A NOTE ON 'EFFECTIVE RECOMBINATION COEFFICIENT' IN THE IONOSPHERIC REGIONS.

By S. N. GHOSH, *Adair, Dutt Research Scholar, Indian Science News Association.*

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ABSTRACT.

The coefficient of recombination of electrons and ions in the different ionospheric regions as deduced from experimental observations is found to be several orders higher than that computed from theory. The discrepancy has to a great extent been reconciled by the so-called hypothesis of 'Effective Recombination' (Massey, 1937; Appleton and Sayers, 1938; Bates and others, 1939), in which the process responsible for the observed rate of electron density decay involves positive and negative ions.

In the present paper, the theory is applied to study in detail the effective recombination coefficients for the Regions E and F both during day and night, as also the laws of decay of electron density in these regions.

It is found that the law of recombination, namely, that the rate of electron disappearance is proportional to square of electron density, holds for Regions E, F_1 and F_2 (daytime). For the combined Region F at night the rate is found to be proportional to electron density only. This is confirmed by comparison of calculated and observed percentages of fall over certain hours of night.

It is found that the expression for the ratio of negative ion-electron density is different for different regions. The difference is traced to the fact that as one proceeds upwards from the lowermost level of ionosphere, the density of neutral particles decreases while that of electrons increases.

Data of the coefficients of the various inelastic collisional processes (recombination, mutual neutralisation, attachment and detachment) as are of importance in ionospheric regions are collected in a table for convenient reference.

1. INTRODUCTION.

The values of the coefficient of recombination of electrons and positive ions in the ionospheric regions as obtained from experimental observations lie between 10^{-9} to 10^{-8} cm.^{3}/sec. for Region E and $10^{-11}-10^{-10}$ cm.^{3}/sec. for Region F (Appleton, 1937; Best, Farmer, and Ratcliffe, 1938). These values are several orders higher than the theoretically computed value of the recombination coefficient which is of the order of 10^{-12} cm.^{3}/sec. (Bates and others, 1939). The difference between the observed and calculated value is very high and is outside the range of uncertainty due to error in observation. The disagreement was for a long time a puzzle, but has been recently reconciled to a great extent by the so-called hypothesis of 'Effective Recombination' (Massey, 1937; Appleton and Sayers, 1938; Bates and others, 1939), in which the negative ion density plays an important part.

In the present paper, the hypothesis is applied to study in detail the effective recombination coefficients for the Regions E and F both during day and night and also the laws of decay of electrons in these regions. It will be shown that the law of recombination, namely, that the rate of electron disappearance is proportional to square of electron density, holds for Regions E, F_1 and F_2 (daytime). But for Region F at night the rate is proportional to electron density only.

2. HYPOTHESIS OF EFFECTIVE RECOMBINATION.

Consider first the processes by which free electrons are lost and produced. They are lost, (i) by recombination with positive ions, and (ii) by attachment to neutral particles like O atoms and O_2 molecules which have high electron affinity. They are produced, (i) by detachment of electrons from negative ions by collisions with neutral particles,

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(ii) by photo-ionisation of neutral particles, and (iii) by photo-detachment of electrons from negative ions. (The two last-named processes are, of course, operative only during daytime.) Again, negative ions are produced by attachment of electrons to neutral particles and are lost, (i) by detachment by collisions with neutral atoms and molecules, (ii) by photo-detachment, and (iii) by mutual neutralisation when a negative ion meets a positive ion. The rates of production and loss of negative ions thus affect the net rates of production and loss of free electrons.

For the time variation of the negative ion density at daytime we may put

$$\frac{dn^-}{dt} = -\alpha_i n^- n^+ + \beta n_e n - kn^- n - k_1\beta n^-, \qquad \ldots \quad \ldots \quad \ldots \quad (1)$$

where α_i—coefficient of mutual neutralisation of positive and negative ions.
β—coefficient of attachment of electrons to neutral atoms and molecules.
k—coefficient of detachment of electrons from negative ions by collisions.
n, n_e, n^-, n^+—densities of neutral particles, electrons, negative ions and positive ions respectively.
$k_1\beta n^-$—rate of loss of negative ions by photo-detachment of electrons (see Appendix I).

Let us for the moment assume that the term $\alpha_i n^- n^+$, the rate of disappearance of negative ions by mutual neutralisation, can be neglected compared to the attachment and detachment rates $\beta n_e n$ and $kn^- n$. The assumption may be justified by the fact that the two last-named terms involve n, the density of neutral particles which is very large compared to n^- or n^+. $\alpha_i n^- n^+$ may also be neglected compared to $k_1\beta n^-$ because k_1 has a very high value (see Appendix I). Since the attachment and detachment rates are great, a dynamical equilibrium is quickly established for these rates and in the equilibrium condition we have

$$\beta n_e n = kn^- n + k_1\beta n^- \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

or,

$$\frac{n^-}{n_e} = \frac{\beta n}{kn + k_1\beta} = \lambda \text{ (say)}. \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

Now, for the variation of electron density at daytime we have,

$$\frac{dn_e}{dt} = q - \alpha_e n_e n^+ - \beta n_e n + kn^- n + k_1\beta n^-, \qquad \ldots \quad \ldots \quad \ldots \quad (4)$$

where α_e—coefficient of recombination of electrons with positive ions.
q—rate of electron (or positive ion) production per c.c. due to photo-ionisation.

Combining equations (1) and (4) and assuming that the ionospheric regions are electrically neutral, so that $n^+ = n^- + n_e = (1+\lambda)n_e$ and using relation (3) we have

$$\frac{dn_e}{dt} = \frac{q}{1+\lambda} - (\alpha_e + \lambda\alpha_i)n_e^2 - \frac{n_e}{1+\lambda}\frac{d\lambda}{dt}.$$

Since k_1 depends on $\cos\chi$ where χ is the zenith distance of the sun, the variation of λ with time will be small except during sunrise and sunset. Therefore,

$$\frac{dn_e}{dt} = \frac{q}{1+\lambda} - (\alpha_e + \lambda\alpha_i)n_e^2,$$

where

$$\lambda = \frac{\beta n}{kn + k_1\beta} \text{ (daytime)}. \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (5)$$

At night $q = 0$ and $k_1 = 0$ so that

$$\frac{dn_e}{dt} = -(\alpha_e + \lambda\alpha_i)n_e^2,$$

where

$$\lambda = \frac{\beta}{k} \text{ (night time)}. \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (6)$$

Thus Appleton and Sayers (1938) and also independently Massey and his collaborators (1939) obtained the law of electron decay by recombination, namely the rate of decay is proportional to the square of electron density. The quantity $(\alpha_e+\lambda\alpha_i)$ is called by them *effective recombination coefficient*. The effective recombination is thus controlled by the negative ion-electron density ratio λ and the coefficient of mutual neutralisation α_i, rather than by the simple recombination coefficient α_e.

In the above in deducing the balance condition of negative ion density, the term $\alpha_i n^- n^+$ has been neglected in comparison to kn^-n and $k_1\beta n^-$. Recent investigations (Bates and Massey, 1943) show, however, that the value of α_i may be as high as $10^{-8}-10^{-7}$ cm.^{3}/sec. In Region F, where the electron density is high and density of neutral particles low, the term $\alpha_i n^- n^+$ may therefore no longer be negligible and its consequential contribution to the expression of λ requires closer examination. This is done below.

We begin by examining in some detail the equilibrium condition and the rate of electron decay in Region E. The case of Region F will then be taken up.

3. Application of the Hypothesis to the different Ionospheric Regions.

(a) *Region E.*

Region E is formed by ionisation of O_2 near the 100 km. level where the density of O_2 diminishes rapidly with height due to photo-dissociation of O_2 to O (Majumdar, 1938; Wulf and Deming, 1938). The positive ions here are those of O_2. The negative ions are of O_2 and also of O. The mutual neutralisation processes here controlling the recombination of electrons are therefore:

$$O_2^+ + O_2^- \rightarrow O_2 \text{ (excited)} + O_2 \text{ (excited)}, \quad \ldots \quad \ldots \quad \ldots \quad \text{(i)}$$

$$O_2^+ + O^- \rightarrow O_2 \text{ (excited)} + O \text{ (excited)}. \quad \ldots \quad \ldots \quad \ldots \quad \text{(ii)}$$

We may draw some conclusions regarding the relative importance of the two processes from the fact that in the night sky luminescence the atomic oxygen lines originate at a very high level, in Region F, while the lines due to molecular oxygen originate at lower heights near Region E (Swings, 1943). It is therefore reasonable to conclude that the predominant process of neutralisation in Region E is the reaction (i) which does not involve excitation of atomic oxygen lines. We may assume the following representative values for Region E:

Maximum electron density (night time)	2×10^4 per c.c.
,, ,, ,, (daytime)	2×10^5 per c.c.
Density of neutral particles	5×10^{13} per c.c.

Also the value of β for O_2 molecules $= 2\times10^{-16}$ cm.^{3}/sec., k for O_2^- ions $= 5\times10^{-15}$ cm.^{3}/sec. and k_1 for photo-detachment from O_2^- ions $= 9\times10^{14}$ (maximum midday value) (see Appendix II). With this value of k_1 we have $\lambda = 1/43$ in daytime and $1/25$ in night time. These values are, of course, approximate ones on account of the uncertainty in the numerical values assumed. Assuming that α_i of reaction (i) is 10^{-7} cm.^{3}/sec. (see Appendix II), we have the value of the effective recombination coefficient as $0{\cdot}2\times10^{-8}$ cm.^{3}/sec. at daytime and 4×10^{-9} cm.^{3}/sec. at night time. The observed values are $1{\cdot}2\times10^{-8}$ cm.^{3}/sec. for daytime and 4×10^{-9} cm.^{3}/sec. for night time.

As already mentioned, the value of λ varies slowly throughout the day on account of the variation of k_1 in the expression for λ. It can, however, be shown that the contribution of $k_1\beta$ to the value of λ will be of nearly equal importance as that of kn. Only when the zenithal distance of the sun is high, the contribution of the former term becomes unimportant. This is easily seen as follows. We can assume that at each instant the rate of ion production balances the rate of ion destruction, so that

$$q = (1+\lambda)(\alpha_e+\lambda\alpha_i)n_e^2 \doteqdot (\alpha_e+\lambda\alpha_i)n_e^2.$$

The rate of ion production when the zenith distance of the sun is χ may be put equal to $q_0 \cos \chi$. Also the value of k_1 at the same instant may be put equal to $k_{10} \cos \chi$. Here q_0 and k_{10} are the maximum noon time values of q and k_1 respectively. Substituting in the above expression for λ, and neglecting α_e in comparison with $\lambda\alpha_i$ we have

$$q_0 \cos \chi = \frac{\alpha_i \beta n}{kn + k_{10}\beta \cos \chi} n_e^2,$$

or,

$$n_e^2 = \frac{kq_0}{\alpha_i \beta} \cos \chi + \frac{k_{10} q_0}{\alpha_i n} \cos^2 \chi.$$

For the numerical values assumed, we have

$$n_e^2 = 2{\cdot}3 \times 10^{10} \cos \chi + 1{\cdot}7 \times 10^{10} \cos^2 \chi.$$

The square of electron density is thus equal to the sum of two terms, one of which varies as $\cos \chi$ and the other as $\cos^2 \chi$. But since the factor multiplying $\cos^2 \chi$ is about 1·5 times less than that multiplying $\cos \chi$, we find that only when the zenithal distance of the sun is high, the second term is unimportant compared to the first term and the variation of electron density will then follow the $\sqrt{\cos \chi}$ law closely.

It should be pointed out that the value of λ would be smaller at daytime than at night on account of the term $k_1\beta$ in the denominator for the daytime expression of λ. The value of effective recombination coefficient should therefore be smaller at daytime than at night time. This, however, is just the reverse of what is observed.

(*b*) *Region F.*

At daytime Region F splits up into two regions, F_1 and F_2. Region F_2 which is at a higher level is formed by ionisation of O and Region F_1 at a lower level by ionisation of N_2. The positive ions in these regions are those of N_2 and O. The negative ions are those of O only because N_2 is known to have very little electron affinity. The mutual neutralisation processes are therefore:

Region F_2 $\quad O^+ + O^- \rightarrow O$ (excited) $+ O$ (excited), ... (iii)
Region F_1 $\quad N_2^+ + O^- \rightarrow N_2$ (excited) $+ O$ (excited). .. .. .. (iv)

At night the two regions merge together to form a single Region F. It is well known that the variation of electron density of Region F_1 is regular following the $\sqrt{\cos \chi}$ law, while that of Region F_2 is irregular. We now consider the two regions separately.

For Region F_1 we may assume the following as the representative values:

Maximum electron density (daytime)	3×10^5 per c.c.
Density of neutral particles	10^{12} per c.c.

Also the value of β for O atoms $= 1 \times 10^{-15}$ cm.³/sec., k for O^- ions $= 5 \times 10^{-16}$ cm.³/sec. and k_1 for photo-detachment of O^- ions $= 1 \times 10^{14}$ when the sun is at zenith (see Appendix II). Inserting the numerical values, we find that kn is many orders smaller than $k_1\beta$ and can be neglected. We have from equation (5)

$$\lambda = \frac{n}{k_1}, \qquad \text{.. .. ..} \qquad (7)$$

and at daytime as before,

$$\frac{dn_e}{dt} = \frac{q}{1+\lambda} - (\alpha_e + \lambda\alpha_i) n_e^2. \qquad \text{.. .. .. ..} \qquad (8)$$

The rate of disappearance of electrons again depends on the square of electron density and the effective recombination coefficient is $(\alpha_e + \lambda\alpha_i)$, where $\lambda = \frac{n}{k_1} = 10^{-2}$. And, since α_i of reaction (iv) has been assumed to be 10^{-7} cm.³/sec. (see Appendix II), the effective recombination coefficient is 10^{-9} cm.³/sec. It is to be noted that the term

$\alpha_i n^- n^+$ which we had neglected in deducing the balance condition (equation (2)) becomes now comparatively large, though it is still small compared to $k_1\beta n^-$. We will presently see that as we go to the higher Region F_2, the mutual neutralisation term becomes the important term.

We also note that the value of λ now varies as $(\cos\chi)^{-1}$ on account of the presence of k_1 in the denominator. The effective recombination coefficient therefore varies as $(\cos\chi)^{-1}$. If, as in the case of Region E, we assume that at each instant the rate of ion production balances the rate of ion destruction, we have

$$q = q_0 \cos\chi = \frac{\alpha_i n}{k_{10}\cos\chi}\, n_e^2 ,$$

or,

$$n_e = \sqrt{\frac{q_0 k_{10}}{\alpha_i n}}\,\cos\chi.$$

According to the theory of effective recombination therefore, the electron density of Region F_1 at daytime varies rather as $\cos\chi$ than as $\sqrt{\cos\chi}$. This law, however, is not borne out by observations. In fact, the variation of Region F_1 electron density tends to follow a law of $\cos\chi$ raised to some power less than half, rather than a law with $\cos\chi$ raised to a power greater than half.

For Region F_2 we assume the following as the representative values:

Maximum electron density (daytime)	3×10^6 per c.c.
" " " (for combined Region F at night time)	5×10^5 per c.c.
Density of neutral particles	5×10^{10} per c.c.

The values of β and k_1 are the same as those for Region F_1 at daytime and the value of α_i for mutual neutralisation of O^+ with O^- may be taken as 5×10^{-8} cm.³/sec. (Bates and Massey, 1943). In deducing the balance condition of negative ion density from equation (1), it is not now justifiable to neglect the term $\alpha_i n^- n^+$ compared to the terms kn^-n and $k_1\beta n^-$. This is because the low value of n (molecule density) lowers the value of kn^-n and, at the same time, the high value of n_e (electron density) increases the value of $\alpha_i n^- n^+$. We therefore write in place of equation (2)

$$\beta n_e n - kn^- n - k_1\beta n^- = \alpha_i n^- n^+,$$

or, remembering that $n^+ = n^- + n_e$,

$$\alpha_i (n^-)^2 + (kn + k_1\beta + \alpha_i n_e)n^- - \beta n_e n = 0.$$

Since $\dfrac{4\alpha_i\beta n_e n}{(kn+k_1\beta+\alpha_i n_e)^2}$ is less than unity, as is easily seen by substituting in it representative numerical values of the symbols as given above, we have from the positive root of the quadratic,

$$\frac{n^-}{n_e} = \lambda = \frac{\beta n}{(kn+k_1\beta+\alpha_i n_e)} \text{ (daytime).} \quad .. \quad .. \quad .. \quad (9)$$

or, since kn is many orders smaller than $k_1\beta$ or $\alpha_i n_e$,

$$\lambda = \frac{\beta n}{k_1\beta+\alpha_i n_e}, \quad .. \quad .. \quad .. \quad .. \quad (10)$$

and the rate of decay of electrons is as before given by equation (8), where λ is given by equation (10). For the numerical values given above, the value of λ becomes 2×10^{-4} and that of the effective recombination coefficient is therefore $0{\cdot}1\times10^{-10}$ cm.³/sec. This is of the same order as the observed recombination coefficient.

For the night time condition, the term $k_1\beta$ is absent and we have

$$\lambda = \frac{n^-}{n_e} = \frac{\beta n}{\alpha_i n_e}.$$

Thus, at night the negative ion density n^-, rather than the negative ion-electron density ratio λ, remains constant. For the representative values assumed the density of negative ions is 10^3 per c.c. In the condition of dynamical equilibrium between the attachment, detachment and mutual neutralisation processes we have, neglecting the term $\alpha_e n_e n^+$,

$$\frac{dn_e}{dt} = -\alpha_i n^- n^+.$$

Substituting $n^- = \frac{\beta n}{\alpha_i}$ and remembering that the ionospheric regions are electrically neutral, we have

$$\frac{dn_e}{dt} = -\beta n(n^- + n_e),$$

or, since n^- is much smaller than n_e,

$$\frac{dn_e}{dt} = -\beta n_e n.$$

According to the above relation the rate of electron decay in Region F at night is proportional to n_e instead of to n_e^2. In the table below is compared the falls in electron density as observed at two ionospheric observatories situated in different latitudes with those calculated according to the above formula. It will be seen that the observed and calculated values agree fairly closely.

Place of observation.	Mean $f^\circ - t$ curve for the month of	Observed % of fall in electron density.	Calculated % of fall for the same period.
Huancayo, Peru, South America.	December 1938	70% (from 20·00 to 04·00).	75%
Do. ..	June 1939	69% (from 23·00 to 05·00).	66%
Do. ..	February 1940	76% (from 23·00 to 05·00).	66%
Do. ..	August 1940	76% (from 22·00 to 05·00).	72%
Do. ..	March 1941	79% (from 20·00 to 04·00).	75%
Do. ..	September 1941	73% (from 22·00 to 05·00).	72%
Watheroo, Western Australia.	September 1938	70% (from 20·00 to 04·00).	75%
Do. ..	February 1939	70% (from 20·00 to 04·00).	75%
Do. ..	March 1940	64% (from 20·00 to 04·00).	75%
Do. ..	October 1940	66% (from 20·00 to 04·00).	75%
Do. ..	September 1941	60% (from 19·00 to 00·00).	59%

It is to be noted that the term $\alpha_i n_e$ in the denominator of the expression of λ is the predominant term even in daytime. If we take the extreme case when $k_1\beta$ can be neglected compared to $\alpha_i n_e$, then the rate of electron disappearance in daytime will be proportional to n_e rather than to n_e^2. An important consequence of this is that the region of maximum ion production is not now the region of maximum electron density.

4. CONCLUSION.

To sum up, we note that the expression for effective recombination coefficient which is dependent on ratio of negative ion-electron density is different for different regions.

The reason for this is that as we proceed upwards from the lowermost level of ionosphere, the density of neutral particles decreases while that of electrons increases. A consequence of this is that the term involving the neutral particle density (such as that representing detachment by collision) becomes less important and the terms involving electron density gain in importance as one goes to the higher regions. Thus of the three terms, kn (detachment by collision), $k_1\beta$ (photo-detachment), and $\alpha_i n_e$ (mutual neutralisation) in the denominator of the expression of λ in equation (9), the first term becomes important in Region E, the second in Region F_1, and the third term in Region F_2.

The law of recombination, namely, that the decay of electron density is proportional to square of electron density, holds for Region E both at day and night and for Region F_1 (daytime). For Region F_2 during daytime the law may not hold in the extreme case, when the effect of photo-detachment is small compared to that of mutual neutralisation. In such case, the decay of electron density of Region F_2 at daytime may vary linearly as n_e. A consequence of this is that the region of maximum electron production may not coincide with that of maximum electron density.

At night the rate of decay of electron density in combined Region F is proportional to n_e rather than to n_e^2. This is because at night time in Region F, it is the negative ion density, rather than the ratio of negative ion-electron density, which remains constant.

It should be noted that the theory of effective recombination can only broadly explain the experimentally observed magnitude of recombination coefficients in the Regions E and F. It cannot explain such details as the variation of electron density with the zenithal distance. This is particularly so for Region F_1 and more so for Region F_2 which is notorious for irregular behaviour.

An important point to be noted is that the values of negative ion density calculated above are quite small both at day and at night. This is sometimes thought of as contradicting the Dynamo Theory which, for explaining the quiet day variation of magnetic elements, demands electric current of high value in the upper atmosphere. According to the recent theory of Taylor-Pekeris (Taylor, 1936; Pekeris, 1937), this high value can be accounted for by winds of high velocity in the upper atmosphere produced by atmospheric tides. This obviates the necessity of assuming a high ion density as done hitherto.

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Wireless Laboratory,
University College of Science,
92 Upper Circular Road,
Calcutta.

APPENDIX I.

The rate of production of electrons per unit volume (say I) from negative ions by absorption of solar radiation is given by (Tukada, 1937),

$$I = n^{-}k_1\beta,$$

k_1 is a constant given by

$$k_1 = \psi^2 \frac{(2\pi m)^{3/2}}{4h^3} k^{3/2} T_s^{3/2} e^{-h\nu_0/kT_s},$$

where ψ—angle subtended by the sun's radius as seen from the earth;
m—mass of an electron;
T_s—temperature of the sun (6000°K.);
ν_0—light frequency corresponding to the electron affinity;
other symbols having their usual significance.

For O atoms (electron affinity = 2·2 e.v. (Lozier, 1934)) $k_1 = 1 \times 10^{14}$ and for O_2 molecules (electron affinity = 1 e.v. (Bates and Massey, 1943)) $k_1 = 9 \times 10^{14}$.

APPENDIX II.

Coefficients of the different types of reactions important in ionospheric regions.

Type of reaction.	Reaction.	Coefficient of the reaction.	Remarks.
Radiative recombination.	$O^+ + e \rightarrow O^* + h\nu$	$\alpha_e = 1{\cdot}5 \times 10^{-12}$ cm.³/sec. at temp. 1000°K.	Calculated by Bates and others (1939) taking into account contributions from ground and excited states.
	$O_2^+ + e \rightarrow O_2^* + h\nu$ $N^+ + e \rightarrow N^* + h\nu$ $N_2^+ + e \rightarrow N_2^* + h\nu$	$\alpha_e = 10^{-12}$ cm.³/sec.	No calculations have been made of these reactions but they may be assumed of the same order as above (Bates and others, 1939).
Dielectronic recombination.	$O^+ + e \rightarrow O^{**}$	Same order as that of radiative recombination.	In this type of reaction energy released on recombination lifts two of the outer electrons of the neutral atom produced to excited states. The probability of the process for O atom is discussed by Massey and Bates (1942-43).
Recombination leading to dissociation and excitation.	$O_2^+ + e \rightarrow O^* + O^{**}$	Not greater than 5×10^{-12} cm.³/sec.	This type of recombination between a positive ion of a molecule and an electron involves coupling between electronic and nuclear motion and is therefore unlikely to have high efficiency (Bates and others, 1939).
Mutual neutralisation.	$O^+ + O^- \rightarrow O^* + O^*$	$\alpha_i = 10^{-8} - 10^{-7}$ cm.³/sec.	Calculated by Massey and Bates (1943).
	$N_2^+ + O^- \rightarrow N_2^* + O^*$	$\alpha_i = 10^{-7}$ cm.³/sec.	For this reaction which was considered by Mitra (1943) to explain the excitation processes of the Night Sky Spectrum, the resonance condition is almost exact. The value of its coefficient, from comparison with the computed value of the preceding process, may be assumed to lie near to 10^{-7} cm.³/sec.
	$O_2^+ + O^- \rightarrow O_2^* + O^*$ $O_2^+ + O_2^- \rightarrow O_2^* + O_2^*$	$\alpha_i = 10^{-7}$ cm.³/sec.	Since the molecules in general possess many excited states, it may be assumed that there is almost exact resonance for these reactions. The coefficients of these reactions may therefore be assumed to be of the same order as above.

APPENDIX II—*continued.*

Type of reaction.	Reaction.	Coefficient of the reaction.	Remarks.
Electron attachment	$O+e \rightarrow O^- + h\nu$	$\beta = 1\times10^{-15}$ cm.^{3}/sec. for electrons of energy ·2 e.v.	Calculated by Massey and Bates (1943).
	$O_2+e \rightarrow O_2^- + h\nu$	$\beta = 1\times10^{-16}$ cm.^{3}/sec.	The electron affinity of O_2 (1 e.v.) is nearly half of that of O (2·2 e.v.). The attachment coefficient may therefore be assumed to be one order less than that of O.
Electron detachment	$O^- + O \rightarrow O_2 + e$	$k = 10^{-16} - 10^{-15}$ cm.^{3}/sec.	Calculated from the reverse process (Massey, 1938).
	$O^- + N_2 \rightarrow N_2O + e$	$k = 10^{-16} - 10^{-15}$ cm.^{3}/sec.	The coefficients of these processes have not been calculated. It is, however, assumed that they are of the same order as the preceding process. For the case of detachment of electrons from O_2^- the value may reasonably be assumed to be higher than that of O^- because the electron here is much more loosely bound.
	$\left.\begin{array}{l} O_2^- + O_2 \rightarrow 2O_2 + e \\ O_2^- + O \rightarrow O_3 + e \end{array}\right\}$	$k = 10^{-15} - 10^{-14}$ cm.^{3}/sec.	
Photo-detachment	$O^- + h\nu \rightarrow O + e$	$k_1 = 1\times10^{14}, \beta = 1\times10^{-15}$ cm.^{3}/sec.	The rate of photo-detachment is $k_1\beta n^-$, where n^- is the density of negative ions. Calculated by Tukada (1937).
	$O_2^- + h\nu \rightarrow O_2 + e$	$k_1 = 9\times10^{14}, \beta = 1\times10^{-16}$ cm.^{3}/sec.	
Photo-ionisation	$O + h\nu \rightarrow O^+ + e$	Cross-section $= 2{\cdot}8\times10^{-17}$ cm^2.	Calculated by Saha and Rai (1938).
		Cross-section $= 1{\cdot}4\times10^{-17}$ cm.^{2} (at λ667).	Calculated by Bates and others (1939).
		Cross-section $= 3{\cdot}7\times10^{-18}$ to $3{\cdot}3\times10^{-17}$ cm.^{2}.	Calculated by Tukada (1937).

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