

# THE EXCITATION FUNCTIONS OF NITROGEN BANDS AND THEIR BEARING ON AURORAL PROBLEMS

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## § 1. Introduction.

Investigations have shown (1) that apart from the strong green  $OI$ -line and the red  $OI$ -triplet the auroral luminescence is dominated by nitrogen bands belonging to the four groups (or systems) corresponding to the following electronic transitions:

- 1) The negative group:  $N_2^+(B'^2\Sigma_u^+ - X'^2\Sigma_g^+)$
- 2) The 2nd positive group:  $N_2(C^3\Pi_u - B^3\Pi_g)$
- 3) The 1st positive group:  $N_2(B^3\Pi_g - A^3\Sigma_u^+)$
- 4) The  $\epsilon$ -system:  $N_2(A^3\Sigma_u^+ - X^1\Sigma^+)$

The last group which was discovered and interpreted by one of us (2) is remarkable because it is due to a forbidden transition from the metastable state  $A^3\Sigma_u^+$  to the normal state of the  $N_2$  molecule which forms the lower state of the transition corresponding to the 1st. positive group. It has been found (3) that a number of bands of the  $\epsilon$ -system appears in the auroral spectrum, but with an intensity which is very small as compared with that of the other three groups.

The relative intensity with which the nitrogen groups appear gives us some valuable information regarding the way in which the auroral light is excited and the state of the upper atmosphere. Starting from this idea, one of us together with several collaborators has during the last 15 years made quantitative measurements for the determination of the typical intensity distribution of bands and lines appearing in the auroral spectrum. The typical intensity distribution is practically defined as the one obtained on spectrograms of very long exposure lasting, say, for some weeks.

Even such spectra, however, may differ considerably as regards intensity distribution especially

in the region of long waves. Thus we find pronounced variations with sunspot frequency.

It should be emphasized that the intensity distribution within the auroral spectrum also changes with altitude and with geographical position, and may change considerably from one moment to another usually accompanied with change of form and position of the aurora. It is evident, therefore, that the typical auroral spectrum does not correspond to one definite condition of excitation, but to a range of conditions varying within wide limits.

In spite of the variability of the intensity distribution within the auroral spectrum, it is still of interest to try to establish experimentally such conditions which may give us spectra of approximately the same type as the typical auroral spectrum.

Such a comparison with spectra obtained under well defined physical conditions, may give us valuable information with regard to the physical processes responsible for the auroral luminescence.

Comparing the nitrogen spectra appearing in the auroral luminescence with those obtained when nitrogen is bombarded with various types of electric rays, it was found (3) that positive canal rays gave spectra differing essentially in type from that of the aurora, while cathode rays of sufficiently high velocity produced nitrogen spectra essentially similar to those of the aurorae.

It was found to be essential that the average cathode ray velocity should surpass a certain value (3), for in the auroral spectrum the intensity of the negative bands is much larger than that of the positive ones, and it was known and also shown by direct experiment that for small velocities of the cathode rays, the negative bands disappeared, so the spectrum essentially consisted of the positive bands. This increase of intensity of the positive groups with

decreasing velocity of the exciting electrons, was used by one of us (3) to explain the appearance of aurorae having a red lower border (type B.)

A qualitative comparison (3) between the typical auroral spectrum and those obtained by bombarding nitrogen with electron rays of varying velocities, indicated that the auroral luminescence might be produced by electron rays having average velocities amounting to some hundred volts.

For the study of the excitation processes of the auroral light, the natural procedure would be to study the excitation functions for the various nitrogen groups. As pointed out by Seeliger (4), we must distinguish between the excitation function of a term and that of an emission band or a line. In our case we are first of all interested in the observed light emission resulting from the transitions from the excited terms, in other words, we want to know how the intensity of a certain line varies with the velocity of the exciting electron.

In order to get a clear conception of what is meant by the excitation function, we assume that the gas at a certain pressure ( $p$ ) is traversed by electrons of a certain velocity ( $v$ ). The value of the excitation function of a line or band under these conditions is a measure of the probability that the electron in unit length of path shall make a collision which results in the emission of the line or band in question. This probability which, generally, will be a function of ( $v$ ), ( $p$ ) and the density of the electron current ( $j$ ), may be written:  $f(v, p, j)$ .

Let the electron ray bundle have the cross-section  $s$ , and let us assume that ( $n$ ) electrons traverse unit area in unit time, then the light intensity per unit length of path ( $L$ ) is given by the expression

$$L = k \cdot n \cdot s \cdot p \cdot f(v, p, j) \quad (1)$$

Now,  $n$  is proportional to the current density  $j$ , and we get:

$$f(v, p, j) = k' \frac{L}{s \cdot j \cdot p} \quad (2)$$

For a given pressure ( $p$ ) and cross-section of the ray bundle ( $S$ ), the excitation function is proportional to ( $L/j$ ).

Thus we have to arrange our experiments in a way which enables us to determine the light intensity per unit length ( $L$ ) and the electron current ( $j$ ) for varying velocities and pressures.

The variation of the excitation function with pressure is due to the fact that the recombination process resulting in the light-emission may be disturbed by collisions with other particles and their field of force. Evidently the influence of pressure will diminish with decreasing pressure. Below a certain pressure ( $p_g$ ), we get an excitation function which is independent of pressure and which may be regarded as the true excitation function. The value of the pressure  $p_g$  will depend on the lifetime of the electronic states engaged in the emission, and on the temperature of the gas. In order to get the true excitation function, the lifetime of the state must be small as compared with the time between two collisions. This means that the value of ( $p_g$ ) must be much smaller for lines or bands which correspond to forbidden transitions than for those resulting from allowed ones. Applied to the case of nitrogen it means that the limiting pressure  $p_g$  is very much smaller for the  $\epsilon$ -system than for the negative and positive groups.

In actual experiments, the occurrence of forbidden transitions is largely reduced from collisions with the walls of the tube. Even if we reduce the pressure, we may not get forbidden lines or bands unless by some means we increase the time which it takes the particle to reach the walls of the tube. This may in certain cases be done by mixing the emitting particles with inert gases of suitable pressure. It would also be advantageous to experiment in large vessels and at low temperature.

There may also be a certain probability for an electron to strike an atom (or molecule) in the excited state. After having suffered two successive collisions without emission, the particle will be in excited states different from those which may result from a single collision, and such double collisions will consequently effect the excitation function. As will be shown later, the relative change of intensity due to collisions with activated molecules is proportional to ( $jT$ ) where  $T$  is the average lifetime of the state considered. For ordinary (not metastable states) the average lifetime is very small and we may use large electron current densities without influencing the excitation function.

The object of the investigations, to be dealt with in the present paper, is to give a quantitative determination of the "true" excitation functions for the negative, and the 1st and 2nd groups of nitrogen for low tensions from the excitation voltage and upwards to about 120 volts. Accurate values of the

excitation tension of the various bands were found by comparing with helium, which was used as a standard gas.

Thus our experiments only deal with bands and lines corresponding to allowed transitions, and under these conditions it has been possible to keep the pressure and current density sufficiently low for obtaining the "true" excitation function.

## § 2. Experimental Procedure and Apparatus.

In the experimental determination of the excitation functions of lines and bands, two different methods have been used.

With one method the electrons are retarded by electric fields as they pass through the gas which is to be made luminous. At each section across the ray bundle we ought to have about the same electron velocity, and if we measure the relative intensity of a line or a band at different sections, we may find the relation between light intensity and electron velocity for any line in the spectrum.

This method was first used by Seeliger (5) for the study of nitrogen bands. It is, however, not well suited for quantitative measurements.

In the second method, which was adopted for our experiments, the electrons are first accelerated in an electric field after which they enter the luminescence chamber where the electric force is zero.

The velocity ( $v$ ) of the exciting electron is given by the expression:

$$\frac{1}{2} m v^2 = e V$$

where  $V$  is the accelerating potential. Instead of regarding the excitation as a function of the velocity, we may regard it as a function of the accelerating potential  $V$ .

In order to obtain accurate results, it is necessary that all electrons have the same velocity when they enter the observation chamber, and when they produce the observed luminescence. Consequently, the experiments must be so arranged that the distance from the cathode to the section where the luminescence is observed is small, as compared with the mean free path of the electrons. Thus we ought to bring the active cathode surface as near as possible to the aperture through which the light is observed, and we have to work at a fairly low pressure.

This method has been used by Schaffernicht (6), Hanle (7) and Thieme (8) for the determination of

excitation functions of mercury, helium and neon. Experiments on the excitation of nitrogen bands at varying velocities of the electrons have been made by Aars (9), Thieme (8) and Bernard (10).

The general experimental arrangement used is shown in Fig. 1.

During the experiment the gas to be investigated was constantly running from the receiver  $R_1$ , through the capillary  $C_1$ , the tube  $A-B$  and further to the pump. In order to reduce the rate of pumping, the gas can be made to pass through the narrow side tube  $C_2$ , by closing the tap  $t_3$  and opening  $t_4$ . Nitrogen from the receiver  $R_2$  could be let into the receiver  $R_1$  in small portions, through a narrow tube containing the two taps  $t_6$  and  $t_7$ . In a similar way helium used as a standardising gas could be introduced from the receiver  $R_3$ .

The receiver system could be connected directly to the pump by opening the tap  $t_2$ .

The pressure in the tube was measured by a McLeod manometer connected to the system through the tube  $D$ . As the gas was moving through the system, the pressure at the side tube  $D$  might be somewhat smaller than that of the tube. This difference, however, was found to be negligible. Stopping the motion of the gas by closing the taps  $t_1$ ,  $t_3$  and  $t_4$ , gave no noticeable change in the reading of the McLeod. The tube was protected against vapours through the two traps  $T_1$  and  $T_2$  which were cooled by liquid air.

The tube finally used is shown in Fig. 2. It consists of two parts ( $A$ ) and ( $B$ ) connected to each other by the ground joint ( $C$ ). The part ( $B$ ) carries an inner glass tube ( $D$ ) which gives support to the electrode arrangement and necessary electric terminals. The cathode ( $K$ ) is supported by brass wire (3) and the wires (4) for the heating current. The anode, consisting of two co-axial cylinders, one outside the other, is kept in position by means of two brass rods (1) and (2). The electrode arrangement is shown in Fig. 3 a and 3 b.

In order to give all the electrons in the bundle as nearly as possible the same velocity, the electrons must be emitted from an equipotential surface. The use of an ordinary unprotected heated wire was, therefore, excluded, because potential differences of several volts may exist between its two ends.

The cathode ( $C$ ) has the form of a cylinder into which the heating wire is introduced. The end plate ( $P$ ) was activated by a paste, containing a mixture of  $SrCO_3$  and  $BaCO_3$ . The activated cathode plate ( $P$ )

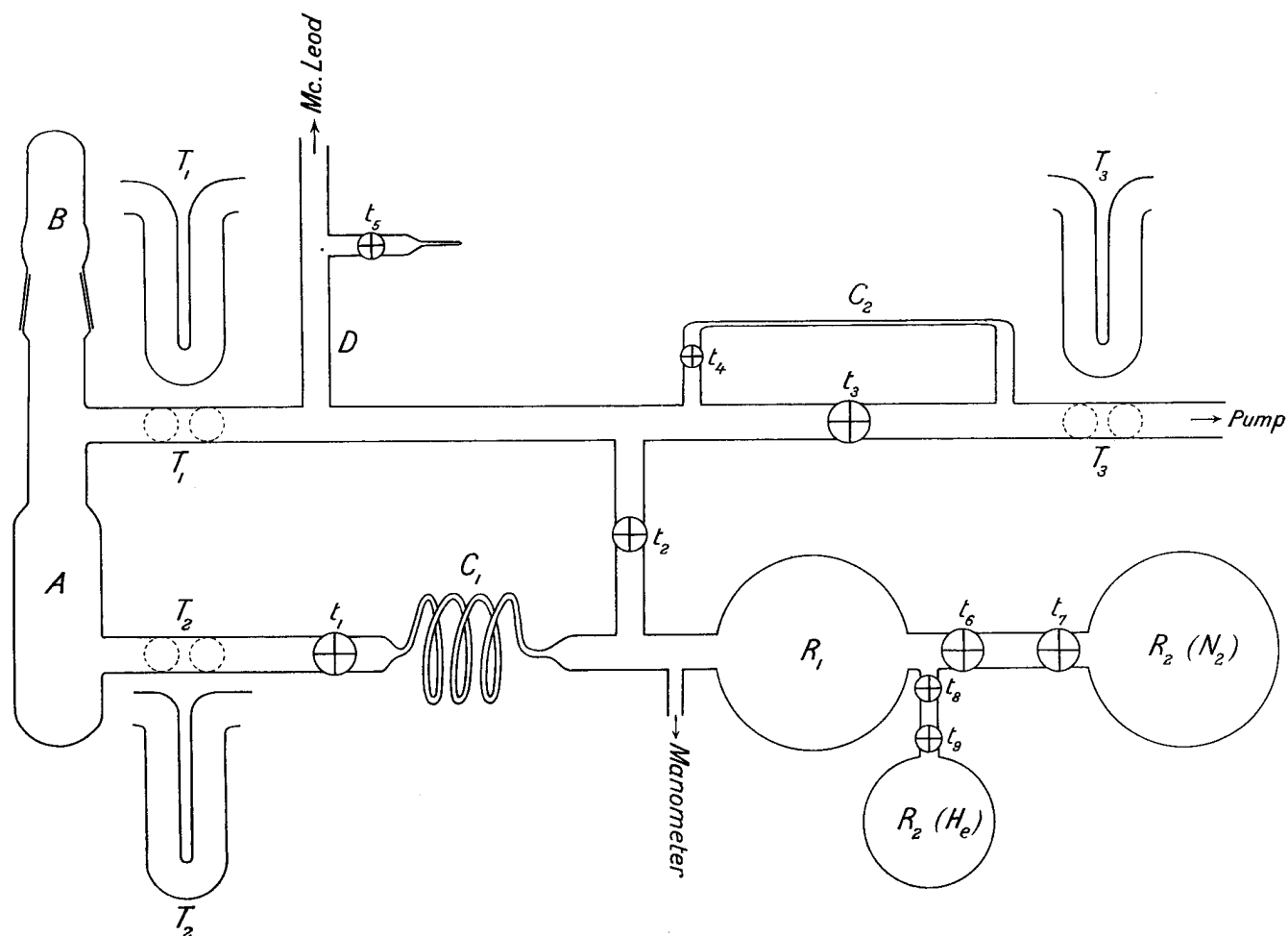


Fig. 1.

was put up close in front of a wire-gauze ( $G$ ) in the end surface of the anode cylinder ( $R_1$ ). Inside this anode cylinder ( $R_1$ ) and insulated from it, was a Faraday cylinder ( $R_2$ ). The electron current, received by the Faraday cylinder was led to earth by means of the wire (5) Fig. 2, and through a galvanometer ( $MA$ ) Fig. 3 a.

The luminescence was observed through the window ( $w$ ) situated close behind the wire-gauze. The accelerating field was applied between the activated cathode-plate ( $P$ ) and the anode surface in front of it.

By means of the screen ( $S$ ) fig. 3 b the weak light from the cathode was prevented from entering the spectrograph.

The electrical connections are shown in Fig. 4. The heating current for the cathode was supplied from a low tension transformer ( $T$ ). The current was regulated by the resistance ( $r_1$ ) and measured with the amp. meter ( $A$ ). The accelerating potential ( $V_a - V_K$ )

was taken from the potentiometer ( $p$ ) through the resistance ( $r_2$ ) of about 1700  $\Omega$ .

Somewhat large accelerating potentials were measured directly with a voltmeter. In order to measure more accurately small potential variations near the excitation potential, the greater part of the applied potential was compensated by the battery ( $b$ ), the potential of which was measured by the voltmeter ( $V_1$ ). The small differences between the accelerating potential and that of the battery, were measured by means of a more sensitive voltmeter  $V_2$ .

The mean distance from the cathode plate and the cross-section (middle of the window) where the light is observed was about 14 mm. At the pressure used in our experiments (0,003 mmHg), the mean free path of an electron is equal to about 5 cm. Thus by far the greater part of the observed light must be due to electrons which make their first collision on its way from the cathode and which have not

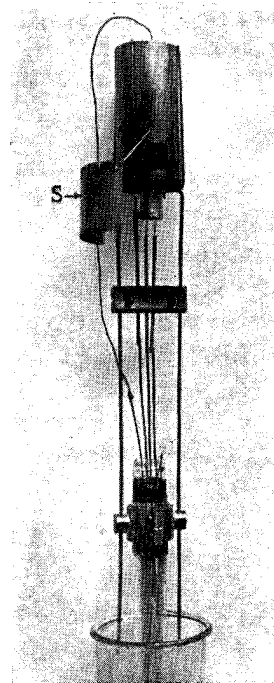
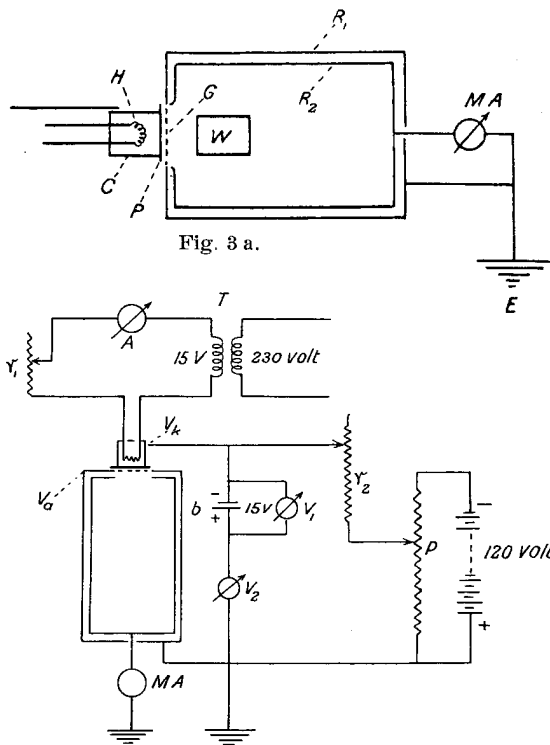
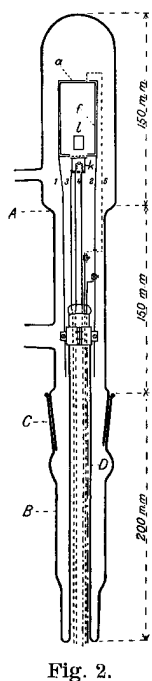


Fig. 4.

lost energy through previous collisions. The electron current density varied in our experiments between  $5 \cdot 10^{-3}$  and  $2 \cdot 10^{-2}$  amp.

Taking into account the short lifetime of the electronic states which form the upper state by the formation of the nitrogen groups here considered, we easily find that the probability that an excited molecule shall be hit a second time before emission takes place, is extremely small, as compared with the probability for a normal molecule to be excited by an electron collision.

To estimate the influence of collisions with excited molecules or atoms, we assume that the upper level of a band or line is excited when the electron hits within a distance ( $\varrho$ ) from the centre of the molecule or atom. The magnitude of ( $\varrho$ ) will depend on the term considered, but must be of the order of  $10^{-8}$  cm.

For each cm. of path, an electron produces  $\pi \varrho^2 N'$  excited molecules, where  $N'$  is the total number of molecules pr.  $\text{cm}^3$ . Is the electron current density ( $j$  el.st. units) the number of electrons ( $n$ ) passing unit area in unit time will be  $\frac{j}{e}$ , where ( $e$ ) is the charge of an electron. The number of mole-

cules ( $q$ ) (atoms) pr.  $\text{cm}^3$  brought into the excited state in unit time is then:

$$q = \frac{j}{e} \pi \varrho^2 N' \tag{3 a}$$

The light intensity per unit length of path ( $L$ ) will be proportional to  $q$  and:

$$L = k \cdot s \cdot q = k \cdot s \cdot \pi \varrho^2 \frac{j N'}{e} \tag{3 b}$$

Let ( $T$ ) be the average lifetime of the state considered, then the number of molecules ( $\nu$ ) per  $\text{cm}^3$ , which is in the excited state, will vary according to the equation:

$$\frac{d\nu}{dt} = q - \frac{\nu}{T} \tag{4}$$

In the stationary state  $\frac{d\nu}{dt} = 0$  and:

$$\nu_{t=\infty} = \nu_0 = q T = \frac{\pi}{e} j \varrho^2 T \cdot N' \tag{5}$$

The number of collisions which the electrons per unit cross-section makes with excited molecules will be:

$$\Delta q = \frac{\pi}{e} j \varrho^2 \nu_0$$

The reduction in light intensity due to collisions with excited molecules (atoms) will be (approximately):

$$\Delta L = k s \Delta q \text{ or:}$$

$$\frac{\Delta L}{L} = \frac{\Delta q}{q} = \left(\frac{\rho_1}{\rho}\right) \frac{\nu_0}{N'}$$

As we are merely interested in the order of magnitude, we may put  $\rho_1 \cong \rho$  and using equation (5) we get:

$$\frac{\Delta L}{L} = \frac{\nu_0}{N'} = \frac{\pi}{e} \rho^2 j \cdot T \quad (6 a)$$

or if ( $j$ ) is measured in ampère:

$$\frac{\Delta L}{L} = \frac{\pi c}{10 e} \rho^2 j T. \quad (6 b)$$

The quantity  $\rho^2$  should be constant for a given excited state and the equation (6) shows that for a given electronic state  $\frac{\Delta L}{L}$  is proportional to ( $j, T$ ) and should be independent of density and pressure. In the case of ordinary not metastable states  $T$  is of the order of  $10^{-8}$  sec.

W. Wien (11) gives  $T=3,7 \cdot 10^{-8}$  sec. for the negative nitrogen bands and  $1,8 \cdot 10^{-8}$  sec. for the  $N_2$  bands. Putting  $\rho=10^{-8}$  cm, we get:

$$\frac{\Delta L}{L} = 7,3 \cdot 10^{-5} j \text{ amp. for the } N_2 + \text{ bands and}$$

$$\frac{\Delta L}{L} = 3,5 \cdot 10^{-5} j \text{ amp. } \gg \gg N_2 \gg$$

This means that current densities of many amperes would be necessary to produce a noticeable influence on the excitation function due to collisions with nitrogen molecules in an excited but not metastable state. The current densities used by us — which were of the order of  $10^{-2}$  amp. should, therefore, have no disturbing influence on the excitation function.

These theoretical considerations agree with results obtained by Schaffernicht (6) who found that current densities up to  $10^{-2}$  amp. had no disturbing influence on the excitation function.

The spectra were taken with a glass spectrograph containing a considerable dispersion with large light power. From  $\lambda=5000$  to  $\lambda=4000$  the dispersion increased from  $79 \text{ \AA/mm}$  to  $23 \text{ \AA/mm}$ . The light intensities were measured by means of a registering photographic photometer of the Moll type.

### § 3. Remarks Regarding the Measurements of the Relative Intensity of Bands and Lines.

Our first problem is to measure the relative intensity with which the band (or line) considered is emitted from the source under varying conditions. The method here adopted for these measurements is essentially the same as described by one of us (12) in a paper dealing with the luminescence produced by canal rays.

We suppose that two spectra corresponding to different, but known conditions, are taken on the same plate. On the *same* plate is photographed an intensity scale which gives us for any wave-length the relation between exposure and the photographic density, which is measured by the deflection ( $u$ ) of our photometer. According to Schwartzschild the photographic density is determined by the product  $i t^p$ , where ( $i$ ) is the light energy falling on unit area in unit time (intensity),  $t$ , is the time of exposure and the exponent ( $p$ ) is nearly equal to unity. For the plates used (Ilford panchromatic hypersensitive), it was put equal to 0,89. Thus we have:

$$i \cdot t^p = \varphi_\lambda(u) \quad (7 a)$$

In order to obtain an intensity scale we may proceed in two ways.

1. We keep ( $t$ ) constant and vary ( $i$ ) in known proportions; and we find a number of corresponding values of ( $i$ ) and ( $u$ ) and plot a photographic density curve, which gives us relative values of ( $i$ ) for any photometric deflection ( $u$ ) or the function  $\varphi_\lambda(u)$ .

2. The same function is found, if ( $i$ ) is kept constant and the time of exposure ( $t$ ) is varied. Then, according to equation (7 a) the curve giving the relations between ( $u$ ) and ( $t^p$ ) also gives us  $\varphi_\lambda(u)$ , or the relative intensities corresponding to given values of ( $u$ ). The latter method is very convenient and reliable, and has been used in our measurements.

In order to apply the intensity-density function  $\varphi_\lambda(u)$  for the measurements of relative intensity of our spectrograms, it is essential that they should appear on the same plate as the intensity scale, and that the ground-fog is as nearly as possible the same all over the plate. The total density of the plate and the photometer deflection ( $u$ ) depends not only on the density due to exposure, but also on the ground-fog, but as long as the ground-fog is the same on the whole plate, there is an unambiguous relation between ( $i t^p$ ) and deflection ( $u$ ).

Taking the log. of equation (7 a) we obtain:

$$\log. i + \log. t^p = \log. \varphi_r(u) \quad (7 b)$$

If for different values of the wave-length, we draw the relation between ( $u$ ) and  $\log. (i)$ , or between ( $u$ ) and  $\log. t^p$ , we obtain parallel curves, so one may be made to cover the other by a translation. This means that we may put:

$$\log. (i t^p) = \log. \varphi(u) - \log. k_\lambda,$$

or we have:

$$k_\lambda \cdot i \cdot t^p = \varphi(u) \quad (7 c)$$

where  $k_\lambda$  is a factor which measures the relative sensitivity of the plate for light of wave-length ( $\lambda$ ).

Let the intensity with which the band considered is emitted be  $I_e$ . The intensity per unit area falling on slit of the spectrograph is equal to  $\frac{I_e}{r^2}$  where ( $r$ ) is the average distance between light source and slit. Let the intensity per unit area on the plate be  $i_p$ , then we may put:

$$i_p = \frac{I_e}{r^2} f(\lambda)$$

where  $f(\lambda)$  is a function which depends on the spectrograph used. The distance ( $r$ ) is kept constant for all spectrograms to be compared and we may write:

$$I_e = \kappa \cdot L_e = \frac{i_p}{f(\lambda)} \quad (8 a)$$

The intensity  $I_e$  corresponds to the luminescence produced by a current which we here denote by ( $j$ ). We are, however, interested in the light intensity per electron or  $\frac{L_e}{s \cdot n}$  where ( $sn$ ) is the number of electrons passing the effective cross-section in unit time, and remembering that  $j = sne$ , we find that the intensity per electron is proportional to  $\frac{L_e}{j}$  which we denote by  $I$ . Then:

$$I = \frac{i_p}{j \cdot f(\lambda)} \quad (8 b)$$

Let the intensity falling on the plate of the band considered for two spectrograms I and II be  $i_1$  and  $i_2$ , the corresponding photometer deflections be  $u_1$  and  $u_2$ , the times of exposures  $t_1$  and  $t_2$  and the electron currents ( $j_1$ ) and ( $j_2$ ). Then:

$$\begin{aligned} k i_1 t_1^p &= \varphi(u_1) = k_\lambda f(\lambda) j_1 I_1 t_1^p \\ k i_2 t_2^p &= \varphi(u_2) = k_\lambda f(\lambda) j_2 I_2 t_2^p \end{aligned} \quad (8 c)$$

The values of  $\varphi(u_1)$  and  $\varphi(u_2)$  are taken from the density curve.

These equations give:

$$\frac{I_2}{I_1} = \frac{\varphi(u_2) j_1 t_1^p}{\varphi(u_1) j_2 t_2^p} \quad (9 a)$$

When we measure relative intensities of the same band or line; we need not know the quantities  $k_\lambda$  and  $f(\lambda)$ . The quantities appearing in equation (9) are all measured. Generally we have for the same band from any comparable spectrum ( $r$ ):

$$I_r = \frac{\varphi(u_r) t_r^p j_r}{\varphi(u_1) t_r^p \cdot j_r} I_1 \quad (9 b)$$

Or the relative intensity of a band per electron ray is determined by the expression:

$$I_r = \frac{\varphi(u_r)}{t_r^p \cdot j_r} \quad (10)$$

If, now, the different spectra correspond to different electron velocities, the  $I$ -values found from equation (10) give us the excitation function of the band (or line) considered.

It will also be of interest to find the relative intensity with which various bands are emitted, and to find how this intensity distribution varies with the velocity of the exciting electrons.

This problem is solved provided we determine the excitation function for each of the bands and the intensity distribution for a spectrum corresponding to one definite electron velocity. Then we may calculate the intensity distribution for any velocity for which the excitation functions have been determined. The problem of determining the relative intensity of bands and lines of different wavelength has been dealt with by one of us (13) in previous papers.

For the sake of convenience we shall briefly describe the procedure.

Let the intensities with which the two bands are emitted be ( $I_{\lambda_1}$ ) and ( $I_{\lambda_2}$ ), the corresponding photometer deflections ( $u_{\lambda_1}$ ) and ( $u_{\lambda_2}$ ). If we use equation (8 c) and put:

$$k_\lambda f(\lambda) = Q(\lambda) \quad \text{we get:}$$

$$\left. \begin{aligned} Q(\lambda_1) I_{\lambda_1} t^p \cdot j &= \varphi(u_{\lambda_1}) \\ Q(\lambda_2) I_{\lambda_2} t^p \cdot j &= \varphi(u_{\lambda_2}) \end{aligned} \right\} \quad (11 a)$$

and

$$\frac{I_{\lambda_1}}{I_{\lambda_2}} = \frac{\varphi(u_{\lambda_1}) Q(\lambda_2)}{\varphi(u_{\lambda_2}) Q(\lambda_1)} \quad (11 b)$$





Table II.  
Band heads of the 2nd positive group.

|   | 0    | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   |
|---|------|------|------|------|------|------|------|------|------|------|------|------|
| 0 | 3371 | 3577 | 3805 | 4059 | 4355 | 4666 |      |      |      |      |      |      |
| 1 | 3159 | 3339 | 3536 | 3755 | 3998 | 4269 | 4574 | 4917 |      |      |      |      |
| 2 | 2977 | 3136 | 3309 | 3500 | 3710 | 3942 | 4201 | 4490 | 4814 |      |      |      |
| 3 | 2820 | 2962 | 3116 | 3285 | 3469 | 3671 | 3894 | 4141 | 4416 | 4723 |      |      |
| 4 |      | 2814 | 2953 | 3104 | 3267 | 3446 | 3642 | 3857 | 4094 | 4356 | 4648 | 4975 |

Table III.  
Bands of the N. G. of nitrogen.

|   | 0    | 1    | 2    | 3    | 4    | 5    |
|---|------|------|------|------|------|------|
| 0 | 3914 | 4278 | 4708 | 5228 | 5866 |      |
| 1 | 3582 | 3884 | 4236 | 4651 | 5151 |      |
| 2 | 3299 | 3563 | 3857 | 4199 | 4599 |      |
| 3 | 3077 | 3296 | 3548 | 3833 | 4167 | 4554 |
| 4 |      | 3075 | 3292 | 3537 | 3817 | 4140 |

Table IV.

|      | Group         | $I_b$ |      | Group         | $I_b$ |
|------|---------------|-------|------|---------------|-------|
| 6126 | 1st P. G. 5-1 | 118   | 4490 | 2nd P. G. 7-2 | 23    |
| 6068 | →→ 6-2        | 143   | 4345 | →→ 4-0        | 38    |
| 6012 | →→ 7-3        | 147   | 4060 | →→ 3-0        | 68    |
| 5957 | →→ 8-4        | 116   | 3999 | →→ 4-1        | 94    |
| 5904 | →→ 9-5        | 82    | 4708 | N. G. 0-2     | 100   |
| 5853 | →→ 10-6       | 72    | 4651 | →→ 1-2        | 43    |
| 5803 | →→ 11-7       | 74    | 4278 | →→ 0-1        | 205   |
| 5754 | →→ 12-8       | 72    |      |               |       |

The number of bands in each group is very large and we have therefore restricted our measurements to a certain selection of bands.

The relative intensities with which the bands appear were determined from spectrograms corresponding to electron rays of 23 volts (directly measured). These spectrograms are reproduced on Pl. I A, Nos. 1, 2 and 3. The results of our measurements are given in Table IV.

The 1st column gives the wavelength, the second column the group and the vibrational quantum numbers of the transition ( $\nu' - \nu''$ ). The last column gives relative intensities ( $I_b$ ) of the bands, when the intensity of the negative band 4708 is put equal to 100.

### § 5. The Corrections to be applied to the measured Potentials determined by means of the known Excitation Potentials of He-Lines.

The accelerating potentials directly measured in the way previously described, may not give the true energy of the electrons as they pass the window through which the luminescence is observed. Instead of tracing the origin of the various sources of errors, we have preferred to find the total correction experimentally by means of a gas for which the ignition potentials are known. As a standard gas we used helium.

Table V.

| Spectr. Pl. I B No. | Intensity           |                         |                       |                     |                         |                       |                         |                       | Measured potential |
|---------------------|---------------------|-------------------------|-----------------------|---------------------|-------------------------|-----------------------|-------------------------|-----------------------|--------------------|
|                     | 5875<br>$2^3P-3^3D$ | 5015<br>$2^1S_0-3^1P_1$ | 4713<br>$2^3P-4^3S_1$ | 4471<br>$2^3P-4^3D$ | 4388<br>$2^1P_1-5^1D_2$ | 4121<br>$2^3P-5^3S_1$ | 3964<br>$2^1S_0-4^1P_1$ | 3888<br>$2^3S_1-3^3P$ |                    |
| 1                   | 8,8                 |                         | 6,7                   | 12,0                | 10,7                    | 3,2                   | 15,2                    | 11,4                  | 50                 |
| 2                   | 11,7                |                         | 12,2                  | 16,6                | 12,5                    | 6,0                   | 11,5                    | 17,4                  | 40                 |
| 3                   | 16,5                | 29,5                    | 23,9                  | 24,2                | 11,1                    | 11,4                  | 5,4                     | 26,2                  | 30                 |
| 4                   | 14,4                | 14,6                    | 23,8                  | 14,6                | 5,2                     | 7,5                   | 3,2                     | 19,0                  | 28                 |
| 5                   | 8,4                 | 8,6                     | 14,4                  | 8,55                | 3,0                     | 4,4                   | (1,6)                   | 11,4                  | 27                 |
| 6                   | 4,6                 | 2,94                    | 4,9                   | 1,05                | 0,6                     |                       |                         | 6,3                   | 26                 |
| 7                   | 1,75                | 0,79                    | 0,73                  | (0,45)              |                         |                       |                         | 3,5                   | 25,7               |
| 8                   | 0,38                | 0,3                     | 0                     |                     |                         |                       |                         | 0,78                  | 25,4               |
| 9                   | 0                   | 0                       |                       |                     |                         |                       |                         | 0,35                  | 25,2               |

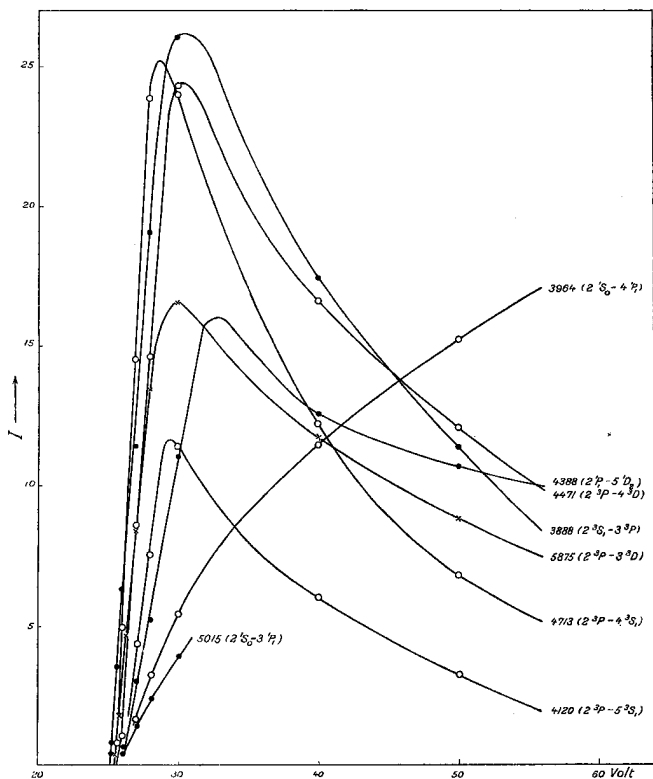


Fig. 6.

A number of He-spectra were taken with the same arrangement as used for nitrogen. The first spectrum was taken at an apparent (measured) potential of 50 volts. By the following the potential was reduced by steps until the luminescence had disappeared. The steps were made small near the ignition potentials of the He-lines. The series of He-spectrograms are shown on Pl. I B, No. 1—9. The last exposure (9) shows no He-lines.

From these spectrograms we determined the excitation function for some of the more prominent lines. The results are given in Table V and are graphically represented in Fig. 6.

It should be remembered that the Table V and the curves Fig. 6 give true relative intensities for each line, but they do not give true relative intensities for different lines of each spectrum.

The excitation functions of the He-lines here given agree well with those found by Thieme (8) for the same lines. The lines of ortho helium corresponding to transitions between triplet-states have excitation functions with a very pronounced maximum, just above the ignition potential, while the singlet lines of parahelium have a function which show a much slower rate of increase when the potential is

Table VI.

| $\lambda$ | True<br>Excit. pot. | - Measured<br>Excit. pot. | Correction |
|-----------|---------------------|---------------------------|------------|
|           | volt                | volt                      | volt       |
| 5875      | 23,02               | 25,25                     | -2,23      |
| 5015      | 23,05               | 25,30                     | -2,25      |
| 4713      | 23,50               | 25,50                     | -2,00      |
| 4471      | 23,64               | 25,60                     | -1,96      |
| 3888      | 22,95               | 24,95                     | -2,00      |

Mean correction = -2,1 volt

increased above the ignition value. This comparison with the He-excitation functions previously found, shows that our experimental arrangement is able to give us the true excitation functions essentially free from secondary effects.

For those He-lines for which we have the most accurate intensity measurements, we have plotted on a large scale the excitation curves just above the point of ignition. By means of these curves we find the points corresponding to  $I=0$  or the measured ignition potentials. The true ignition potentials are known from the term values, and were taken from Grotrians graphical representations (14). From these data we find the correction to be applied to our measured potentials. The results are given in Table VI.

The voltages given hereafter are the true corrected voltages.

### § 6. The Excitation Functions of the Nitrogen Bands.

In order to obtain the excitation functions, twelve spectrograms were taken on the same plate for accelerating potentials which increased in small steps from 11,4 to 24,9 volts. The spectrograms are reproduced on Plate II. C. Nos. 1—12. The neon spectra (a, b, c, d, e) taken with increasing time of exposure, form the density scale used for the determination of relative intensities with which a band appears on the different spectrograms.

The bands of the 1st positive group are seen to the left, where the sequences  $\nu' - \nu'' = 3$  (red) and  $\nu' - \nu'' = 4$  (yellow) appear with great intensity. At the highest potential 24,9 volts the negative and the second positive group appear quite strong. The intensity of the negative bands gradually decreases as the potential diminishes. At 16,9 volts, the band 4278 is just visible, but is absent at 15,9 volts.

The intensity of the 2nd positive group still increases and is greatest on the spectrogram corresponding to 14,9 volts, after which it suddenly drops off. On the spectrogram No. 10 (12,9 volt), the 2nd positive group has vanished, while the 1st positive still remains although the bands corresponding to higher quant numbers ( $\nu'$ ) gradually vanishes as the potential gets smaller.

In order to determine the excitation function for somewhat higher electron energy, a second plate was taken (Pl. II D), which contained an intensity scale (a, b, c, d, e, f) and 11 spectrograms (1—11) from nitrogen. The potential was increased from one spectrogram to the next in steps of 10 volts up to 118 volts. We notice that the bands of the 1st positive group, corresponding to the sequence ( $\nu' - \nu'' = 3$ ) diminishes less rapidly with increasing electron energy than those of the sequence ( $\nu' - \nu'' = 4$ ).

The intensities are found in arbitrary units. In order to make them comparable with those found for the smaller tensions (Pl. II C), we multiply the intensities for each band with a certain factor which is determined in such a way that the intensity corresponding to the lowest potentials of the series Pl. II D. are the same as they are for the same potentials of the series Pl. II C. In this way the results of the two series are connected up as if they were taken on the same plate. The excitation functions derived from the two plates II C and II D are represented by the curves of Figs. 7, 8 and 9. The curves of Fig. 7 represent the excitation functions for four bands of the 1st positive group all belonging to the sequence ( $\nu' - \nu'' = 4$ ). Fig. 8 represents the excitation functions for three bands of the 2nd positive group and Fig. 9 for two bands of the negative group belonging to the sequence ( $\nu' - \nu'' = -2$ ).

We notice that the excitation functions of the 1st and the 2nd positive group are very similar. If from small voltages we pass the ignition potential, the intensity rapidly increases to a maximum after which it decreases first rapidly and then more slowly. For somewhat large velocities the intensity produced per unit length of path by an electron, seems to be nearly independent of velocity. In the case of the 1st positive group, the maximum is obtained at 13,5 volts, in the case of the 2nd positive group, it is situated at about 15,0 volts.

Comparing the curves Fig. 9 of the N. G. with those of Fig. 7 and 8 (1st and 2nd P. G.), we notice that the excitation curves for the bands of the N. G.

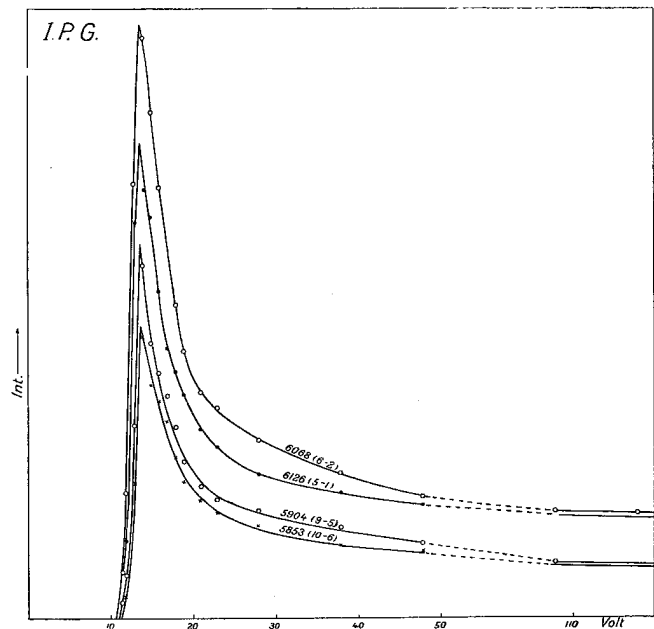


Fig. 7.

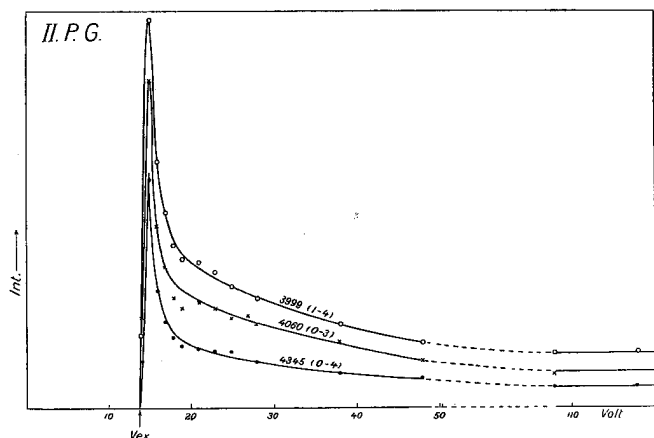


Fig. 8.

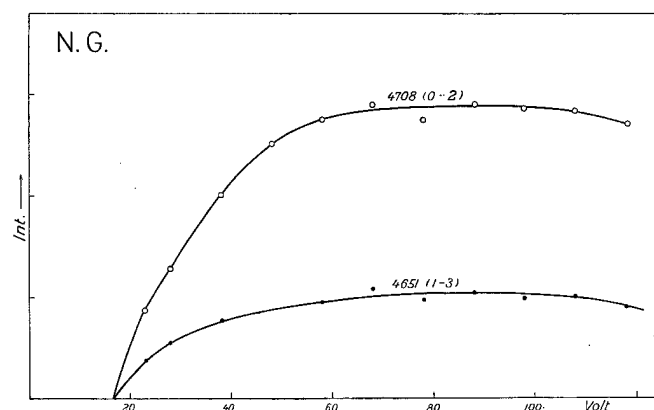


Fig. 9.

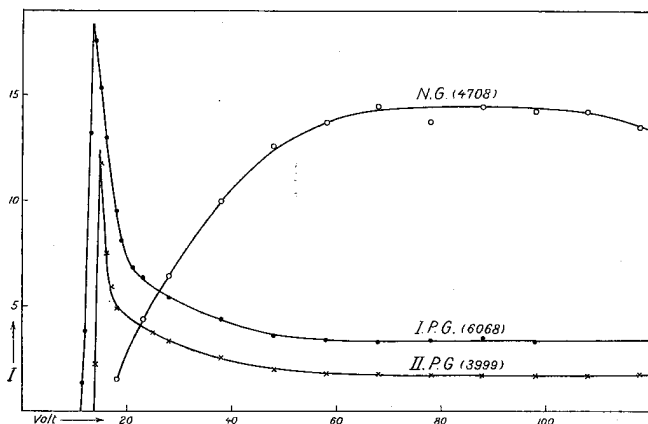


Fig. 10.

differ essentially from those of the two positive groups. When the potential increases above the point of ignition, the intensity increases, but quite slowly and the curves indicate a flat maximum at about 90 volts. The typical difference between the excitation function of the N.G. and those of the positive group are shown by curves Fig. 10 giving the curve for one band of each of the three groups.

Comparing these results with those found for helium and for other atomic spectra, we notice that the curves for the two positive groups are very similar to those obtained for atomic lines resulting from transitions between triple-states, while the excitation function for the N. G. resembles that of a singulet line. The difference between the excitation functions of the positive and those of the negative nitrogen bands, therefore, ought to be seen in relation to the fact that the positive bands are associated with the triplet-states  $C^3\Pi_u$ ,  $B^3\Pi_g$  and  $A^3\Sigma_u^+$  of  $N_2$  while the negative bands are connected with the state  $N_2^+$  doublets-states,  $B'^2\Sigma_u^+$  and  $X'^2\Sigma_g^+$ .

Our measurements are restricted to electron energies below 118 volts, or just above the maximum of the excitation functions of the negative bands. This limitation is due to the fact that the determination of the excitation functions for higher voltages would require certain changes in our experimental arrangements. It is, however, intended to continue these measurements in order to determine the rate of fall of the excitation curve for the N. G. above the maximum point.

### § 7. The Ignition Potentials.

In order to fix accurately the ignition potentials of the various bands, a series of spectra must be taken for which the accelerating potential is varied by small steps in the neighbourhood of the point of extinction.

The steps for the spectra on Pl. II C varied from 0,5 volts for the lowest accelerating potentials and 2 volts for the highest. From these spectra the ignition point may be determined fairly accurately for the bands of the 1st positive group; but for those of the 2nd positive and the negative group, the potential interval between successive spectra is too large.

We therefore took two series of spectra with potential steps of 0,1 and 0,2 volts. One series (Pl. III E) was taken for potentials in the neighbourhood of the excitation point of the 2nd P. G., and one (Pl. III F) near the potential at which the N. G., is extinguished. The relative intensity per electron as it is given by equation (10) was determined for a number of bands of the 2nd positive and for two bands of the negative group. The results are given in the tables VII and VIII.

Table VII.

| V<br>(volt) | Intensity (I) of II P. G. |               |               |               |               |               |               |               |               |
|-------------|---------------------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
|             | 4666<br>(0-5)             | 4345<br>(0-4) | 4060<br>(0-3) | 4575<br>(1-6) | 4270<br>(1-5) | 3999<br>(1-4) | 4491<br>(2-7) | 4201<br>(2-6) | 3942<br>(2-5) |
| 14,9        | 7,90                      |               |               | 19,8          |               |               | 17,9          |               | 12,3          |
| 14,7        | 6,20                      |               |               | 12,5          |               |               | 6,55          | 9,50          | 4,28          |
| 14,5        | 4,52                      | (23,9)        |               | 7,35          | 19,6          | 14,0          | 3,70          | 5,13          | 2,70          |
| 14,3        | 3,14                      | 13,4          | 18,4          | 4,44          | 10,3          | 7,68          | 3,10          | 4,33          | 2,26          |
| 14,1        | 2,15                      | 7,73          | 9,45          | 3,35          | 7,55          | 5,93          | 2,50          | 3,60          | 1,71          |
| 13,9        | 1,65                      | 5,72          | 6,74          | 2,67          | 5,84          | 4,57          | 1,97          | 2,80          | 1,55          |
| 13,7        | 1,25                      | 3,90          | 4,40          | 1,80          | 4,30          | 3,17          | 1,30          | 1,96          | 1,16          |
| 13,6        | trace                     | 2,04          | 2,41          | trace         | 1,70          | 1,40          | trace         | trace         | trace         |
| 13,5        | 0                         | trace         | trace         | 0             | trace         | trace         | 0             | 0             | 0             |
| 13,4        | 0                         | 0             | 0             | 0             |               | 0             | 0             | 0             | 0             |
| $V_i =$     | 13,4 volt                 |               |               | 13,5 volt     |               |               | 13,6 volt     |               |               |

Table VIII.

| V<br>volt | Intensity (I) |            |
|-----------|---------------|------------|
|           | 39 4 (0-0)    | 4278 (0-1) |
| 17,5      | 9,4           | 4,0        |
| 17,3      | 8,0           | 3,32       |
| 17,1      | 6,28          | 3,00       |
| 16,9      | 4,35          | 2,64       |
| 16,7      | 3,30          | 2,18       |
| 16,5      | 1,60          | 1,72       |
| 16,3      | 0             | 0          |

In order to fix the ignition potentials, the intensity curves were drawn on a large scale and the potential corresponding to  $I=0$  was found by a small extrapolation. Some such curves are shown in Fig. 11. The ignition potentials ( $V_i$ ) found for a number of bands of the 1st positive group are given in Table IX. The bands are put up in the order of increasing values of ( $\nu'$ ).

Table IX.

| Band | $\nu' - \nu''$ | $V_i$ |                        |
|------|----------------|-------|------------------------|
|      |                | Volt  |                        |
| 6126 | 5-1            | 10,8  | } 10,9 ( $\nu' = 6$ )  |
| 6068 | 6-2            | 11,0  |                        |
| 6012 | 7-3            | 11,0  |                        |
| 6476 | 8-5            | 11,1  | } 11,1 ( $\nu' = 9$ )  |
| 6293 | 9-6            | 11,1  |                        |
| 5904 | 9-5            | 11,1  |                        |
| 6321 | 10-7           | 11,0  | } 11,3 ( $\nu' = 11$ ) |
| 5853 | 10-6           | 11,0  |                        |
| 5803 | 11-7           | 11,4  |                        |
| 5754 | 12-8           | 11,5  |                        |

The values of  $V_i$  show some small increase with increasing quant number  $\nu'$  as was to be expected.

If the potentials are reduced to the zero level ( $\nu' = 0$ ), we find that the ignition potential of the vibrational zero level of the  $B^3\Pi_g$ -state should be 9,4 volts. The interpretation of the  $\epsilon$ -system ( $A^3\Sigma_u^+ - X^1\Sigma^+$ ) by one of us (15) showed that the true value of ( $V_i$ ) of the zero  $B^3\Pi_g$ -level is 7,36 volts.

Before the true positions of the levels A, B and C of the nitrogen molecule were fixed by means of the  $\epsilon$ -system, the heights then given to these levels, which were derived from the direct determination of the ignition potentials of the positive bands of Duncan (16) and Sponer (17) were about 2 volts too large.

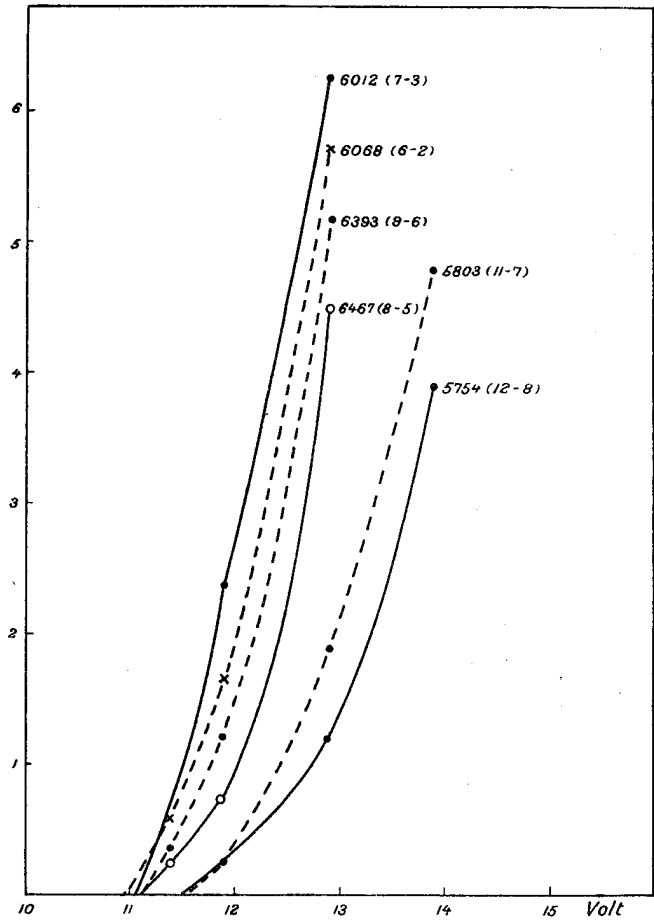


Fig. 11.

Now, for the vibrational zero-level of the  $B^3\Pi_g$ -state, Duncan finds 9,5 volts and Sponer 9,3 volts. Our value 9,4 volts is just the mean of these two values previously found. Thus for some reason the direct determination of the ignition potentials of the nitrogen bands, leads to results which place the electronic  $N_2$ -levels A, B, C about 2 volts too high.

Whatever may be the cause of the discrepancy, it is of interest to notice that our direct determinations of the ignition potentials by means of electron bombardment agree with previous results obtained by similar methods.

As seen from Table VII, the ignition potential of the bands ( $0 - \nu''$ ) of the 2nd positive group is 13,4 volts. For the ( $0 - 0$ ) band Sponer (17) finds  $13,0 \pm 0,3$  volts and Duncan  $12,0 \pm 0,5$  volts. Also in the case of the 2nd positive group, the ignition potentials of the ( $0 - \nu''$ ) bands do not give us the true position of the upper electronic state ( $C^3\Pi_u$ ) of these bands, but a value which is about 2 volts too high.

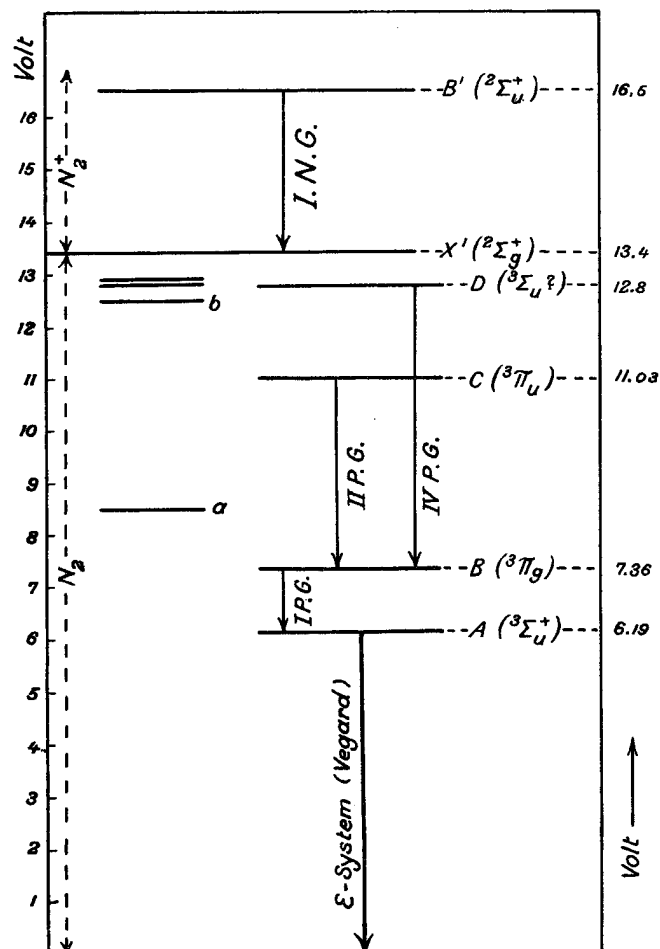


Fig. 12.

In the case of the negative group, we find for the zero-bands ( $0 \rightarrow \nu''$ ) an ignition potential 16,4 volts. Spomer (17) finds an ignition potential for the zero bands of the N. G. 19,6 volts which is about 3 volts higher. Our value, however, is about equal to the ionisation potential, for which Mohler and Foote (18) give 16,9 Brandt (19) 16,9 and Mackay (20) 16,3 volts.

As regards the interpretation of our result regarding the ignition potential of the zero band of the N. G., two possibilities should be considered.

- a. The value 16,4 volts found by us may be due to a secondary effect due to collisions between the electrons and  $N_2^+$  ions. By such collisions the  $N_2^+$ -ion should be transferred from the  $X'(^2\Sigma_g^+)$ -state to the  $B'(^2\Sigma_u^+)$ -state. This explanation, however, cannot be upheld. On account of the small pressure (0,003 mm Hg) and of the

small distance (about 1,5 cm) from the axis of the ray bundle to the walls of the Faraday cylinder, the life time of an ion is of the order of  $3 \cdot 10^{-6}$  sec.

Considerations similar to those leading to equation (6) lead to the result that the intensity produced by such secondary excitations of  $N_2^+$ -ions would only be  $1/100$  0/00 of the light intensity produced by primary collisions with unexcited molecules. The intensity due to collisions with ionised molecules should therefore be negligible as compared with that observed.

- b. The way in which the  $N_2$ -molecule is brought to the  $N_2^+$  ( $B'^2\Sigma_u^+$ )-state by electron collisions has been discussed by one of us in previous papers (3, p. 55). On the basis of excitation experiments made by Aars (9), he comes to the conclusion that the  $N_2$ -molecule may be brought directly to the  $N_2^+$  ( $B'^2\Sigma_u^+$ )-state as the result of a single collision between an electron and a normal nitrogen molecule. The correctness of this conclusion is also shown by our experiments, by the fact that the intensity of the negative bands is of the same order of magnitude as that of the positive ones.

Now, our results indicate that this direct transition from the normal molecule to the  $B'^2\Sigma_u^+$ -state of the ion ( $N_2^+$ ) is the only one which occurs under ordinary conditions.

This means that after the electron is removed by the ionisation process, the ion is left in an unstable electronic state ( $B'^2\Sigma_u^+$ ) and first after ionisation the ion is stabilised by performing the transition  $B'^2\Sigma_u^+ \rightarrow X'^2\Sigma_g^+$  which results in the emission of the negative group.

This means further that the ionisation potential gives us directly the height of the  $N_2^+$   $B'^2\Sigma_u^+$ -level, which according to our measurements of the ignition potential of the N. G. and the values found for the ionisation potential should be situated about 16,5 volts above the normal state of the  $N_2$ -molecule. This means that the height of the levels  $X'$  and  $B'$  of the  $N_2^+$ -ion has to be lowered by about 3,1 volts.

The  $X'^2\Sigma_g^+$  level should be rightly placed 13,3 volts (and not 16,5 volts) above the normal (ground) level of the  $N_2$ -molecule.

The new positions of the  $X'$  and  $B'$  electronic states are shown in Fig. 12, which gives a level diagram of  $N_2$  and  $N_2^+$ .

### § 8. Application of our Results to the Study of the Auroral Spectrum.

As already mentioned in the introduction to this paper, the study of the excitation of the nitrogen bands is of particular interest in connection with the interpretation of the auroral spectrum and its variations (3).

From the well-known fact that the relative intensity of the various nitrogen groups varies with the velocity of the cathode rays, we might think it would be possible from the intensity distribution within the spectrum to determine the velocity of the electric rays which produce the aurorae.

As previously stated by Vegard (21), the matter is not quite so simple. Taking into account the way in which the aurorae are produced, we know that the electric rays enter the atmosphere with a fairly large energy of the order of thousands of electron volts.

If we follow an electron on its way down into the atmosphere, its energy is gradually reduced until either the electron is turned back into space through the effect of the magnetic field, or it is completely absorbed usually somewhere near the bottom edge of the auroral streamer. Thus the auroral light is excited by electron rays having velocities which vary from some thousand volts down to the ignition potentials of the various bands and lines appearing in the auroral spectrum.

Now the light intensity per unit length of path must be small for the higher energies, first of all on account of the large increase of density downwards, secondly on account of the fact that the excitation function has its maximum for small velocities usually not far above the ignition point.

The spectrograms which form the basis of Vegard's determination of the intensity distribution within the auroral spectrum, are taken in such a way that the spectrograph is directed towards that part of the sky where the auroral luminescence has its greatest brightness, and these places will usually be situated somewhat near the lower limit. We should therefore expect that the average intensity distribution within the auroral spectrum determined by Vegard, would correspond to fairly small electron velocities.

The relative intensity of the bands of the 1st positive group in the auroral spectrum, has not been so accurately determined as that of the 2nd positive and the negative groups. The relative intensity of bands within the same group seems to keep fairly

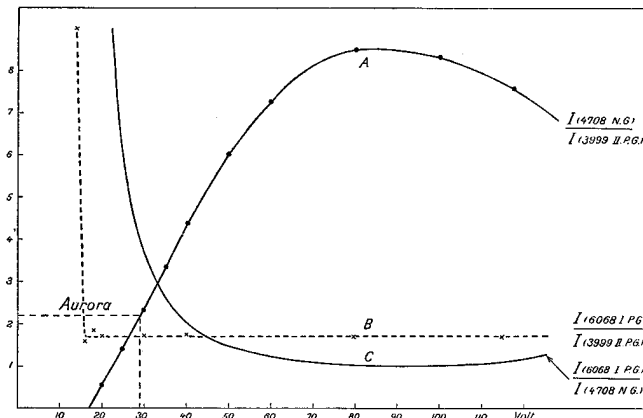


Fig. 13.

constant both for the auroral light and for that of our experiments.

This holds at any rate fairly well for the measured bands of the 2nd positive and the negative group. The relative change of intensity of these two groups may therefore be studied by comparing one band of the 2nd positive group e. g. the band  $\lambda=3999$  with e. g. the band 4708 of the N. G.

The ratio  $\frac{I(4708 \text{ N. G.})}{I(3999 \text{ II. P. G.})}$  as a function of electron energy, is represented by the curve (A) Fig. 13. In the case of the auroral spectrum, Vegard's determinations show that for the average auroral spectrum  $\frac{I_{4708}}{I_{3999}}$  is equal to about 2.2.

From Fig. 12 we see that this ratio corresponds to an electron energy of about 29 volts.

The determination of the average electron energy corresponding to the typical auroral spectrum, may not be quite unambiguous, for as we see from the curve A, Fig. 13, the ratio  $\frac{I(\text{N. G.})}{I(\text{II. P. G.})}$  shows a marked maximum and it is possible that for energies of some hundred volts or more, the ratio may come down again to that found for the auroral spectrum.

In fact Vegard (3,21) found that spectrograms corresponding to electron energies of some hundred volts, showed an intensity of the II. P. G. relative to that of the N. G. very similar to that found for the typical auroral spectrum.

Applying Vegard's measurements of the intensity distribution within the auroral spectrum to measurements of the excitation function, Bernard (22) drew the conclusion that the auroral luminescence is produced by electrons of a fairly definite energy of about 27

volts, and he regards his result to be in favour of an ultraviolet theory of the aurorae.

For reasons pointed out by Vegard (3, 21, 23), and already referred to in this paper, Bernard's application of the excitation experiments to the auroral luminescence is not justified.

If the conditions under which auroral light is produced are comparable with those of our excitation experiments, and if the point corresponding to 29 volts of the ratio curve Fig. 13 is the only one, which gives a ratio  $\frac{I(N.G.)}{I(II.P.G.)}$  approximately equal to that (2,2) found for the auroral spectrum, it would only mean that the auroral luminescence which is produced by electrons of varying energy, and accumulated on the plate by long exposures, gives an average intensity of the *II. P. G.* relative to the that of *N. G.* equal to that which would have been obtained by an excitation with homogenous electron rays having an energy corresponding to 29 volts. The large variability of the auroral luminescence shows that our interpretation in this respect must be the right one.

Curve *B* of Fig. 13 represents the variation of the ratio  $\frac{I(6068 I.P.G.)}{I(3999 II.P.G.)}$  with electron energy. Except for a small interval just above the ignition point, the ratio keeps nearly constant. When the electron energy decreases towards the ignition points of the bands of the 2nd *P. G.*, the ratio increases rapidly towards infinity.

If, therefore, during an auroral display a comparatively large number of electrons have velocities near or below the ignition points of the *II. P. G.*, the bands of the 1st positive group may be largely enhanced. According to Vegard, such conditions of excitation with rays of small velocities occur near the bottom edge of such aurorae which reach fairly low altitudes (say below 90 km). The predominance of the 1st positive group will have the effect that the auroral bands appears intensively red all along the bottom edge (Red aurora of type *B*).

Curve *C* Fig. 13 gives the variation of the ratio  $\frac{I(6068 I.P.G.)}{I(4708 N.G.)}$  with electron velocity. We notice a very large decrease of this ratio, as we pass upwards from the ignition point of the *N. G.*

In the case of the aurora, the average velocity of the electrons increases from the bottom edge and upwards. Consequently the relative intensity of the bands of the *I. P. G.* ought to diminish upwards.

This effect was observed by Vegard (23, 24) on four pairs of spectrograms taken at Oslo Oct. 11—13 1937. In each pair, one of the spectrograms corresponds to the lower border, the other one to regions near the upper limit of the auroral streamers.

On a pair of spectra corresponding to the upper and lower limits of aurorae observed at Oslo on Sept. 19th this year, Vegard<sup>1</sup> measured this altitude effect quantitatively. The intensity ratio:

$$\frac{\left(\frac{I(I.P.G.)}{I(N.G.)}\right)_{\text{upper}}}{\left(\frac{I(I.P.G.)}{I(N.G.)}\right)_{\text{lower}}}$$

was found to be equal to 0,75. During this evening the aurorae usually consisted of fairly long streamers, and the two spectra correspond to a fairly large average difference of altitudes which may be estimated at about 60—80 km.

### Summary of results.

1. An experimental arrangement has been built by means of which the true excitation function may be determined practically free from secondary effects due to disturbances through collisions of the second kind or multiple electron collisions.
2. The effective potentials were determined by measuring the ignition potential for helium used as a standard gas.
3. The excitation functions determined from a number of He-lines were in good agreement with those found by other investigators showing that our apparatus worked satisfactorily.
4. The excitation functions were determined for a number of bands belonging to the 1st and 2nd positive and the 1st negative group of nitrogen and for electron energies ranging from below the ignition potential to about 120 volts.
5. The ignition potential of the (0—0) band of the *I. P. G.* was found to be 9,4 volts in good agreement with previous direct measurements e.g. by Duncan and Sponer. The value, however, is about 2 volts higher than the true value (7,36 volts) which is found by Vegard from his interpretation of the  $\epsilon$ -system, which results from the transition  $A(8 \Sigma_u^+) - X(1 \Sigma^+)$ .

<sup>1</sup> The results are not yet published, but more details will be given in a subsequent paper.



6. The ignition potential of the ( $0-\nu''$ ) series of 2nd positive group was found to be 13,4 volts in good agreement with previous measurements. But also in this case the ignition potential would place the zero levels of the *A* and *B* states about 2 volts too high.
7. For the ( $0-0$ ) band of the N. G. the ignition potential is found to be 16,4 volts. Within the limit of error, this value is equal to the ionisation potential as it was measured by Mohler and Foote, by Brandt and by Mackay. As under our experimental conditions no noticeable light can result from excitation of  $N_2^+$  with colliding electrons, the only explanation of our result seems to be that the  $N_2$ -molecule immediately after ionisation is left in the unstable  $B'(^2\Sigma_u^+)$  state. This involves that the height of the  $X'(^2\Sigma_g^+)$  level of the normal  $N_2^+$ -ion should be 13,3 volts instead of the value 16,5 volts now commonly accepted.
8. For the "typical" or average auroral spectrum Vegard finds that the ratio between the band (4708) of the N. G. to that of the band (3999) of the *II. P. G.* is about 2,2. From our determinations of the excitation functions of these bands, we find the same ratio for an electron energy, corresponding to 29 volts and possibly also for some higher potential of the order of some hundred volts.
9. Such a comparison gives us merely a kind of average velocity for the electrons which have produced the observed auroral light. It is not allowed, as done by Bernard, to assume that a comparison with excitation function may give us a definite value for the energy of the electron ray bundle. The auroral luminescence is produced by electron rays, whose energy gradually diminishes as they penetrate into the atmosphere, and therefore the luminescence does not correspond to a definite electron energy.
10. The average velocity of the exciting cathode rays increases as we pass from the bottom edge to the upper limit of an auroral streamer. The correctness of this view is confirmed by the fact that certain aurorae with red lower borders owe their redness to the enhancement of the 1st positive group, and by the fact found by Vegard that the intensity of the bands of the *I. P. G.* relative to that of the negative bands decreases as we pass upwards from the bottom edge.

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# PLATES

**Plate I. A.**

The spectra ( $\alpha$ ) are taken as a density scale from a He-source. Spectra 1--4 are due to nitrogen excited by cathode rays, the directly measured accelerating potential  $V$  and time of exposure  $T_e$  are:

| Nr. | $V$ (volt) | $T_e$ (min)    |
|-----|------------|----------------|
| 1   | 23         | $\frac{1}{2}$  |
| 2   | 23         | 1              |
| 3   | 23         | $1\frac{3}{4}$ |
| 4   | 40         | $1\frac{1}{2}$ |

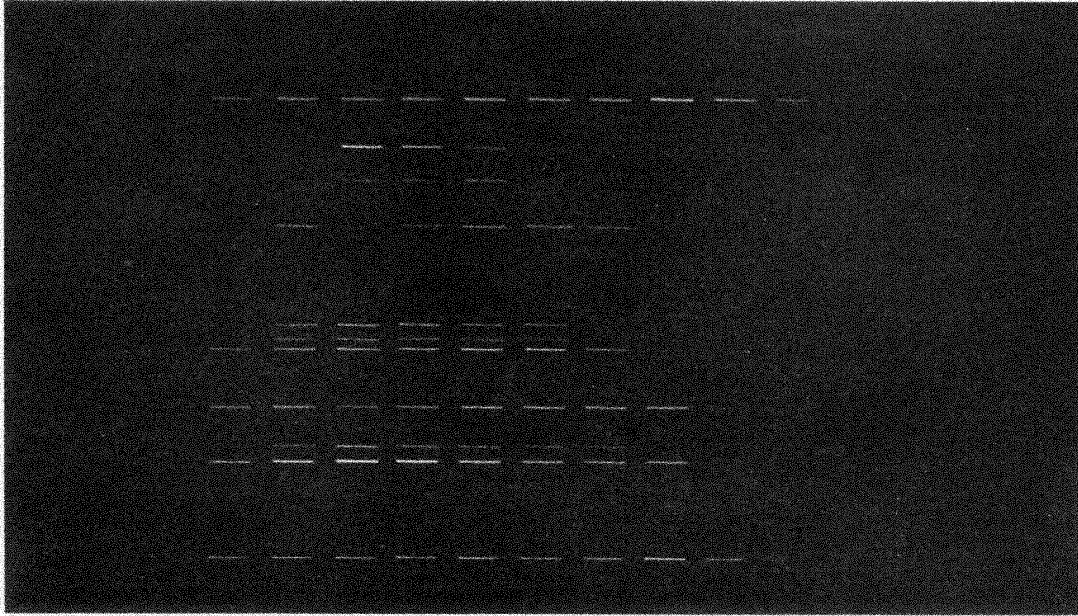
Each pair of the spectra  $a, b, c, d$ , consists of a continuous spectrum from a standard lamp with known spectral intensity distributions with a He-comparison spectrum. The time of exposure for the continuous spectra  $a-d$  are 5, 10, 20 and 180 sec. respectively.

**Plate I. B.**

The series ( $\alpha$ ) form a density scale from a constant He-source. Spectra 1--9 correspond to He excited by electrons of varying energy in the apparatus used for the determinations of excitation functions. For each spectrum we have observed the apparent accelerating voltage  $V$ , the total current ( $i_e$ ) carried by the electrons and the time of exposure ( $T_e$ ).

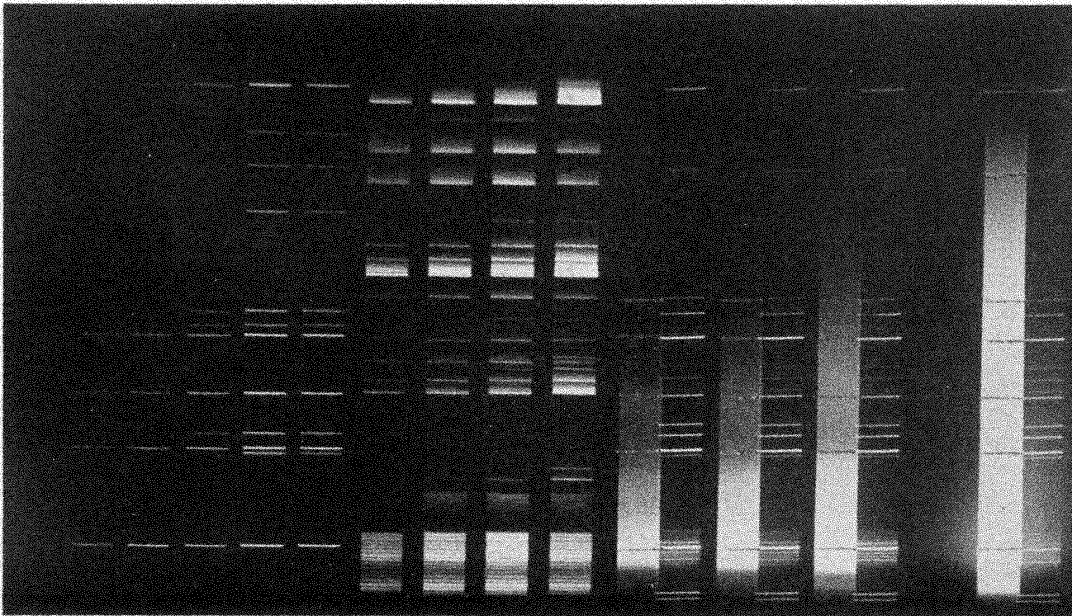
| Nr. | $V$     | $i_e$       | $T_e$               |
|-----|---------|-------------|---------------------|
| 1   | 50 volt | 19,5 Mil.A. | 60 sec.             |
| 2   | 40 »    | 17,2 »      | 50 »                |
| 3   | 30 »    | 19,8 »      | 45 »                |
| 4   | 28 »    | 18,0 »      | 45 »                |
| 5   | 27 -    | 17,1 »      | $1\frac{1}{2}$ min. |
| 6   | 26 »    | 17,0 »      | $1\frac{1}{2}$ »    |
| 7   | 25,7 »  | 16,9 »      | 5 »                 |
| 8   | 25,4 »  | 16,8 »      | 7 »                 |
| 9   | 25,2 »  | 16,5 »      | 10 »                |
| 10  | 25,0 »  | 16,5 »      | 10 »                |

B



1 2 3 4 5 6 7 8 9

A



1 2 3 4 a b c d

**Plate II. C.**

(*a-e*) photographic density scale.

| Nr. | $V_e$     | $i_e$       | $T_e$                              |
|-----|-----------|-------------|------------------------------------|
| 1   | 24,9 volt | 23,9 Mil.A. | 2 <sup>3</sup> / <sub>4</sub> min. |
| 2   | 22,9 »    | 20,8 »      | 2 <sup>1</sup> / <sub>2</sub> »    |
| 3   | 20,9 »    | 17,8 »      | 2 <sup>3</sup> / <sub>4</sub> »    |
| 4   | 18,9 »    | 15,0 »      | 2 <sup>1</sup> / <sub>4</sub> »    |
| 5   | 17,9 »    | 13,6 »      | 2 <sup>1</sup> / <sub>2</sub> »    |
| 6   | 16,9 »    | 12,4 »      | 3 »                                |
| 7   | 15,9 »    | 11,1 »      | 3 <sup>1</sup> / <sub>2</sub> »    |
| 8   | 14,9 »    | 9,2 »       | 4 »                                |
| 9   | 13,9 »    | 8,1 »       | 6 »                                |
| 10  | 12,9 »    | 7,0 »       | 9 »                                |
| 11  | 11,9 »    | 6,3 »       | 35 »                               |
| 12  | 11,4 »    | 5,5 »       | 65 »                               |

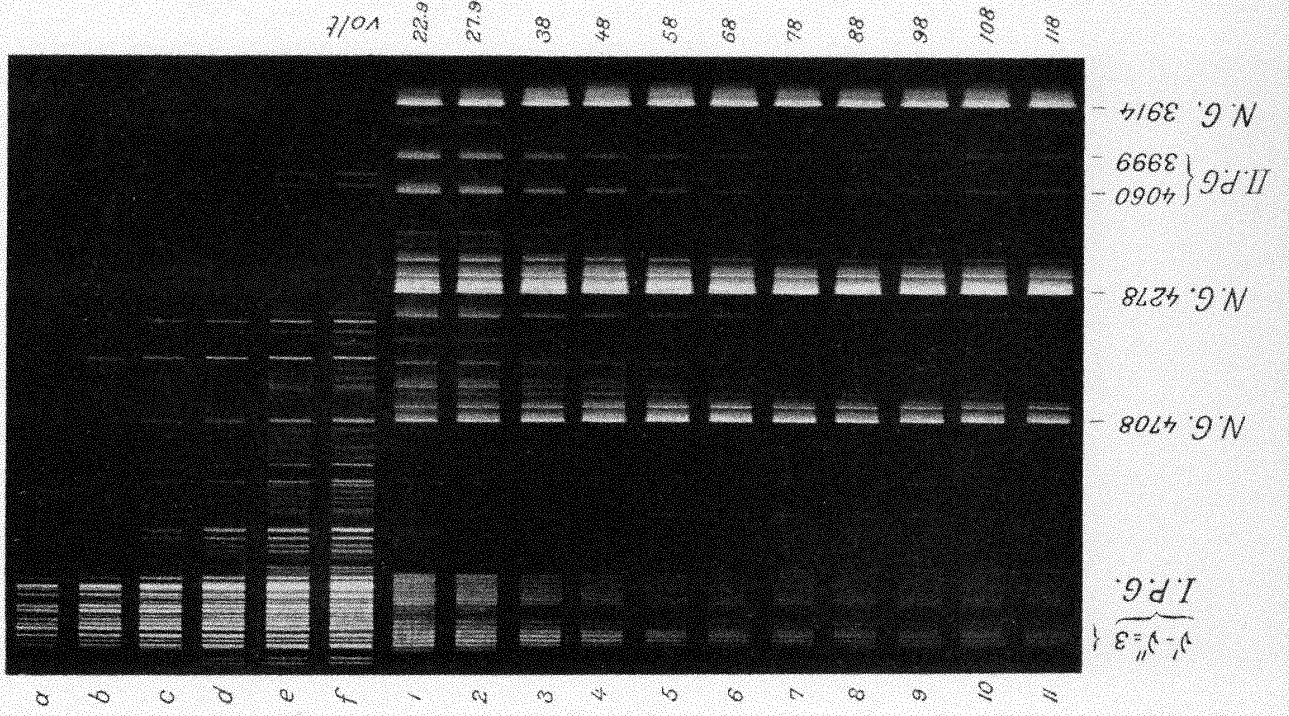
$V_e$  is the true effective accelerating voltage corrected by means of the ignition potentials of He-lines.

**Plate II. D.**

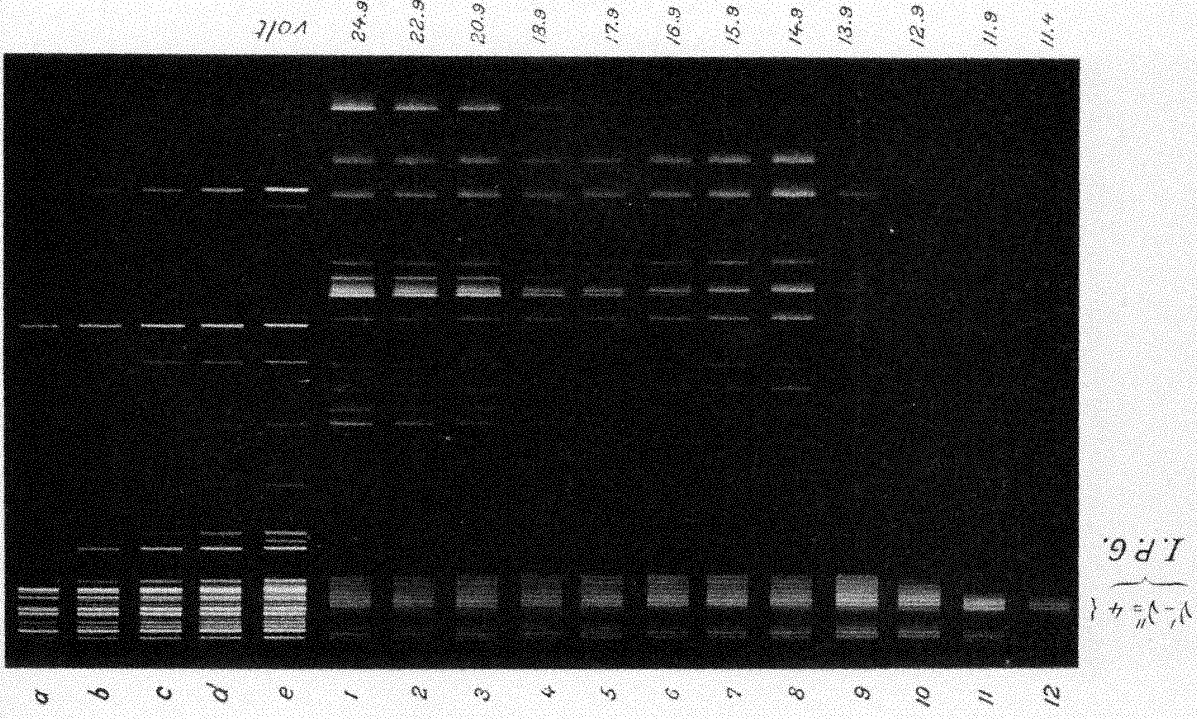
*a-f*: photographic density scale.

| Nr. | $V_e$     | $i_e$       | $T_e$    |
|-----|-----------|-------------|----------|
| 1   | 22,9 volt | 16,2 Mil.A. | 180 sec. |
| 2   | 27,9 »    | 20,0 »      | 135 »    |
| 3   | 38 »      | 20,3 »      | 105 »    |
| 4   | 48 »      | 19,0 »      | 105 »    |
| 5   | 58 »      | 17,0 »      | 90 »     |
| 6   | 68 »      | 19,3 »      | 70 »     |
| 7   | 78 »      | 18,3 »      | 75 »     |
| 8   | 88 »      | 19,5 »      | 60 »     |
| 9   | 98 »      | 17,3 »      | 70 »     |
| 10  | 108 »     | 18,0 »      | 70 »     |
| 11  | 118 »     | 18,0 »      | 60 »     |

D.



C.



**Plate III. E.**

Spectra  $\alpha-2$ : Photographic density scale.

| Nr. | $V_2$     | $i_e$      | $T_e$   |
|-----|-----------|------------|---------|
| 1   | 14,9 volt | 9,4 Mil.A. | 5½ min. |
| 2   | 14,7 »    | 9,0 »      | 6 »     |
| 3   | 14,5 »    | 8,7 »      | 6½ »    |
| 4   | 14,3 »    | 8,45 »     | 7 »     |
| 5   | 14,1 »    | 8,25 »     | 8 »     |
| 6   | 13,9 »    | 8,0 »      | 9 »     |
| 7   | 13,7 »    | 7,8 »      | 12 »    |
| 8   | 13,6 »    | 7,56 »     | 11 »    |
| 9   | 13,5 »    | 7,55 »     | 11½ »   |
| 10  | 13,4 »    |            |         |
| 11  | 13,3 »    |            |         |
| 12  | 13,2 »    |            |         |

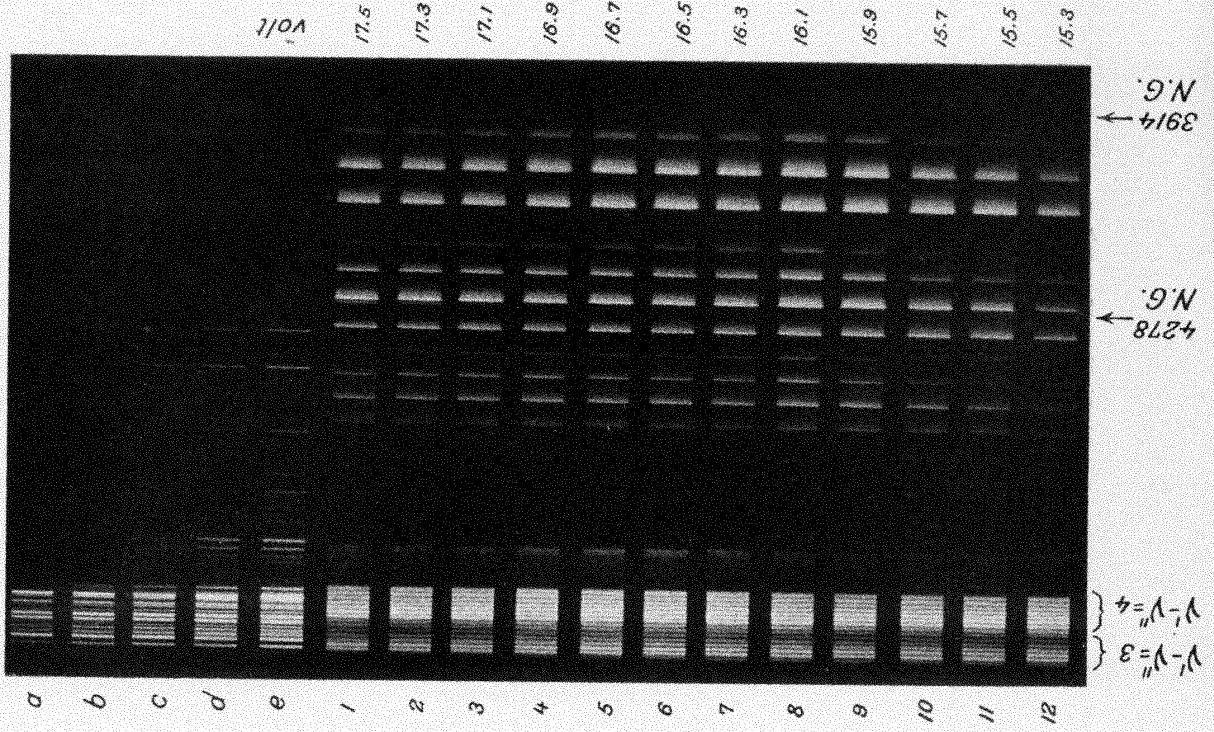
**Plate III. F.**

Spectra  $\alpha-e$ : Density scale.

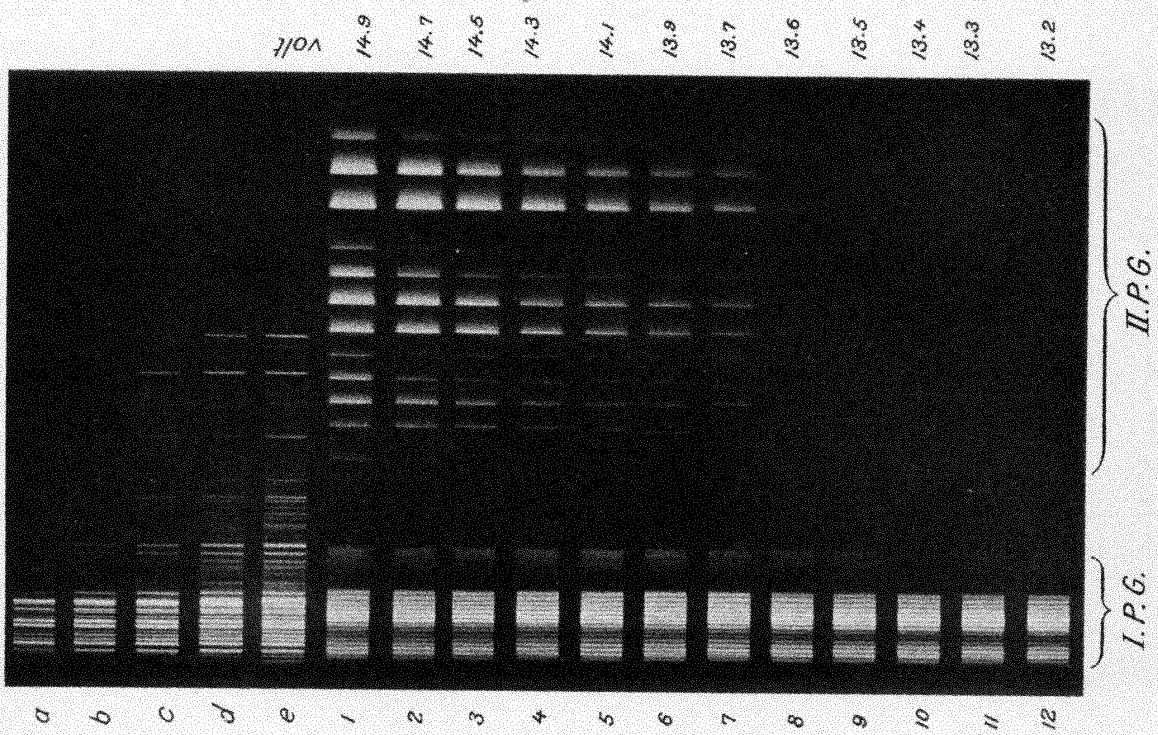
| Nr. | $V_e$     | $i_e$       | $T_e$   |
|-----|-----------|-------------|---------|
| 1   | 17,5 volt | 11,4 Mil.A. | 4½ min. |
| 2   | 17,3 »    | 11,2 »      | 4½ »    |
| 3   | 17,1 »    | 11,0 »      | 4½ »    |
| 4   | 16,9 »    | 10,7 »      | 4½ »    |
| 5   | 16,7 »    | 10,4 »      | 5 »     |
| 6   | 16,5 »    | 10,1 »      | 5 »     |
| 7   | 16,3 »    | 9,0 »       | 5 »     |
| 8   | 16,1 »    |             |         |
| 9   | 15,9 »    |             |         |
| 10  | 15,7 »    |             |         |
| 11  | 15,5 »    |             |         |
| 12  | 15,3 »    |             |         |



F



E



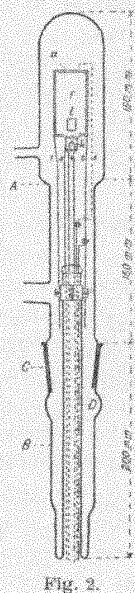


Fig. 2.

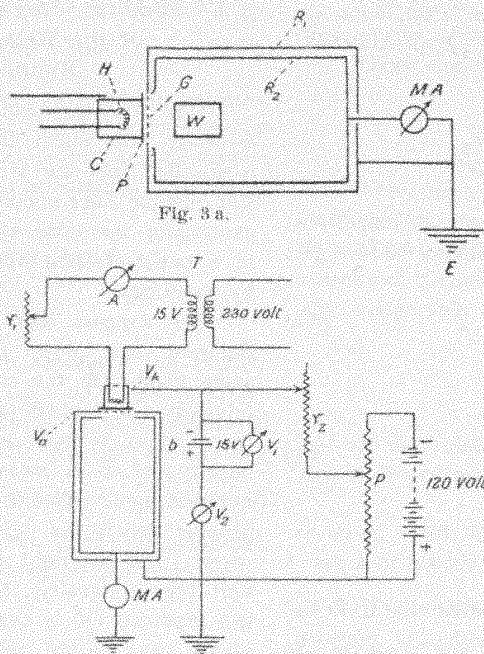


Fig. 4.

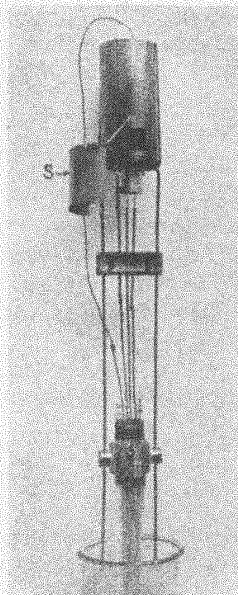


Fig. 3 b.

lost energy through previous collisions. The electron current density varied in our experiments between  $5 \cdot 10^{-3}$  and  $2 \cdot 10^{-2}$  amp.

Taking into account the short lifetime of the electronic states which form the upper state by the formation of the nitrogen groups here considered, we easily find that the probability that an excited molecule shall be hit a second time before emission takes place, is extremely small, as compared with the probability for a normal molecule to be excited by an electron collision.

To estimate the influence of collisions with excited molecules or atoms, we assume that the upper level of a band or line is excited when the electron hits within a distance ( $q$ ) from the centre of the molecule or atom. The magnitude of ( $q$ ) will depend on the term considered, but must be of the order of  $10^{-8}$  cm.

For each cm. of path, an electron produces  $\pi q^2 N'$  excited molecules, where  $N'$  is the total number of molecules pr.  $\text{cm}^3$ . Is the electron current density ( $j$ ) el.st. units) the number of electrons ( $n$ ) passing unit area in unit time will be  $\frac{j}{e}$ , where ( $e$ ) is the charge of an electron. The number of mole-

cules ( $q$ ) (atoms) pr.  $\text{cm}^3$  brought into the excited state in unit time is then:

$$q = \frac{j}{e} \pi q^2 N' \tag{3 a}$$

The light intensity per unit length of path ( $L$ ) will be proportional to  $q$  and:

$$L = k \cdot s \cdot q = k \cdot s \cdot \pi q^2 \frac{j N'}{e} \tag{3 b}$$

Let ( $T$ ) be the average lifetime of the state considered, then the number of molecules ( $\nu$ ) per  $\text{cm}^3$ , which is in the excited state, will vary according to the equation:

$$\frac{d\nu}{dt} = q - \frac{\nu}{T} \tag{4}$$

In the stationary state  $\frac{d\nu}{dt} = 0$  and:

$$\nu_{t=\infty} = \nu_0 = q T = \frac{\pi}{e} j q^2 T \cdot N' \tag{5}$$

The number of collisions which the electrons per unit cross-section makes with excited molecules will be:

$$\Delta q = \frac{\pi}{e} j q^2 \nu_0$$