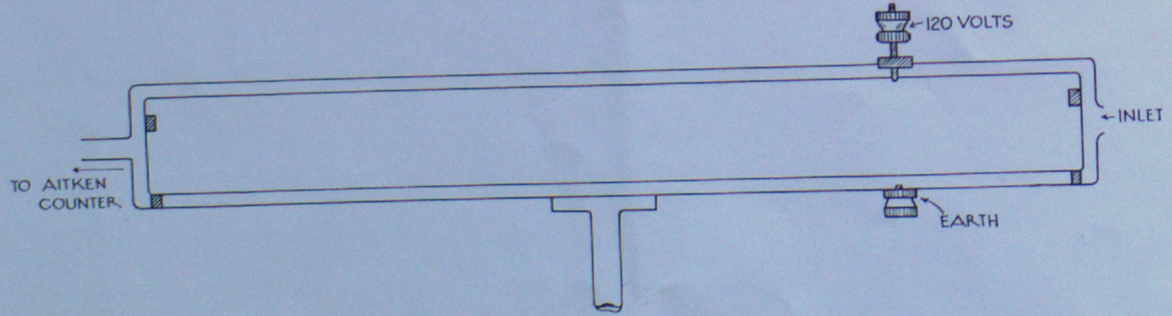

FIG. 2.—CYLINDRICAL CONDENSER FOR ELIMINATING CHARGED NUCLEI.

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THE CHARGED AND UNCHARGED NUCLEI IN THE ATMOSPHERE AND THEIR PART IN ATMOSPHERIC IONISATION

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THE CHARGED AND UNCHARGED NUCLEI IN THE ATMOSPHERE AND THEIR PART IN ATMOSPHERIC IONISATION

§ 1—INTRODUCTION

It is well known that atmospheric ionisation is greatly influenced by the presence of nuclei of condensation in the lower layers of the atmosphere. The variations in the concentration of nuclei at Kew Observatory have been studied by H. L. Wright (1)* who also examined, from a statistical point of view, the effect of nuclei on the electrical conductivity of the air (2). The problem has been attacked from the theoretical standpoint by Dr. F. J. W. Whipple (3), who has put forward formulæ to explain the relation between the rates of combination of small ions with charged and uncharged nuclei.

The observations of nucleus content used by Wright were confined to measurements of the total numbers of nuclei, irrespective of whether the nuclei were charged or uncharged. In the present investigation the attempt has been made to separate the charged and the uncharged nuclei. It was thought that by so doing further information would be obtained as to the effect of the nuclei on atmospheric ionisation. Moreover, by an application of Whipple's formulæ, simultaneous observations of the electrical conductivity and the concentration of charged and uncharged nuclei enable us to obtain an estimate of the rate of production of ions in the open air.

§ 2—METHODS OF OBSERVATION

The apparatus used for the observations of nucleus content consists of a "portable" Aitken counter (Casella No. 281), a description of which is to be found in Aitken's Collected Works (4). The only departure of the Casella design from the original is in the omission of the stirring vane ; it is considered that sufficient mixing is produced by the rapid entry of the sample. Since the concentrations of nuclei at Kew are always comparatively high, only small samples of air are required for making a count. The samples were therefore always taken by means of one or other of the two calibrated taps ($\frac{1}{4}$ c.c. or $\frac{1}{20}$ c.c.) on the instrument and never by means of the graduated pump. In view of the fact that some workers subject each sample to more than one expansion it should be stated that with the apparatus in use at Kew expansions subsequent to the initial one rarely bring down any additional droplets, so the practice is to take the number of droplets produced by one expansion only.

For eliminating the charged nuclei a cylindrical condenser, made of brass, is attached to the inlet of the Aitken counter. A photograph of the whole apparatus is reproduced in Fig. 1 of the *Frontispiece*, and a diagram of the condenser is shown in Fig. 2. The outer tube of the condenser is 3·65 cm. diameter and 32 cm. long,

* The numbers in brackets refer to the bibliography on page 15.

while the inner tube is 3·2 cm. diameter and 30 cm. long. There is therefore an air gap 0·23 cm. across between the two tubes. The inner tube is insulated by ebonite bushes at each end and it is charged up, when required, to about 130 volts by means of a dry battery which is carried on the stand of the apparatus. Each end of the condenser is fitted with a brass cap ; one cap has a small hole 0·3 cm. diameter for the air to enter, the other carries a short tube through which the connexion is made to the sampling tap of the counter.

The method of using the condenser differs from that employed by other workers. Instead of allowing a continuous stream of air to flow slowly through the condenser the practice is to suck a sample of air into the condenser and allow it to remain a sufficient time for the charged nuclei to be caught on one or other of the cylinders. A portion of the sample is then drawn into the measuring tap of the Aitken counter and the count is made in the usual manner. The samples are left in the condenser for about 10 seconds ; with the condenser charged to 130 volts this time interval is sufficient to remove all ions of mobility greater than 0·00004 cm./sec. per volt/cm. Each observation of the nucleus content consists of the mean of 20 separate counts and the counts of the uncharged nuclei are sandwiched between those of the total nuclei so that effects due to a progressive change in conditions are eliminated. In measuring the total nuclei the samples were taken through the uncharged condenser, but about half-way through the experiments it was found that there was an appreciable loss of nuclei in the condenser even when it was uncharged. This will be referred to again later. After this effect was noticed the observations of total nuclei were made both with air drawn through the uncharged condenser and with air taken directly into the tap of the counter.

All the observations were made in the open air between 14h. and 15h. G.M.T., so that they were simultaneous with the routine observations of positive conductivity at ground level by the Wilson test-plate method, an account of which has been given recently (5). Further information as to the state of ionisation during many of the observations was obtained from a photographic recording apparatus set up by P. A. Sheppard. An account of this apparatus will be published shortly by L. H. Starr, who maintained the instrument in operation during 1933.

The observations were carried out from November 1932 to December 1933, and, excluding numerous test comparisons, there were about 120 altogether.

§ 3—TESTS OF THE APPARATUS

The probable error of a single observation of nucleus content as represented by the mean of 20 counts is ±6 per cent., but it appears that part of the scatter shown by observations in the open air is due to short period fluctuations in the nucleus content, for observations made with samples taken from a closed vessel are a little more consistent.

The loss of total nuclei in the uncharged condenser was measured on 50 occasions by making alternate observations on samples taken through the condenser and directly into the counter. The mean value of the ratio Z'/Z, where Z' is the number of nuclei left in the sample after passing through the condenser and Z is the number of nuclei in the sample taken directly, is $0{\cdot}85 \pm 0{\cdot}01$. Individual observations of the ratio varied from 0·70 to 1·00. This loss of nuclei has been experienced by other observers and it appears that the effect is due to deposition on the walls of the vessel. In the present investigation the mean value, 0·85, of the ratio Z'/Z has been used to obtain Z for the earlier observations when no direct counts were made.

A point of importance in connexion with the loss of nuclei is the question whether the loss is the same for charged and for uncharged nuclei. In other words, is the ratio N_0'/Z', where N_0' is the number of uncharged nuclei passing through the charged condenser, the same as the true ratio N_0/Z ? The question was settled by measuring the loss of uncharged nuclei. This was done by comparing samples which had passed through one uncharged condenser and then through a similar charged condenser with samples which had passed through a charged one only.

The mean ratio from thirteen comparisons was $0{\cdot}85 \pm 0{\cdot}02$, i.e. exactly the same as the ratio for total nuclei. It is concluded, therefore, that the loss of nuclei by deposition does not depend on whether they are charged or not.

Some comparisons were also made to test the efficiency of the charged condenser for removing the charged nuclei. The comparisons were made between a sample which had passed through two condensers both of which were charged and a sample which had passed first through a charged condenser and then through an uncharged condenser. In both cases the uncharged nuclei would suffer the same loss, but if one charged condenser were insufficient to remove all the charged nuclei, the ratio in the two cases would depart from unity. The mean ratio for seven comparisons was found to be $0{\cdot}99 \pm 0{\cdot}04$, which is near enough to unity for us to conclude that practically all the charged nuclei are removed when the condenser is charged. This indicates that practically all the large ions at Kew must have mobilities exceeding 0·00004 cm./sec. per volt/cm.

§ 4—NOTATION

Before discussing the chief results of the investigation it will be convenient to introduce the notation which will be used. It is practically the same as that adopted by Whipple (3).

q = rate of production of small ions per unit volume ;
n_1 = number of small positive ions ,, ,, ,, ;
n_2 = ,, ,, small negative ions ,, ,, ,, ;
Z = ,, ,, Aitken nuclei ;
N_1 = ,, ,, large positive ions (i.e. nuclei with + charges) ;
N_2 = ,, ,, large negative ions (i.e. nuclei with — charges) ;
$N = \frac{1}{2}(N_1+N_2)$;
N_0 = number of uncharged nuclei ;
e = electronic charge, and
w_1 and w_2 are the mobilities of the small ions.

The combination coefficient η_{10} is such that the frequency of combinations of small + ions with uncharged nuclei is $\eta_{10}\, n_1\, N_0$ per unit volume per unit time. The coefficients η_{20}, η_{12} and η_{21}, are defined in a similar way and the mutual combination coefficient for small ions of opposite sign is denoted by α.

The equilibrium conditions of ionisation may then be expressed by four equations thus :—

$$q = \alpha\, n_1 n_2 + \eta_{12}\, n_1\, N_2 + \eta_{10}\, n_1\, N_0 \qquad \text{(i)}$$
$$q = \alpha\, n_1 n_2 + \eta_{21}\, n_2\, N_1 + \eta_{20}\, n_2\, N_0 \qquad \text{(ii)}$$
$$\eta_{10}\, n_1 N_0 = \eta_{21}\, n_2\, N_1 \qquad \text{(iii)}$$
$$\eta_{20}\, n_2 N_0 = \eta_{12}\, n_1\, N_2 \qquad \text{(iv)}$$

It is assumed that the ions carry one elementary charge and also that the combination of small ions with smoke and dust particles is negligible. The question as to how far the latter assumption is justified is discussed in the latter part of this paper. The work of Nolan and others indicates that N_1 and N_2 are practically equal and this appears to be borne out by some recent measurements of space charge at Kew, so we shall assume that these numbers are equal and use N to indicate the number of large ions of either sign. The observations with the Aiken counter and condenser apparatus give Z and N_0 directly ; N is obtained from the identity $Z=N_0+2N$.

§ 5—RATIO OF NUMBERS OF CHARGED AND UNCHARGED NUCLEI

The individual values of the ratio N_0/N show a considerable scatter since they are very sensitive to errors in the measurements of N_0 and N. The observations have therefore been arranged in groups according to the total nucleus content and for each group the ratio of the mean of the values of N_0 to the mean of the values of N has been obtained. The results are given in Table I.

TABLE I

	Number per mm³			Ratio
	Z	N_0	N	N_0/N
	11·8	7·6	2·1	3·6
	17·0	11·0	3·0	3·7
	20·1	13·4	3·35	4·0
	22·1	13·9	4·1	3·4
	26·1	16·6	4·75	3·5
	30·9	19·7	5·6	3·5
	36·8	23·8	6·5	3·7
	49·0	32·0	8·5	3·8
	62·4	38·5	11·95	3·2
	95	52	21·5	2·4
Mean	37·1	22·9	7·1	3·5

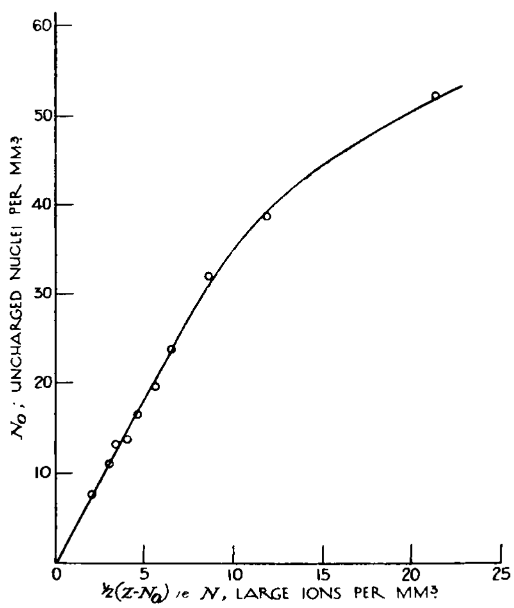

FIG. 3.—THE RELATION BETWEEN THE NUMBERS OF LARGE IONS AND UNCHARGED NUCLEI.

In this table each group is the mean of either 11 or 12 observations, so that practically equal weight can be assigned to each mean. It will be seen that there is no systematic change in the ratio N_0/N until the nucleus content exceeds 50 per mm³, when there appears to be a definite drop in the ratio. This change is shown more clearly in Fig. 3 in which N is plotted against N_0. Most observers have found no systematic variation of N_0/N with nucleus content, but in a recent investigation at Washington O. W. Torreson and G. R. Wait (6) obtained some evidence that the ratio increases with nucleus content. The mean value of N_0/N at Kew is 3·5, but if we exclude the two estimates which correspond to the nucleus concentrations exceeding 50 per mm³ the mean value is 3·7. Some estimates obtained at other places are given in Table II.

TABLE II

Author	Station	Z per mm³	No/N
J. J. & P. J. Nolan (7)	Glencree	2·2	2·2
A. R. Hogg (8)	Canberra	2·6	1·4
V. Hess (9)	Heligoland	6	2·2
A. Gockel (10)	Freiburg	8	2·4
P. F. Schachl (11)	Innsbruck	8	2·3
		15	2·8
J. Scholz (12)	Potsdam	17	2·2
C. O'Brolchain (13)	Graz	21	2·7
Torreson & Wait (6)	Washington	21	5·8
F. J. Scrase	Kew	27	3·7
		79	2·8

It will be noticed that the highest ratios have been obtained at Kew and Washington, where nuclei are comparatively numerous. On the other hand when the nucleus content is extremely high at Kew the ratio is not much above the average found at places comparatively free from nuclei. The equations (iii) and (iv) representing the equilibrium between large ions and uncharged nuclei show that N_0/N_1

depends partly on the ratio n_2/n_1 and partly on the ratio of the combination coefficients between small ions and large ions and small ions and uncharged nuclei. By combining the equations and remembering that $N_1 = N_2 = N$ we have

$$\frac{N_0}{N} = \sqrt{\frac{\eta_{12}\,\eta_{21}}{\eta_{10}\,\eta_{20}}}$$

Thus any changes in the value of N_0/N are likely to be associated with changes in the combination coefficients. The factors on which these coefficients depend are the size of the nuclei and the mobilities of the small ions. Now some preliminary results obtained from ionisation measurements by L. H. Starr at Kew indicate that there is very little systematic variation of these mobilities with nucleus content. It is probable therefore that the change in the ratio N_0/N is due to variation in the size of the nuclei.

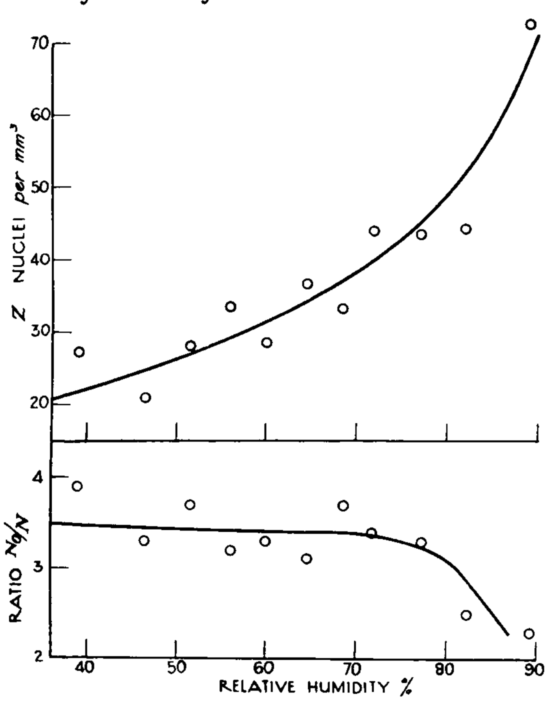

FIG. 4.—VARIATION OF NUCLEUS CONTENT WITH RELATIVE HUMIDITY.

In this connexion it is of interest to examine the effect of relative humidity. For this purpose the measurements of Z and N_0 have been arranged in groups of equal numbers of observations according to the humidity. The values of N_0/N obtained from the means of each group are shown against the relative humidity in Fig. 4, which also gives the variation of Z with humidity. It will be seen that the two lowest values of N_0/N are associated with the highest humidities. The increase in size of the nuclei at high concentrations is apparently due to the condensation of water round the nuclei which appears to start when the humidity exceeds 80 per cent. This fits in with the idea, which is now generally accepted, that the nuclei are hygroscopic particles, and it accounts for the fact that fogs are often observed to occur at humidities as low as 80 per cent.

The connexion between nucleus content and visibility has been examined and the results are given in Table III.

TABLE III

Visibility: Meteorological Office Code* / International Code†	C, D 1, 2	E 3	F 4	G 5	H 6	I 6	J 7	K 8
Visual Range (Km.)	0·1—0·5	0·5—1	1—2	2—4	4—7	7—10	10—20	20—30
Z (per mm.^{3})	103	106	64	55	43·3	34·8	23·4	21·2
N_0/N	2·1	2·4	2·1	3·0	4·0	3·3	3·6	3·9
No. of observations	4	4	4	11	18	20	28	27
Humidity %	89	81	83	74	69	67	60	51

*See Meteorological Observer's Handbook, 1934 edition, p. 59.
†*Ibid.* p. 63.

The numbers of observations in poor visibilities are small (on account of the relatively infrequent occurrence of these conditions in the afternoon), so too much reliance should not be placed on the figures in these groups. The data are plotted in Fig. 5. Poor visibility appears to be associated with the lower values of N_0/N and therefore with the presence of larger nuclei, the growth of which is favoured by the high humidities. It is a little difficult to decide how much the visibility is dependent on the size of the nuclei. That the visibility is not wholly dependent on the numbers of nuclei is shown by the graph in Fig. 5 in which the logarithms of Z and of the visual range are plotted. The five points corresponding to the higher ranges of visibility lie fairly close to a straight line ; for these points there is probably not much variation in the size of the nuclei since the humidities are less than 80 per cent. and N_0/N does not fall below 3·0. This straight line, therefore, probably represents fairly

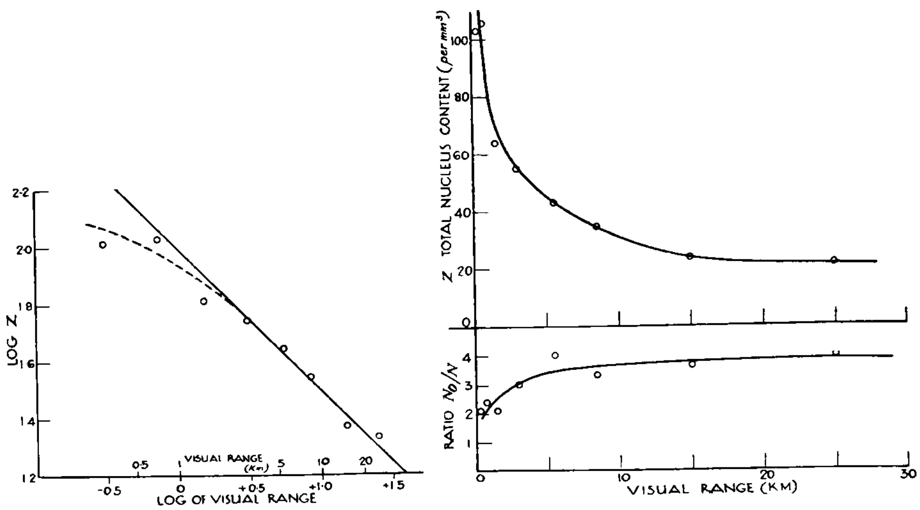

FIG. 5.—VARIATION OF NUCLEUS CONTENT WITH VISUAL RANGE.

well the connexion between visibility and nucleus content. The remaining three points, however, which are associated with high humidity and low values of N_0/N, indicate that there is some tendency for the visibility to fall off a little more rapidly when the nucleus content exceeds about 50 per mm³. This effect is probably due to the growth of the nuclei. The straight line in the logarithmic graph leads to the relation

$$V = 10^4/Z^2$$

where V is the visual range in kilometres and Z is the number of nuclei per mm³. We may regard this formula as valid for Kew so long as the humidity is less than 80 per cent. If the humidity exceeds 80 per cent. the visibility will probably be less than that indicated by the formula. The work of M. G. Bennett (14) shows that the effect of humidity is great when the visibility is low, but it is not very marked when the visibility is good.

§ 6—COMBINATION COEFFICIENTS

F. J. W. Whipple (3) has recently put forward two formulæ* connecting the combination coefficients between small ions and large ions and small ions and uncharged nuclei. These formulæ are :—

$$\eta_{12} = \eta_{10} + 4\pi e w_1 \quad \text{(v)}$$

$$\eta_{21} = \eta_{20} + 4\pi e w_2 \quad \text{(vi)}$$

Combining these formulæ with the equations (iii) and (iv) Whipple derived expressions for each combination coefficient, e.g.

$$\eta_{10} = \frac{4\pi e N_1 (w_1 n_1 N_2 + w_2 n_2 N_0)}{n_1 (N_0^2 - N_1 N_2)}$$

If we again assume $N_1 = N_2 = N$, then we have

$$\eta_{10} = \frac{4\pi e w_1\left(1 + \dfrac{w_2 n_2 N_0}{w_1 n_1 N}\right)}{\dfrac{N_0^2}{N^2} - 1} \quad \text{(vii)}$$

and similarly

$$\eta_{20} = \frac{4\pi e w_2\left(1 + \dfrac{w_1 n_1 N_0}{w_2 n_2 N}\right)}{\dfrac{N_0^2}{N^2} - 1}$$

* The validity of these formulæ has not been fully established but it has been thought worth while to trace the consequences of accepting them. It should be noted, however, that the formulæ are not accepted by W. R. Harper (24) who has more recently developed a theory of the combination of ions.

These formulæ enable us to determine the combination coefficients without using the absolute values of the large and small ion contents, but we require to know the mobilities of the small ions and also the ratio of the numbers of small ions. Some preliminary information about these quantities has been provided by L. H. Starr from records of ionisation obtained at Kew. The data were available for about half the occasions on which the Aitken measurements were made, but they are sufficient to show whether they are influenced by the nucleus content. It appears that the mobilities of the small ions do not vary very much with the number of nuclei ; the mean values of w_1 and w_2 at 14h. 30m. G.M.T are 0·98 and 1·05 cm./sec per volt/cm. respectively. The ratio n_1/n_2 on the other hand changes appreciably when the nucleus content is high, i.e. when the numbers of small ions are low. In these conditions, however, the measurements of the ratio are subject to considerable errors ; there is for example the well-known difficulty in ion-counting experiments of eliminating entirely the repulsion of negative ions due to induced charges on the apparatus and although precautions were taken to reduce this effect as far as possible it is not certain that the measurements made when the potential gradient was high were quite free from this source of error. The full account of these ionisation measurements will be published in due course by Mr. Starr. For our purpose smoothed values of n_1/n_2 have been extracted after plotting individual values against Z.

Using these data and the measurements of N_0/N the values of the combination coefficients at Kew have been calculated. The results are given in Table IV, each group, as before, being derived from the means of about a dozen nucleus observations. The last two columns contain the dissipation coefficients β_1 and β_2, of the positive and negative small ions calculated from the combination coefficients and the nucleus contents. These dissipation coefficients are defined by

$$\beta_1 = q/n_1 \text{ and } \beta_2 = q/n_2$$

and so the equation of equilibrium (i) may be written

$$\beta_1 = \alpha n_2 + \eta_{10} N_0 + \eta_{12} N_2$$

or neglecting the combination of small ions of opposite sign and putting

$$N_2 = N$$

$$\beta_1 = \eta_{10} N_0 + \eta_{12} N \quad \text{(viii)}$$

similarly

$$\beta_2 = \eta_{20} N_0 + \eta_{21} N \quad \text{(ix)}$$

The reciprocal of β is the average life of the small ion.

TABLE IV

Observations			Applying formulæ (iii) & (iv)		Applying Whipple's formulæ (v) & (vi)				Formulæ (viii) & (ix)	
Z per mm^3	N_0/N	n_1/n_2	η_{21}/η_{10}	η_{12}/η_{20}	η_{10} $\times 10^6$	η_{12} $\times 10^6$	η_{20} $\times 10^6$	η_{21} $\times 10^6$	$\beta_1 \times$ 10^3 sec^{-1}	$\beta_2 \times$ 10^3 sec^{-1}
11·8	3·6	1·32	4·8	2·7	·55	2·3	·85	2·7	9	12
17·0	3·7	1·33	4·9	2·8	·55	2·3	·83	2·7	13	17
20·1	4·0	1·34	5·4	3·0	·48	2·3	·76	2·6	14	19
22·1	3·4	1·35	4·6	2·5	·62	2·4	·94	2·8	18	25
26·1	3·5	1·36	4·8	2·6	·58	2·3	·91	2·8	20	28
30·9	3·5	1·38	4·8	2·5	·58	2·3	·93	2·8	24	34
36·8	3·7	1·40	5·2	2·6	·53	2·3	·87	2·8	28	39
49·0	3·8	1·48	5·6	2·6	·48	2·3	·87	2·8	35	52
62·4	3·2	1·55	5·0	2 1	·62	2·4	1·28	3·2	53	87
95	2·4	(2·1)	5·0	1·1	·81	2·6	2·5	4·4	98	225

The combination coefficients, like the ratio N_0/N, remain fairly steady when the nucleus content is less than 50 per mm^3. The increase when Z becomes high is most marked for the coefficients of the negative small ions ; this is partly due to the high value of n_1/n_2 which, as already explained, is subject to considerable error. If n_1/n_2 remained at about 1·5 the increase in η_{10} and η_{12} would be more marked and the increase in η_{20} and η_{21} less marked. All the values of the coefficients calculated above are less than those of Nolan and de Sachy(15) which lie between 6·8 and $9{\cdot}7 \times 10^{-6}$ (Z ranged from about 10 to 40 per mm³), but it should be remembered that these refer to indoor air whereas our estimates are based on observations made in the open. It would appear that the nuclei in laboratory air are larger than those in the open air.

Omitting the values corresponding to Z greater than 50 per mm³ we find that the ratio η_{10}/η_{20} is 0·63 whilst the ratio η_{12}/η_{21} is 0·84. We should not be justified therefore in assuming, as Nolan and de Sachy (15) have done, that these ratios are equal. If this assumption is made, Whipple's formulæ (v) and (vi) would show that these ratios must also be equal to w_1/w_2 which in our case is 0·93, and further, if we are correct in assuming that $N_1 = N_2$, then w_1/w_2 should be equal to n_2/n_1, and this is far from being the case at Kew. Nolan and de Sachy state that the theories of mobility of the small ions indicate that the ratio of the concentrations of the ions is equal to some power, not very different from unity, of the inverse ratio of the mobilities. From the simpler type of mobility formulæ they deduce that $n_1/n_2 = (w_2/w_1)^{\frac{1}{2}}$ and they obtained some confirmation of this from observations in room air. Starr's measurements on outside air indicate that no such simple relation holds at Kew, and we must conclude either that η_{10}/η_{20} is not equal to η_{12}/η_{21} or that Whipple's formulæ are not applicable to the theory of the equilibrium of ionisation. It should be pointed out however that these formulæ were approximately verified by applying them to the observations of Nolan and de Sachy on indoor air.

A rough confirmation of the results obtained by the application of Whipple's formulæ has been obtained by using Schweidler's second method (16) for an estimation of β_1. This method consists in measuring the variation of ionisation current with applied voltage in a closed vessel containing small and large ions, but whereas Schweidler regarded the current in the vessel as being carried by the transfer of small ions of both signs, both Whipple (3, p. 375) and Hogg (17) have pointed out that the current which flows into one electrode is caused by ions of one sign. In this case the connexion between the applied voltage V and the current i measured is given by

$$qve/i = 1 + \beta_1 v/4\pi w_1 CV$$

where q is the rate of production of ions inside the vessel and C is the capacity. A measurement carried out by this method immediately after filling an ionisation vessel with fresh outside air gave a value of β_1 of about 63×10^{-3} sec⁻¹. The nucleus content measured in the open at about the same time was 65 per mm³ and the value of β_1 corresponding to this concentration in Table IV is about 55×10^{-3} sec.⁻¹. The agreement between the two values obtained by entirely independent methods is reasonably good.

§ 7—RATE OF PRODUCTION OF IONS AT KEW

The application of Whipple's formulæ to the equations of equilibrium (i) and (ii) lead to the following expression for q, the rate of production of ions :

$$q = \alpha n_1 n_2 + \frac{4\pi e\, N_0\, [n_1 w_1\, N_2\, (N_1 + N_0) + n_2 w_2\, N_1\, (N_2 + N_0)\,]}{N_0{}^2 - N_1 N_2}.$$

If we again assume $N_1 = N_2 = N$,

$$q = \alpha n_1 n_2 + \frac{4\pi e\, N_0\, (n_1 w_1 + n_2 w_2)}{(N_0/N) - 1}.$$

In general the term $\alpha n_1 n_2$, representing the rate of combination between small ions of opposite sign, is negligible. Further, the conductivity of the air is usually almost wholly due to small ions and therefore no great error is introduced if we write

$$q = \frac{4\pi\, (\lambda_1 + \lambda_2)\, N_0}{(N_0/N) - 1} \quad \cdot\cdot \quad \cdot\cdot \quad \cdot\cdot \quad \text{(x)}$$

where $(\lambda_1 + \lambda_2)$ represents the total conductivity of the air.

The observations with the Aitken counter and the charged condenser give us N_0 and N, whilst the simultaneous observations with the Wilson apparatus give us λ_1, the positive conductivity. To obtain $(\lambda_1+\lambda_2)$ we have made use of the records of positive and negative conductivity obtained by Starr. These recorded values were only available for about half the occasions on which the nucleus counts were made, so instead of applying them as absolute values we have used smoothed values of their ratio λ_1/λ_2 to obtain $(\lambda_1+\lambda_2)$ from the observations of positive conductivity with the Wilson apparatus. The variation of the ratio is shown by the following figures which refer to 14h. 30m. G.M.T. :

λ_1 ohm^{-1}cm.$^{-1}\times 10^{18}$:	5	10	20	40	60	80
λ_1/λ_2 :	1·92	1·59	1·42	1·25	1·15	1·06

As in the case of n_1/n_2 the ratios corresponding to very low conductivities are subject to considerable error. Applying the observed data to the simple formula for q we have obtained estimates of this quantity, each estimate referring to the mean of a group of 11 or 12 nucleus observations. The figures are given in Table V.

TABLE V

Observed with Aitken counter and condenser.			Observed with Wilson apparatus.	From λ_1 and ionisation recorder.	Calculated by Whipple's formulæ (x)
Z per mm^3	N_0 per mm^3	N_0/N	λ_1 ohm^{-1}cm.$^{-1}\times 10^{18}$	$(\lambda_1+\lambda_2)$ ohm^{-1}cm$^{-1}\times 10^{18}$	q per c.c. per sec.
11·8	7·6	3·6	62	115	4·2
17·0	11·0	3·7	41	75	3·8
20·1	13·4	4·0	36	66	3·7
22·1	13·9	3·4	41	75	5·5
26·1	16·6	3·5	31	55	4·6
30·9	19·7	3·5	26	46	4·7
36·8	23·8	3·7	26	46	5·1
49·0	32·0	3·8	18	30	4·3
62·4	38·5	3·2	19	33	7·3
95	52	3·4	11	17	7·9

Omitting the last two values of q, which are considerably higher than the rest, the average rate of production of ions is 4·5 per c.c. per sec. This is rather low compared with values obtained at other places over land, but the generation of ions from ground radiations must be small at Kew since the lithologic foundation in the district does not include any rocks which are likely to be radioactive. A rough confirmation of this has been obtained by some measurements of the ionisation in a closed vessel. The apparatus has been described by P. A. Sheppard (18), who used it during the British Polar Year Expedition to Fort Rae, Canada, in 1932–3. Over the frozen Great Slave Lake Sheppard obtained a value of about 4·7 per c.c. per sec. for the rate of production of ions in the vessel. Using the same apparatus at Kew the author has obtained a value of about 5·9 and the difference, 1·2 ions per c.c. per sec., may be attributed to the ions generated by ground radiations at Kew. The contribution from cosmic rays at ground level is now fairly well established at about 1·8 ions. There remains the contribution from radioactive substances in the air; Hess(19) gives 4·5 ions as the average for this, but values as low as 1·4 have been noted at some places. The figure for Kew would probably lie somewhere near the minimum since no large sources of radioactivity are known to exist in the surrounding country. The total of these three contributions amounts then to about 4·4 ions per c.c. per sec. and we may conclude that the estimate of q obtained above are not unreasonably low.

The two higher values of q which are associated with high nucleus content require some explanation. At first sight we might attribute these to the low values of N_0/N and conclude that these are at fault. Errors in the measurements of very low conductivity may account for part of the discrepancy, and part is certainly due to the fact that we have assumed the conductivity to be wholly due to small ions, whereas when large ions are very numerous they make an appreciable contribution to the whole conductivity. A rough allowance for this can be made by using the measurements of N. The conductivity due to the large ions of each sign is NeW where W is their mobility, which we may assume to be 1/3000 cm./sec. For the last group of observations N is 21·5 per mm.^{3} and the whole conductivity due to these ions is about $2{\cdot}5\times10^{-18}$ohm.$^{-1}$cm.$^{-1}$. This should be deducted from 17, the value of conductivity $(\lambda_1+\lambda_2)$ which we have used to evaluate q. When this adjustment is made, q for the last group becomes 6·7 ions per c.c. per sec. A corresponding adjustment for the penultimate group gives a value of 7·0 instead of 7·3; similar corrections for the other groups are too small to make any appreciable difference. Our neglect of the term $\alpha n_1 n_2$ does not introduce any great error; for example if we allow for this term when the small ions are most numerous the first value of q would only be increased by about five per cent. The most probable explanation of the discrepancy which still exists after allowing for the large ion conductivity is that the theory assumes that there is equilibrium between the processes of generation of ions and the processes of combination, and it ignores the transport of ions by the turbulent motion of the air and by the conductivity current. It is significant that our highest values of q are associated with high nucleus content and therefore with foggy or misty conditions when the air is comparatively stagnant. This would indicate that the effect of turbulence on the equilibrium of ionisation is appreciable. There is one other possible explanation that might be suggested and that is that when nuclei are very numerous some of them are radioactive.

§ 8—RESISTIVITY, NUCLEI AND SMOKE PARTICLES

The formula (x) for the rate of production of ions may be written:

$$q = \frac{4\pi\,(\lambda_1+\lambda_2)\,Z.\ \ N_0/N}{\left(\frac{N_0}{N}+2\right)\left(\frac{N_0}{N}-1\right)}$$

and the fact that on the whole the observations of N_0/N and the calculated values of q are reasonably constant implies that the total conductivity $(\lambda_1+\lambda_2)$, is inversely proportional to Z, or, since the mobilities of the small ions are constant, that the number of small ions is inversely proportional to the number of nuclei. From observations made with air in a closed vessel, P. J. Nolan (20) concluded that the number of small ions is inversely proportional to $Z^{\frac{1}{2}}$, and more recently (21) he states that measurements made in the open air at Glencree only lead to a constant value for q with a formula of the type q = constant $\times\, nZ^{\frac{1}{2}}$.

The effect of the number of nuclei on the resistivity at Kew was examined by Wright (2); for the resistivity, which we will call R_1, he used the reciprocal of the positive conductivity as measured by the Wilson test-plate apparatus on a tripod. As pointed out by G. M. B. Dobson(22) the disturbance of the electric field by the presence of the tripod results in the values of the conductivity being lower than those obtained when the apparatus is used at ground level; the difference is small when the conductivity is high, but it is very considerable when the conductivity is low. Wright was aware of this, and therefore in deducing a linear relationship between the resistivity and Z he gave more weight to the observations associated with low resistivity than to those associated with high resistivity. In a recent investigation (5) the author examined the variation of the difference between the positive conductivity as measured on a tripod and that obtained at ground level. A satisfactory method of correcting the tripod values was arrived at, and it is of interest therefore to apply this to Wright's observations so as to make them comparable with those obtained in the present investigation, in which all the observations of positive conductivity were made at ground level. The graph in

Fig. 6 connecting the resistivity R_1 with the nucleus content Z shows Wright's mean values after the corrections have been made together with the more recent values. Since in Wright's analysis the individual observations were grouped according to nucleus content and the mean of the associated values of resistivity was determined for each group, the later observations were treated in the same way, and so the resistivities plotted on the graph do not correspond exactly with the reciprocals of the means of λ_1 given in Table V, although they represent the same groups of observations. It will be seen that most of the points lie fairly close to a straight line which may be represented by the empirical formula :

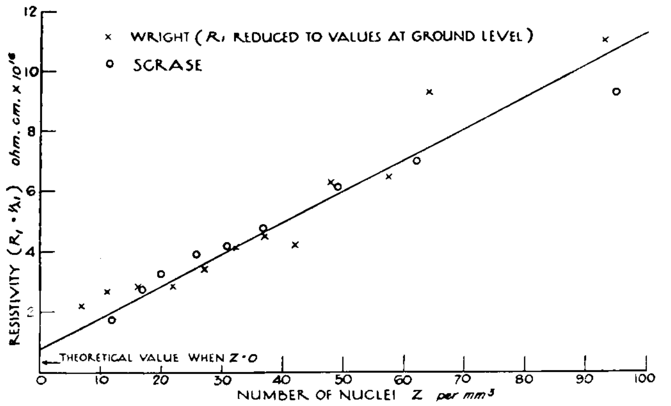

FIG. 6.—VARIATION OF POSITIVE RESISTIVITY WITH NUCLEUS CONTENT.

$$10^{-16}R_1 = 0{\cdot}1Z + 0{\cdot}8$$

where Z is given as a number per mm.³ and R_1 is in ohm.cm. For Wright's uncorrected observations the coefficient of the Z term was about 0·15.

The empirical relationship between R_1 and Z is not expected to hold when Z is extremely small. In such circumstances the combination between small ions of opposite sign becomes more important than the combination between nuclei and small ions. When the air is quite free from nuclei the equations (i) and (ii) for the equilibrium of ionisation reduce to

$$q = \alpha n_1 n_2$$

and if we ignore the difference between n_1 and n_2 the resistivity may be expressed by

$$R = \frac{1}{\lambda} = \frac{1}{new} = \frac{1}{ew}\sqrt{\frac{\alpha}{q}}.$$

Laboratory experiments [23] indicate that α is $1{\cdot}6 \times 10^{-6}$ and if we take q to be 5 ions per c.c. per sec. then R is of the order of $0{\cdot}3 \times 10^{16}$ ohm.cm.

It is generally assumed that the small ion content in the atmosphere is governed by the number of nuclei and only slightly, if at all, by the number of smoke and dust particles. Wright, however, concluded that gross particles have an appreciable effect. Since nucleus content and dust content are very closely associated it is very difficult to separate completely the two effects. A method employed by Wright was to group the observations according to the values of resistivity, to determine the mean values of nucleus content and gross particle content for each group, and then to plot R_1/Z against P/Z, P being the number of particles per unit volume. In this way he arrived at the following formula connecting the three variables :

$$10^{-16}R_1 = 0{\cdot}077Z\left(1 + 48\frac{P}{Z}\right),$$

where P and Z are numbers per mm³ and R_1 is in ohm. cm. When, however, the values of R_1 are corrected so as to correspond with measurements at ground level the influence of the smoke particles is found to be considerably smaller. The corrected values of R_1 have been used in the graph shown in Fig. 7 which also includes the data obtained in the present investigation (grouped according to the values of resistivity). It should be mentioned that the observations of P used by Wright represent direct counts of gross particles by means of the Owens' dust counter, whereas in the recent measurements P was obtained indirectly from the records of atomspheric pollution made by the Owens automatic air filter, the results of a comparison of measurements with the two instruments being utilised for the purpose.* Nearly all the points in Fig. 7 lie well below the line adopted by Wright. The new line which has been drawn through the points corresponds with the formula :

$$10^{-16} R_1 = 0{\cdot}1\, Z\left(1+7\frac{P}{Z}\right),$$

Z and P being numbers per mm³ and R_1 being in ohms cm. It appears therefore that the effect of smoke particles on resistivity is very much less than the earlier

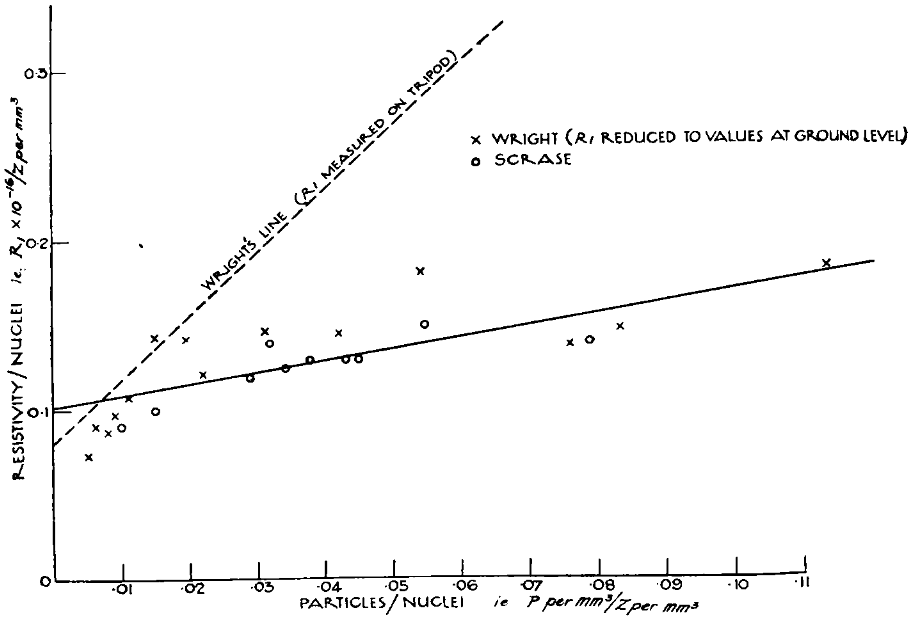

FIG. 7.—ILLUSTRATING THE RELATIVE INFLUENCE OF SMOKE PARTICLES AND NUCLEI ON THE POSITIVE RESISTIVITY.

uncorrected observations led Wright to believe and there is some justification therefore for our ignoring the effect in the discussion, in the earlier part of this paper, of the equilibrium of ionisation.

§ 9—SUMMARY

Using an Aitken nucleus counter with an electrical condenser attached measurements have been made of the concentration of nuclei and the ratio of charged to uncharged nuclei simultaneous with observations of the positive conductivity of the air by the Wilson method.

The mean of the ratio of the numbers of uncharged nuclei and large ions of each sign at Kew was found to be 3·5 but smaller values were obtained when nuclei were very numerous, i.e. in conditions of high humidity and poor visibility. It is probable that the nuclei are larger when these conditions occur. The range of vision was found to be roughly inversely proportional to the square of the nucleus content.

Using formulæ put forward by F. J. W. Whipple, estimates of the combination coefficients between small ions and charged and uncharged nuclei have been obtained.

* See H. L. Wright (1). The factors connecting the measurements made with the two instruments are different in summer and winter. The results of the comparison are given in the following table :—

Atmospheric Pollution : mgm/m³ (Air Filter)		<0·1	0·1	0·2	0·3	0·4	0·6	>0·9
Smoke particles per c.c. (Dust Counter)	Winter ..	116	675	1550	2000	3700	5220	10000
	Summer	85	265	391	—	—	—	—

The coefficients show a tendency to increase when nuclei are very numerous. The formulæ have also been used for estimating the rate of production of ions in the open air ; the average rate at Kew is about **4·5** ions per c.c. per sec.

The influence of smoke particles on the resistivity of the air has been examined and it is concluded that the effect is much smaller than earlier observations at Kew appeared to indicate.

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