The Minimum Electron Energies Associated with the Excitation of the Spectra of Helium.

Figures and Spectrograms

A. C. Davies

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THE MINIMUM ELECTRON ENERGIES ASSOCIATED WITH THE EXCITATION OF THE SPECTRA OF HELIUM.

By

Ann Catherine Davies, M.Sc, Assistant Lecturer in Physics in the Royal Holloway College.

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Synopsis.

In view of the recent developments in the theory of the possible stationary states of the helium atom, and the bearing on this theory of recent experimental work on the critical potential differences for the production of radiation and of ionisation in helium, it was thought that a spectroscopic investigation of the excitation of helium under different potential differences might be fruitful.

An investigation of the minimum potential differences required for the stimulation of the different lines of the ordinary helium line spectrum, and also of the enhanced lines, and the helium band spectrum, was therefore made under various conditions of gas pressure and intensity of bombarding electron stream. In particular the possibility of exciting lines in the visible region of the spectrum, without the occurrence of ionisation, was examined. The conditions for the appearance of the band spectrum and for its maintenance, were investigated with special reference to the recent suggestion of Franck and Knipping that it originates from He_2 molecules which are produced by the combination of pairs of abnormal helium atoms resulting from 20·4 volts electron impacts with normal helium.

The experimental results which have been obtained are as follows:-

1. (a) There are no genuine differences in the minimum voltages required for the excitation of different individual lines in the ordinary series spectrum of helium.

(b) The minimum voltages at which these lines were ever excited (as distinct from maintained) was 20·4 volts, and this only with a high gas pressure and a dense bombarding electron stream. In a large number of observations the lines were not excited until 25·2 volts (i.e. the ionisation voltage) was reached.

(c) Under very special conditions the series lines were maintained at potential differences as low as 13 - 14 volts. There seems, moreover, to be no reason for supposing that they cannot be maintained below this value.

11. The minimum voltage for the excitation of λ 4686, a prominent line of the enhanced system of helium, has three different well defined values under different experimental conditions. Two of these values, 80 volts, and 54·2 volts, correspond respectively to the voltages required theoretically (and confirmed experimentally) for the removal from the helium atom of both electrons simultaneously, and for their removal by two separate electron impacts. The third value, 50·8 volts, corresponds to the energy required by Bohr's theory for the removal of the remaining electron in an already ionised helium atom to orbit 4, the line λ 4686 being, on the same theory, the

radiation which is emitted when the second electron in such an atom falls from orbit 4 to orbit 3.

III. (a) The band spectrum of helium is not always present when the ordinary series spectrum is excited though the minimum voltage at which the band spectrum was ever excited was the same as the corresponding minimum for the ordinary series spectrum.

(b) The band spectrum was never observed in the absence of the ordinary series lines, but when these were maintained at voltages below 20.4 volts the band spectrum could be maintained below this value also.

(c) The band spectrum became more intense relatively to the ordinary line spectrum as the pressure was increased, and at the same time the lowest voltage at which it could be seen was reduced.

The results given under I lead to the conclusion that the occurrence of ionisation is essential for the production of the ordinary line series spectrum of helium. This conclusion is difficult to reconcile with some of the recent conclusions of Franck and Knipping, but it is in complete agreement with the results of the work of McLennan and Ireton, and of Foote and Meggers, on certain metallic vapours.

In contrast with this the results given under II lead to the conclusion that in the case of the helium positive ion, further ionisation is not essential for the production of the enhanced lines of helium. The results of the investigation of the conditions for the excitation of the enhanced line λ 4686 are in accord with Bohr's general theory of radiation.

The results given under III lead to the conclusion that the band spectrum originates from some system whose production depends upon the presence of abnormal helium atoms, and they therefore support the view that it originates from He_2 molecules. The results of the present research alone afford no particular reason for concluding that the abnormal atoms concerned are those resulting from 20 ·4 volts electron impacts, but considered in conjunction with the results of a recent investigation by Horton and Davies, they lend strong support to this suggestion.

INTRODUCTION.

In addition to the two well known serial systems of helium, discovered by Runge and Paschen,[1] viz, the helium and the parhelium series, the spectrum of this gas includes the lines known as the enhanced lines and the many lined or band spectrum. It was at one time held by Stark[2] and others that the parhelium or single line series originated from helium atoms which had lost two electrons, while the helium or doublet series arose from helium atoms which had lost only one electron. The investigations of Rau[3] first, and later those of Richardson and Bazzoni,[4] of Horton and Bailey,[5] and of Compton and Lilly,[6] on the minimum velocities with which bombarding electrons can stimulate helium atoms to the emission of lines of these series, showed, however, that there is very little, if any,

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1. Runge and Paschen. Berl. Ber. 639 (1895)
2. Stark, Fischer and Kirschbaum, Ann. der Phys. XL.3. p.449 (1913)
3. H. Rau, Würzburg Phys.Med.ges.Ber.Feb.1914.
4. O.W.Richardson and C.B.Bazzoni, Nature XCVIII p.5 (1917)
5. F. Horton and D. Bailey. Brit.Ass. Report p.153 (1919)
6. K.T. Compton and E.G. Lilly. Astro. Phys. Journal July (1920)

genuine difference in the velocities required to excite any of the lines of these different series such as would be anticipated if Stark's view were correct. The lines of both the helium and the parhelium series are now attributed to the transitions of one of the electrons in the uncharged helium atom, while the transition of the remaining electron in a positively charged hhlium atom are taken to be those which give rise to the lines of the enhanced system.

It has recently been suggested by Lenz[7] and by Sommerfeld[8] that the band spectrum of helium, which is intermediate in character to the hydrogen secondary spectrum and ordinary band spectra, is not due to the helium atom, but to helium molecules which have a transitory existence under the conditions in which this spectrum has been observed. Both Lenz and Sommerfeld suggest that this molecule is He_2. Such a supposition is not in contradiction to the chemical evidence regarding the inert character of helium, because electrical excitation is postulated as a preliminary condition for the formation of the molecules. Moreover, evidence of the existence of diatomic helium has been obtained in the positive ray experiments of Sir J. J.Thomson.[9]

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7. W. Lenz. 'Deutsch. Phys. Ges. Verh'., 21 p.632 (1919)
8. A. Sommerfeld. Atombau und Spektrallinien p.563
9. Sir J.J.Thomson. Rays of Positive Electricity. (1921)

None of the ordinary helium and parhelium series are concerned with transitions involving a return of the displaced electron to the orbit normally occupied by it, for the frequencies of the radiations corresponding to such transitions will all lie in the extreme ultra violet region of the spectrum. This follows from the fact that the results of investigations on the production of radiation and of ionisation by electron impacts in helium, have shown that the minimum radiation potential difference is 20·4 volts and the minimum ionisation potential difference is 25·2 volts. According to Bohr's theory, when the radiation potential difference is reached, electrons are moved from the orbits within the atoms normally occupied by them, to the next outer stationary orbits, so the frequency of the radiation emitted when the electrons return to their normal orbits after this displacement, must be the smallest frequency corresponding to the return of an electron to the normal orbit. The voltages which correspond to the limiting frequencies of the helium and the parhelium principal series are 4·78 volts and 3·98 volts respectively. The limiting frequency of a series is that frequency which corresponds to the return of an electron from right outside the atom to the orbit characteristic of the series, so that it is connected by the quantum relation with the potential difference required to remove an electron from that orbit to infinity. The voltage corresponding to the limit of the helium principal series, 4·78 volts, is in good agreement with the difference between the observed ionisation and radiation potential differences i.e. (25.2 volts - 20·4 volts) 4·8 volts, and this latter must be the potential difference required for an electron in a helium atom to be removed from the orbit to which it is lifted at the radiation voltage, to infinity. It is therefore reasonable to associate the helium principal series with the orbit to which an electron in a helium atom is removed by collision with an electron having 20·4 volts energy.

By taking into account the mutual disturbance of the electron orbits, Landé [10] was able to work out the general sequence of the lines of the two serial systems of helium, and he attributed the existence of two independent serial systems to the existence of two independent sets of outer orbits. According to Landé one of these sets of outer orbits is coplanar with the orbit of the undisturbed electron, while the plane of the second set of orbits is at an angle with the plane. These are known as the "coplanar" and the "crossed" systems of orbits respectively, and it is the doublet or helium series of lines which correspond to the coplanar system, and the single line or parhelium series which correspond to this crossed system. Since the helium principal series originates from the orbit to which an electron is displaced at 20.4 volts, this orbit must belong to the coplanar system and it might be

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10. A Landé, Phys. Zeits. XX p.228 (1919)

expected that another radiation potential difference would exist, at which an electron from a normal atom would be removed to that orbit of the crossed system from which the parhelium principal series originates. The difference between the two radiation potential differences would be expected to be equal to the difference between the voltages corresponding to the limits of the two principal series, i.e. (4.78 - 3.98 =) 0.8 volt. A second radiation voltage, differing by this interval from 20.4 volts, was found by Franck and Knipping [11] and the existence of two critical radiation voltages has been confirmed by Horton and Davies.[12] In a later paper, Franck and Knipping[13] describe experiments from which they conclude that though inelastic collisions occur when electrons with 20.4 volts energy collide with helium atoms, such collisions are not followed by an emission of radiation unless there is impurity present in the helium. Franck and Knipping's experiments confirm Franck and Reiche's suggestion[14] that the abnormal coplanar helium atoms produced by such collisions are "metastable", and that they can only revert to the normal state by first undergoing ionisation, or in the presence of strong momentary disturbing fields such as those which would be generated by the formation of short-lived chemical combinations

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11. J. Franck and P. Knipping, Phys. Zeits. XX p.481 (1919)
12. F. Horton and A.C. Davies, Phil. Mag. November (1921)
13. J. Franck and P. Knipping. Zeits.f. Phys. i p 320 (1920).
14. J. Franck and O. Reiche, Zeits. f. Phys. i p 54 (1920).

between the metastable helium atoms and impurity atoms. This suggestion of Franck[8] and Reiche's follows from the hypothesis put forward by them, that the normal state of the helium atom corresponds to the unit quantum sharp series state of the crossed orbit system. In the metastable state, helium atoms bear some resemblance to hydrogen atoms because, to a first approximation, the nucleus and inner electron can be regarded as a singly charged nucleus alone, with respect to the outer electron. In this state, therefore, the atoms would, like hydrogen atoms, be capable of combining chemically with other atoms and also of forming He_2 molecules. In the absence of impurities the coplanar atoms resulting from the 20·4 volts electron collisions may either form He_2 molecules or remain in the abnormal state. According to Franck and Knipping, the forces generated by the formation of He_2 molecules are not sufficiently strong to enable the displaced electrons to return to their normal orbits, and hence, on their view, no radiation is obtained at 20·4 volts unless impurity is present.

The work of Paschen[15] who records the discovery that the line λ 10830 is a resonance line, while no such statement is recorded of the corresponding line λ 20582, is quoted by Franck and Knipping in support of their view. The lines λ 10830 and λ 20582 are the first lines of the helium and parhelium principal series respectively, and they therefore

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15. F. Paschen. Ann. der Phys. XLV p.625. (1914)

originate from the orbits to which the outer electron of the helium atom is displaced by collision with an electron having 20·4 volts and 21·2 volts energy respectively, and the fact that the line corresponding to the 20·4 volts orbit is a resonance line, is taken by Franck and Knipping as establishing the metastable character of this orbit.

In a recent investigation of the extreme ultra violet spectrum of helium, Lyman and Fricke[16] have detected a line at λ 585. This is the only line in this region which they definitely attribute to helium, and its frequency is connected by the quantum relation with the voltage 21·2.

The conclusions drawn by Franck and Knipping from the curves given in their paper are criticised in a recent paper by Horton and Davies,[12] who found that even in pure helium some radiation was obtained at 20·4 volts, though a much more intense supply was obtained at 21·2 volts. Moreover it was shown by these writers that the radiation produced as the result of 21·2 volts electron collisions, caused ionisation of something resulting from the 20·4 volts collisions, presumably abnormal atoms or He_2 molecules. It was not possible in the apparatus used for the investigation of ionisation and of radiation, by Horton and Davies, to obtain any conclusive evidence as to the production of He_2 molecules and it was thought that some light might be thrown on the subject by a

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16. H. Fricke and T. Lyman, Phil. Mag. XLI p.814. (1921)

careful study of the spectroscopic changes which might take place at the different critical voltages.

In addition to the critical voltages already mentioned, it has been shown both by Franck and Knipping,[11] and by Horton and Davies,[17] that further ionisation of helium takes place at about 80 volts, the exact values given by these investigators being 79·5 volts and 80 volts respectively. This increased production of ionisation is attributed to the removal simultaneously of both electrons from the helium atom. Horton and Davies have further shown that when an intense bombarding electron stream is employed there is an increased production of ionisation at 55 volts, due to the removal of the second electron from helium atoms which have already been ionised by previous electron collisions. This value is in fair agreement with the value 54·16 volts calculated from Bohr's theory as the energy required to ionise a positively charged helium atom. It would therefore be expected that under suitable conditions the enhanced lines of helium could be caused to make their appearance at these critical voltages. The frequencies of these lines are given by the relation $\nu = 4N\left(\frac{1}{n^2} - \frac{1}{m^2}\right)$ derived by Bohr, where ν denotes the frequency, N is Rydberg's constant and n and m are integers. The best known of the enhanced lines is λ4686, the first line of the Fowler series given in Bohr's notation by $\nu = 4N\left(\frac{1}{3^2} - \frac{1}{m^2}\right)$ where

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17. F. Horton and A.C. Davies, Phil. Mag. XXXIX p.592. (1920)

m may have any value from 4 to ∞ . In 1914, in an investigation of the electron energies required for the excitation of the helium spectrum, Rau[3] obtained evidence that the line λ4686 was produced at 80 volts but not at 75 volts. In a paper published while the present investigation was in progress, Compton, Lilly, and Olmstead[18] record the observation of this line as low as 55 volts, but never below this value, and they found that its intensity was much increased above 80 volts.

As the frequency of the line λ4686 is given by the equation $\nu = 4N\left(\frac{1}{3^2} - \frac{1}{4^2}\right)$ it is the line emitted when the second electron in an ionised helium atom falls from orbit 4 back to orbit 3, so that when the second electron in an already ionised helium atom is removed from its normal orbit to orbit 4, the atom will be in a condition to emit this line. The energy required to remove the second electron in such an atom to orbit 4 is given by $h\nu$, where $\nu = 4N\left(\frac{1}{1^2} - \frac{1}{4^2}\right)$, and h denotes Planck's constant. Therefore an electron would have to acquire the energy corresponding to a potential difference V, given by $h.\ 4N\left(\frac{1}{1^2} - \frac{1}{4^2}\right)/e$, or 50·8 volts, in order to be able to excite λ4686 by collision with a positively charged helium atom. The detection of the line λ4686 down to 50.8 volts as a lower limit, would serve to establish that the complete removal of the second electron from a helium atom is

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18. K.T. Compton, E.G. Lilly, P.S. Olmstead, Phys. Rev. XVI p 282 (1920)

not necessary for the stimulation of this line, and that it can be excited by the displacement only, of the electron.

The investigation of this point appears to the writer to be of some importance in view of the apparently contradictory evidence in existence as to the possibility of exciting a spectrum intermediate to the single-lined spectrum and the complete lined spectrum. The direct evidence on this point has shown that, in general, the single-lined spectrum is produced at the minimum radiation potential difference, and the complete lined spectrum when the ionisation potential difference is reached. In certain circumstances arcs have been obtained at voltages below the ionisation value,[19] and in these cases, the complete lined spectrum was produced. In the cases of zinc and cadmium, a second line has been observed at certain voltages intermediate to the respective minimum radiation and ionisation potential differences. The second line to appear was, in each of these cases, the first line of a series having the same limiting frequency as the series whose first term corresponded to the minimum radiation voltage, i.e. the first line of a series having the same limiting frequency as the series to which the single-lined spectrum belonged. These lines were observed by McLennan and Ireton[20]

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19. T.C.Hebb, Phys. Rev. IX p 371 (1917) and others.

20. J.C. McLennan and H.J.C.Ireton, Phil.Mag.XXXVI p.450 (1918)

who were led to the conclusion that mercury showed the same effect, though the second line was not actually observed in this case. In each of these instances, indirect evidence obtained from bends in the current-potential difference curves indicated the existence of two critical radiation potential differences connected by the quantum relation with the frequencies of the two lines observed before the complete lined spectrum appeared. In none of these instances were any of the higher lines of the two series, whose first lines correspond to the two radiation voltages, observed until the complete line spectrum was obtained.

Special attempts to detect the presence of higher terms of the series whose first and last frequencies correspond to the radiation and ionisation voltages respectively, before the complete lined spectnum appeared, were made by Foote and Meggers[21] in the case of caesium vapour. This vapour was selected for the reason that all the terms of this particular series lie in that part of the spectrum which can be readily photographed. Their experiments showed however no evidence of group or single series spectra between the single-lined spectrum and the conplete lined spectrum.

Indirect evidence that different lines do make their appearance at different voltages intermediate to that required for the production of the single-lined spectrum and that required for the complete lined spectrum, is however provided

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21. P.D. Foote and W.F.Meggers. Phil.Mag.XL.p.80 (1920)

by the recent work of Franck and Knipping[13] on helium, and of Franck and Finsporn[22] on mercury vapour. These investigators obtained a series of discontinuities in their current-potential difference curves at voltages intermediate to the minimum radiation and minimum ionisation values. In the case of helium, Franck and Knipping claim that their discontinuities correspond to the potential differences required to excite the successive lines of the series whose first term corresponds to 21·2 volts, and whose last term corresponds to the ionisation voltage, because by adding to 21·2 volts the potential differences corresponding to the successive terms of the parhelium principal series, i.e. the series originating from the 21·2 volts orbit, good agreement is obtained between the calculated values of the potential differences corresponding to the excitation of successive lines of this ultra-violet series, and their observed discontinuities. No discontinuities were obtained in Franck and Knipping's curves at the voltages obtained by adding to 20·4 volts the potential differences corresponding to the successive lines of the helium principal series, i.e. the series originating from the 20·4 volts orbit, and the absence of these discontinuities affords, according to Franck and Knipping, confirmation of their view as to the metastable character of the 20·4 volts orbit because their view involves that only lines in the infra-red, visible, and

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22. J.Franck and F. Finsporn, Zeits.f.Phys.ii.p.18 (1920)

long-waved ultra-violet, would be obtainable from displacements to orbits of the same system as the 20·4 volts orbit. These radiations, with the possible exception of the higher members of the series, would not give a photoelectric effect, and hence could not cause discontinuities in the current-potential difference curve. Franck and Knipping's curves therefore show only the discontinuities which would be expected if Franck and Reiche's suggestions were correct. It has, however, been shown in a recent theoretical paper by Kemble[23], that Franck and Reiche's identification of the normal state of the helium atom with the unit quantum sharp series orbit of the crossed system, does not lead to quite the same value for the ionisation potential difference as that which has been determined directly, and that it also is not in accordance with the recent observations of Lyman and Fricke on the extreme ultra-violet spectrum of helium. According to Kemble, the identification of the normal state with this particular orbit should lead to a line at λ 568 as the brightest line in the ultra-violet region of the helium spectrum and not to λ 585, the line recorded by these observers.[*]

In the case of mercury vapour some of the voltages at which discontinuities occur in the curves of Franck and

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[*] It has been shown (Horton and Davies, Phil. Mag. Nov. 1921) that the radiations which are emitted at the radiation potential differences (20·4 volts and 21·2 volts) can be absorbed and re-emitted by other helium atoms. This will cause a scattering of these radiations and might be expected to prevent them from being detected with a vacuum grating spectroscope. The absence of lines corresponding to these potential differences, in Lyman's early researches with helium, is therefore not surprising. On the contrary, Fricke and Lyman's recent detection of a line at λ585 (i.e. 21·2 volts), even with a grating of 97 cms radius, is so surprising as to leave a doubt as to whether the line can be a genuine helium line.

23. F.C.Kemble. Phil. Mag. XLII.p.123. (1921)

Einsporn have been identified with specified lines in the mercury spectrum but not all of them. These results of Franck and Knipping, and of Franck and Einsporn, appear to be in direct opposition to the results of Tate and Foote,[24] Mohler, Foote and Meggers[25] etc., who have shown in the case of so many of the metallic vapours, that only two types of inelastic collision occur (there are, however, three types in the case of mercury zinc and cadmium). The partial current method, employed by these investigators, for determining resonance potential differences depends largely upon the possibility of obtaining discontinuities at multiples of the minimum potential difference for inelastic collision, and it is difficult to reconcile the occurrence of these discontinuities at multiple points with the existence of a series of voltages at which new types of inelastic collisions occur.

As the lines corresponding to Franck and Knipping's discontinuities in helium all lie in the extreme ultra-violet region of the spectrum, the appearance of these lines one by one as the voltage is increased can only be tested spectroscopically with a vacuum grating spectroscope, and in the absence of such an instrument, the question as to whether it is possible to excite certain lines (other than the single

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24. J. Tate and W.F. Meggers, Phil. Mag. XXXVI p.64 (1918)

25. F.L.Mohler, P.D. Foote and W.F. Meggers. Bur. Stan. p.734. (1920)

line) without exciting all the lines of the helium and parhelium series, can only be investigated by determining whether any genuine difference exists in the voltages required for the excitation of different lines. Rau[3] records no such genuine difference and gives 24·5 volts as the minimum voltage at which he ever observed helium lines. Richardson and Bazzoni[4] on the other hand, came to the conclusion that a genuine difference of about 0.5 volt existed in the energies required for the excitation of λ4472 and λ5876, the latter line appearing at the lower voltage. A difference of 0.25 volt between the appearance of λ 4713 and λ 5876 is also recorded by them, λ 5876 being again observed before the other line. The lines λ 4472 and λ 4922 are recorded as appearing and disappearing together. The lowest voltage at which Richardson and Bazzoni ever observed the helium spectrum was 22·5 volts, this value being subject to a correction of not more than + 1 volt for the velocity of emission of electrons etc. Horton and Bailey,[5] and Compton and Lilly,[6] agree in concluding that no genuine difference exists in the energies required for the excitation of different lines of the same series or corresponding lines of different series, such slight differences as may have been observed being attributed to differences in the intensities of the different lines.

Table I gives the minimum voltages at which certain lines of the helium spectrum might be expected to appear if direct transitions, from the normal orbit to the orbit from which the electron has to fall to give rise to the particular line in question, were possible in each case. It is assumed that the helium principal series arises from the orbit to which an electron is removed at 20·4 volts, and that the parhelium principal series arises from the orbit to which an electron is removed at 21·2 volts. These numbers, therefore, form the basis for the calculation of the voltages given in the Table. It will be seen that the voltages in the Table are given to 2 places of decimals though the numbers which serve as the basis for their calculation are only given to one place of decimals. It is not claimed that the numbers are correct to the degree given in the Table but since any error which occurs is the same throughout, the figures are given to the second decimal place in order to show small differences. The lines are given in the order in which they might be expected to appear on the assumption made above. The letters s,p,d, are used in designating terms of the sharp, principal, and diffuse series of helium, and the letters S,P,D, for the corresponding series of parhelium.

TABLE I.

Wave length.	Series.	Exciting Voltages.
7066	2,p - m,s	23.29
7282	2,P - m,S	23,48
3889	1,s - m,p	23.58
5876	2,p - m,d	23.64
6678	2,P - m,D	23.65
5016	1,S - m,P	23,66
4713	2,p - m,s	24.16
5048	2,P - m,S	24.25
3188	1,s - m,p	24.28
4472	2,p - m,d	24.30
4922	2,P - m,D	24.31
3965	1,S - m,P	24.32
4438	2,P - m,S	24.59
4026	2,p - m,d	24.61
4388	2,P - m,D	24.62
4121	2,p - m,s	24.64
4169	2,P - m,S	24.77
4144	2,P - m,D	24.78
4024	2,P - m,S	24.87

Table II gives the corresponding voltages in the case of some of the lines, on the assumption that direct displacement from the normal orbit can only take place to principal series orbits, as is suggested by the discontinuities in Franck and Knipping's curves, but that there is no limitation of the possible transitions as the displaced electron returns to the normal orbit.

TABLE II.

Wave length.	Series.	Exciting Voltage.
3889	1,s - m,p	23·58
7066	2,p - m,s	"
5016	1,S - m,P	23.66
6678	2,P - m,D	"
7282	2,P - m,S	"
3188	1,s - m,p	24·28
5876	2,p -m,d	"
4713	2,p - m,s	"
3965	1,S - m,P	24·32
4922	2,P - m,D	"
5048	2,P - m,S	"
4472	2,p - m,d	24·60

All the other lines would require still higher voltages for their excitation.

According to Table I a difference of 0.66 volt should exist between the voltages at which λ 5876 and λ 4472 appear. This is a little higher than the difference recorded by Richardson and Bazzoni. The difference in the case of λ 5876 and λ 4713 should, according to the same table be 0.52 volt, which is double the difference recorded by Richardson and Bazzoni. Table II on the other hand, which is based on an assumption for which there appears to be more justification, gives differences which are smaller than those recorded by these observers. It is interesting to note that the second table predicts that the yellow line λ 5876 should not appear until 0.62 volt after the brightest green line λ 5016, a difference which should readily be detected in practice because of the approximately equal visibility of these two lines.

The difficulty of predicting accurately the voltages at which the lines of the enhanced system of helium might be expected to appear if the complete removal of the second electron from the atom is not necessary, clearly does not arise since it has been established that Bohr's theory is applicable to the system which gives rise to these lines. As has already been stated, the minimum voltage for the excitation of λ 4686 without the complete removal of the second electron from the atom is 50.8 volts, a value clearly distinguishable from the ionising voltage 54·16. More definite evidence regarding the possibility of exciting a spectrum intermediate to the single-lined spectrum and the complete lined spectrum may therefore be expected in the case of this line, than from any of the lines of the ordinary helium and parhelium series.

The following experiments were made to determine the minimum voltages at which lines of the ordinary serial systems, lines of the enhanced system, and lines of the band spectrum of helium, could be obtained under different conditions of gas pressure and electron current density, and to investigate also the changes in the spectrum at different electron energies, and the order of disappearance of the various lines under these different conditions, with a view to determining whether the association of the helium band spectrum with the He_2 molecule can be reconciled with the recent suggestions as to the production of the helium molecule, and also with a view to testing the possibility of the excitation of lines in the spectrum, other than the single line, without ionisation occurring.

DESCRIPTION OF APPARATUS ETC.

Two forms of apparatus were used to investigate the excitation of the helium spectrum, one being designed mainly with a view to detecting differences in the voltages required for the stimulation of different lines, and the other with a view to the obtaining of low voltage arcs. Several modifications of each form were used during the course of the experiments, as it was found necessary on several occasions to renew the filaments which supplied the bombarding electrons.

One of these two forms is shown in Fig 1. It was a three electrode apparatus of total length about 3 cm. and was arranged vertically between the pole pieces N and S. of an electromagnet which served to concentrate the luminosity into a bright column. The bombarding electrons were obtained from an incandescent lime-coated platinum filament. Two such filaments were arranged horizontally side by side as shown in Fig. 1 which represents a section of the apparatus at right angles to the filaments. The middle of each filament was 2 mm.above a circular gauze-covered hole H in the centre of a platinum disc which almost filled the cross section of the discharge chamber. This disc formed the top of a cylinder G of fine platinum gauze about 15 mm. long. The third electrode A was a circular platinum plate about 1 cm. in diameter which was fixed horizontally with its centre vertically below the centre of the hole H as indicated in the Figure. By maintaining G and A at the same potential, and controlling the energy of the bombarding electrons by means of a potential difference applied between F and G, it was arranged so that these electrons suffered no change of velocity throughout the space viewed by the spectroscope except that resulting from collisions with helium atoms. The apparatus was arranged so that the lengths of the filaments were at right angles to the plane of the slit of the spectroscope. In this way the maximum concentration of luminosity was obtained in line with the axis of the collimator of the spectroscope. This arrangement was adopted with all the forms of apparatus used.

In one of the modifications of the form of apparatus already described, the anode A was dispensed with. The gauze cylinder G was, however, closed at the bottom as well as at the top with a platinum disc with a gauze-covered hole, this hole being vertically beneath the other. Two parallel filaments were used, one 2 mm. above the upper disc, and the other 2 mm. below the lower disc, the middle of each filament being in the same vertical line as the holes. The two filaments were heated simultaneously by independent insulated heating circuits and their two negative ends were connected together and to the negative end of an insulated battery, whose positive terminal was connected to the electrode G. The maximum velocity with which electrons could enter the space bounded by the gauze cylinder, for any given value of the applied potential difference, was thus the same from whichever filament the electrons originated. It was thought that this particular arrangement might have special advantages in the investigation of the minimum voltage for which the line λ 4686 could be produced from atoms which had already been ionised by previous collisions because the supply of bombarding electrons from two directions simultaneously might facilitate the occurrence of collisions between electrons and ionised helium atoms. In practice, however, the simultaneous use of both filaments was of no advantage and the forms of apparatus finally adopted was that shown in Fig 1.

In the other form of apparatus, designed primarily for the investigation of low voltage arcs, filaments of fine tungsten wire were employed to supply the bombarding electrons. The apparatus was fitted with three filaments so as to avoid delay when one of them burned through. Fig. 2 shows the arrangement of the electrodes in the modification of this form of apparatus which was eventually found to be most suitable, the section being in a plane at right angles to the lengths of the filaments, which were all parallel to one another. The three filaments F_1, ~~and~~ F_2, and F_3, were sealed as shown into a spherical glass bulb of about 3.5 cm. radius. The anode A was a hollow platinum sphere about 1 cm. in diameter, rigidly attached by a stout platinum wire B to the soft iron piece C. The wire L was connected with the sphere by means of a strip of platinum foil about 2 mm. wide. The soft iron piece C fitted loosely into the side tube D of the enclosing glass bulb and by means of an electromagnet it could be moved to different parts of this tube, thereby enabling the distance of the anode from the filaments to be varied over a range of about 2 cm. A limit to the forward motion of the anode was provided by a constriction E in the tube D, which just prevented it from touching the filament F_1.

The helium used in these experiments was freed from hydrogen by means of oxide coated copper spirals which were electrically heated in it to about 500° C for a fortnight. During this time a slight excess of electrolytic oxygen was maintained in the helium and the copper spirals were replaced when they burned through. The excess of oxygen, together with any other impurities, was removed from the helium by allowing it to stand for several hours over charcoal cooled in liquid air, before admitting it to the storage bulb. From this bulb it was allowed to enter the apparatus from time to time by opening a stopcock. The helium passed from the storage bulb down a fine capillary tube, entering the apparatus through a U-tube containing carbon cooled in liquid air. The two forms of apparatus were connected independently by side tubes to the carbon purifying tube through which the helium entered, and annother tube from the arcing apparatus led through a stopcock to the pumps and pressure gauge and to a long vertical tube, about 3 cm. in diameter, containing mercury. By varying the level of the mercury in this tube the pressure of helium in the apparatus could be varied.

All the platinum electrodes used were boiled for several days in strong nitric acid before being sealed into the apparatus. Before beginning the experiments, the apparatus was

pumped out by means of a mercury vapour pump, and the residual gas was removed as completely as possible from the electrodes and the glass by prolonged heating and pumping. Mercury vapour from the pump and pressure gauge was prevented from passing over into the apparatus by a U-tube immersed in liquid air, on the far side of the stopcock which served to cut off the apparatus from the pumps etc. when this was desired.
A Hilger wave length spectrometer was employed for the examination of the spectrum and voltages were read on a high resistance voltmeter which was connected directly to the negative end of the filament and to the anode throughout the observations. The first appearance of the different lines, as the energy of the electrons was gradually increased, was investigated both visually and photographically. In order to investigate any connection that might exist between discontinuities in the current-potential difference curves and the appearance of a new line or group of lines in the spectrum, the currents between the electrodes were measured at the same time as the visual observations of the spectrum of the luminosity were made.

For the photographic investigation of the green, blue, or violet regions of the spectrum, Wellington Speedy plates were used, but when it was desired to include the red end of the spectrum in the investigation, Wratten Panchromatic plates were employed. For the investigations of λ 4686 Wellington Speedy plates were used, as these were found to give satisfactory results for considerably shorter exposures than the

Panchromatic plates.

The E.M.F. in the circuit was supplied by a 110 volts storage battery, the potential difference across the discharge and the current through it being regulated by means of series and parallel resistances. The currents between the electrodes were read on a Weston milliammeter provided with shunts, which was placed in series with the discharge tube. A small fuse made of a strip of tin-foil was used in series with the discharge tube to prevent too large currents from passing. In investigating the minimum voltages at which the helium series lines could be stimulated, a potentiometer arrangement, by means of which the potential difference across the discharge tube could be varied in steps of one tenth of a volt, was employed, and no resistance was used in parallel with the discharge tubes.

The potential differences read on the voltmeter were all subject to a correction to allow for the velocity of emission of electrons from the filament, etc. This correction was estimated in each case from the position of the ionisation bend in the current-potential difference curves, and it has been taken into consideration in the curves given and in the critical values stated.

During all the observations the carbon tube through which the helium was admitted to the apparatus was immersed in liquid air. In spite, however, of this and of all the other precautions taken to secure the purity of the helium used in these experiments, the presence of certain spectrum lines, other than those belonging to helium, was detected on some occasions. Of these lines the hydrogen line H_β was the most persistent. This line was nearly always observed when the band lines were present, and in intense arcs, H_α and H_γ could sometimes be detected as well as H_β. This latter line could sometimes be seen even when the band lines were not present. It was always most clearly visible in the part of the discharge in which the helium band spectrum was most intense. No lines were ever detected visually or photographically before the helium lines appeared.

It seems probable that the hydrogen originated from the bombardment of the glass walls and metal parts of the apparatus, since, in view of the special steps taken to remove this gas from the helium used, it is exceedingly unlikely that it was admitted with the helium. An effect which was observed when the platinum filament apparatus was being employed seems to confirm this suggestion. The slit of the spectroscope was so arranged as to enable the luminosity produced between the filament and the second electrode to be observed at the same time as the luminosity produced in the space bounded by this latter electrode and the anode. Spectrum lines were first seen when the ionisation potential difference was reached. The luminosity between the second electrode (the grid) and the anode did not increase greatly in intensity as the potential difference was increased beyond the ionisation value, but the luminosity between the filament and the grid became very brilliant. On increasing the potential difference still further a sudden change in the distribution of the luminosity took place without there being any discontinuous change in the current-potential difference relations. The glow between the filament and the grid diminished in intensity and a brilliant discharge occurred between the back of the filament and the upper glass wall of the apparatus. This glow was at first much yellower in colour than the glow between the filament and the grid, but became bluer on further increasing the potential difference. The slit of the spectroscope was adjusted so that these two discharges could be observed simultaneously. Before the glow between the filament and the glass was present, the hydrogen line H_β could not be detected in the brilliant discharge between the filament and the grid, but immediately the redistribution of luminosity occurred this line was quite clearly seen in <u>both</u> parts of the field of view, even though the glow between the filament and the grid was reduced in intensity. On decreasing the potential difference the changes occurred in the reverse order and H_β disappeared suddenly when the glow behind the filament vanished. This makes it appear probable that the hydrogen was produced from the glass walls under the electron bombardment.

In one or two instances at the highest pressures used, it was observed that certain of the bright lines in the red and orange, which were present when the helium band spectrum was very intense, appeared to coincide in position with certain of the brightest lines of the neon spectrum. The results obtained in the exceptional instances when this was the case, were in no way different from the results obtained when these lines were not observed. In certain circumstances the mercury line λ 5461 was seen. The particular conditions under which the line was observed are given in detail later in the paper.

THE EXCITATION VOLTAGES FOR THE LINES OF THE HELIUM AND PARHELIUM SERIES UNDER DIFFERENT CONDITIONS.

The investigation of the minimum voltages at which different lines of the ordinary helium and parhelium series could first be detected, as the potential difference was gradually increased, led to the conclusion that there is no genuine difference in the electron energy required for the excitation of different lines of the same series, or corresponding lines of different series, and it thus indicates that the occurrence of ionisation of the helium atom is essential for the production of any of these lines. In many instances the lines made their appearance very suddenly as the energy of the bombarding electrons was increased, and there was a simultaneous discontinuity in the current-potential difference curve, signifying a marked increase of current. In other instances the lines were seen very faintly at first, and they gradually grew brighter as the electron energy was further increased. On these occasions the yellow line λ 5876 was generally seen one or two tenths of a volt, and the green line λ 5016 about one tenth of a volt, before the other lines. That this does not signify that the stimulation of these lines requires less electron energy than that required for the excitation of the other lines was shown by observation of the order of disappearance of the lines with decreasing potential difference when, as was possible in certain circumstances, this could be backed to 20.4 volts before the lines vanished. When the lines disappeared without there being a marked discontinuity in the current-potential difference curve, the lines λ 5876 and λ 5016 remained visible for one or two tenths of a volt after the other lines had vanished. It has been shown in the introduction that there seems to be reason for the view that the helium and the parhelium principal series, respectively, originate from the orbits to which an electron in a helium atom is removed as the result of 20.4 volts, and 21.2 volts, electron impacts. If this is the case, the values given in Table I are the minimum voltages at which the respective lines could possibly be excited as the result of single electron impacts. Any limitation of possible electron displacements, such as that which is the basis on which Table II is drawn up, results in higher voltages than the corresponding values in Table I, being required for the excitation of the various subordinate series lines of both the helium and the parhelium systems. All of the voltages in Table I are greater than 23 volts, so that when lines of the helium spectrum are detected as low as about 20.4 volts, their presence cannot be due to the displacements of the electrons within the atoms, by single electron impacts, ~~without ionisation occurring~~. They must therefore be due to the cumulative effects of two or more electron impacts, and such cumulative effects would produce ionisation. ~~so that the lines in such a case result from the~~

~~occurrence of ionisation.~~ Since the order of disappearance of the lines, when their presence is known to be due to ionisation, is the converse of the order of their appearance at higher voltages as the potential difference is gradually increased, it is concluded that the detection of λ 5876 and λ 5016 before the other lines, in a few instances, is due to the fact that these lines are two of the brightest lines in the visible spectrum of helium at low voltages, and that it does not indicate any difference in the energy required for the excitation of different lines.

The curve in Figure 3 shows how the current-potential difference relations varied during one series of visual observations when the spectrum lines did not all appear simultaneously. From the curve it may be seen that a discontinuous change occurred when the potential difference was increased after the reading at 25.8 volts. The potential difference increased slightly for an instant and then dropped suddenly to 20.4 volts, the current meanwhile being increased fivefold. After this discontinuous change had occurred, all the lines of the ordinary helium and parhelium series, which fall in the visible part of the spectrum, were quite brilliant. The lines λ 5876 and λ 5016 could, however, be seen faintly at 25.4 volts, i.e. two of the voltage steps before the discontinuity occurred. The other lines became visible for voltages between 25.4 volts and 25.8 volts, for they could all be seen faintly at the latter voltage. After the discontinuity, the current in the discharge could be made to vary very considerably without any change occurring in the potential difference across the tube. When the current had been reduced to about 5 milliamperes, there was an abrupt decrease to 0.28 milliampere with a simultaneous increase in the potential difference and a disappearance of all the lines. This particular series of observations was taken with the tungsten filament apparatus, the distance between the anode and the cathode being 2 mm., and the pressure of helium in the apparatus being 25 mm.

The values of the minimum voltage at which lines were first seen as the potential difference was gradually increased, and the voltage at which they disappeared as the potential difference was backed, varied very considerably in different experiments. The various instances, however, all come under the following classification.

I. Those cases in which the voltage had to be increased to some value above the ionisation voltage, 25.2 volts, before lines could be seen, and in which the potential difference could not be backed below 25.2 volts without all the lines disappearing.

II. Those cases in which the lines became visible at 25.2 volts, and disappeared, as the voltage was backed, at some value of the voltage between 25.2 volts and 20.4 volts, the latter voltage being the lowest value to which it could be backed without the lines disappearing.

III. Those cases in which the lines became visible for values of the potential difference between 20.4 volts and 25.2 volts, and in which they disappeared at some value between the same limits as the voltage was backed. In some cases the lines could be maintained at potential differences as low as 13 - 14 volts. In such cases it was not possible to go on reducing the voltage until the lines vanished at some potential difference lower still, because the voltage reached a minimum value and began to increase again while the lines were still present.

Although the three classes themselves are quite distinct, the line of demarcation between the conditions which will give one class of result and those which will give the next class of result is not sharp. Moderate intensity of electron emission combined with a gas pressure of not more than 1 mm. may be given as a general summing up of the conditions which lead to results of class I. By making either the electron emission or the heating current sufficiently low, results of this class were obtained however much the other factor was increased, and in the extreme case no lines were seen at all up to the highest voltages tried. (150 volts).

Results coming under Class II were obtained for rather higher values of the pressure and filament temperature than those which led to results of Class I, and results of Class III. at still higher pressures (above about 10 mm.) and for very high filament temperatures. The pressures which have been given as dividing one class from the next are however only approximate, for the change from Class I to Class II, or from

Class II to Class III, could frequently be effected by varying the intensity of the emission alone. For instance, on first using the lime coated filaments of the apparatus shown in Fig.1, currents of 25 - 30 milliamperes were obtained, and a bright glow, whose spectrum showed all the ordinary helium lines, was seen when the electron energy had been increased to about 21 volts. Plate I is a photograph of the spectrum of the glow taken with 22.25 volts between the electrodes, and with a current of 20 milliamperes passing. The exposure given was one hour and the brightest lines of the helium spectrum are shown clearly. After the filament had been run for about six hours, the maximum current that could be obtained was 3 milliamperes, and all attempts to excite the lines below 25 volts were unsuccessful, judging from visual and photographic tests. This shows that the more intense electron bombardment caused ionisation to occur, by cumulative effects, below the normal ionising voltage. The pressure at which this effect was observed was about 4 mm.

The curves given in Figures 4 and 5 are examples of the current-potential difference relations for cases coming under Classes II and III respectively. These two series of observations were taken at the same pressure, 19 mm, but the filament temperature was much higher for the series recorded in Fig.5. than for that recorded in Fig.4. The continuous curve in Fig.4 gives the variations of the current as the potential difference was gradually increased. It may be seen that a marked increase of current occurred at 25·6 volts. When this increase had taken place lines of the helium spectrum were seen for the first time, all of the brighter lines being easily visible. The curve drawn with a broken line gives the corresponding values of the current as the potential difference was decreased. These curves show that the current-potential difference relations were not reversible between 25·6 volts and 20·4 volts, for the decrease in the current, with gradually decreasing voltages, did not occur until 20·4 volts. Lines of the helium spectrum remained visible until the drop occurred but no lines were seen after this had happened.

From the corresponding curves in Fig.5, it may be seen that, for gradually increasing values of the potential difference, an abrupt increase of current occurred just after 22·7 volts (the voltage then falling to 21, and the current increasing from 0·3 milliampere to 2·8 milliamperes) and that an abrupt decrease in the current occurred just below 20·7 volts for decreasing values of the potential difference. The current and voltage did not at once attain their final values after the discontinuity, for, in the case of the increasing voltages, the current continued to increase slowly and the voltage to decrease slowly for a few seconds after the main part of the change had occurred. When the decrease occurred, the current fell from 3·1 milliamperes to 0·27 milliampere and the voltage increased to 20·9 volts. For increasing values of the potential difference, lines were first seen while the increase of current was occurring, the line λ 5876 being detected at the stage marked on the curve. All the lines of the helium and parhelium series, in the visible region of the spectrum, could be seen by the time the discontinuous change was complete. Conversely for decreasing values of the potential difference, the lines were seen at 20.7 volts, before the drop in the current occurred, but could not be seen afterwards.

In the two series of observations recorded in the figures just described, the lines were first seen when a marked discontinuity in the current-potential difference curve took place. This was not always found to be the case, however, for on several occasions the lines were first seen when no marked discontinuity in the curve took place. In the cases which come under Class I in particular, the lines were seen very faintly at first and they gradually brightened as the potential difference was increased, without any big change of current occurring in the current-potential difference relations.

It has already been pointed out that the failure to detect certain lines definitely before certain other lines, indicates that the occurrence of ionisation is essential for the production of lines of the ordinary helium and parhelium series. Therefore the fact that in cases belonging to Classes II and III, lines have been observed well below 25.2 volts, the normal ionising voltage, must mean that ionisation of the helium by cumulative effects occurs in these cases. The marked discontinuity in the current-potential difference relations, which occurs simultaneously with, or shortly after, the first detection of spectrum lines, in these cases, is presumably caused by the increase of electron current resulting from the neutralisation of the space charge of the emitted electrons, by the positive ions produced by ionisation of the helium. In cases belonging to Class II, lines are not seen below the normal ionising voltage for increasing values of the potential difference, because the amount of ionisation occurring below this voltage is very small until the space charge has been neutralised and the electron current increased. The increase in the electron current causes an increase in the supply of ionisation by cumulative effects. This decreases as the potential difference is backed but so long as there is a sufficient number of positive ions to maintain the neutralisation of the space charge, the increased ionisation by cumulative effects remains and spectrum lines are seen, and hence the limit for the disappearance of lines as the potential difference is backed lies between 25.2 volts and 20.4 volts. In cases belonging to Class III the amount of ionisation by cumulative effects, which occurs after the radiation potential difference, 20.4 volts, is passed but before 25.2 volts is reached, is sufficient to bring about the neutralisation of the space charge of the emitted electrons and hence to cause the spectrum lines to appear quite brightly before the normal ionising potential difference is reached.

The maintaining of the lines down to about 13 volts or 14 volts was only possible when the reduction of the potential difference was brought about in a certain manner. The following are the different ways in which the potential difference across the discharge tube was varied on different occasions:-

1. By varying the series resistance.
2. By varying the resistance in parallel with the discharge tube.

3. By varying the heating current through the filament. When the reduction was effected by varying the resistance in parallel with the discharge tube, the potential difference could not be reduced below 20.4 volts without the current decreasing considerably, and the lines disappearing. Lowering the potential difference by either of the other methods made it possible to maintain the lines below 20.4 volts. Whichever of the two methods was used, however, the voltage could not be backed indefinitely, for it ultimately reached a minimum value, and all subsequent attempts to cause a further reduction resulted in a gradual increase of the potential difference across the discharge tube, and a gradual decrease in the current through it. The relative intensities of the different series lines, at the same potential difference before and after the minimum value was passed, were not the same. The difference is shown by the two last columns of Table III. The two left hand columns give the wave length and series of the observed helium and parhelium series lines, and the third column gives their intensities, as judged from visual observations, at 19.0 volts, before the minimum value of the potential difference was reached. The right hand column of the Table gives the intensities of the same lines at 19.0 volts after the minimum value was passed.

TABLE III.

λ	Series.	Intensity (before)	Intensity (After)
7066	2,p - m,s	5	1
6678	2,P - m,D	15	3
5876	2,p - m,d	20	8
5048	2,P - m,S	3	3
5016	1,S - m,P	15	4
4922	2,P - m,D	10	0·5
4713	2,p - m,s	10	0.5
4472	2,p - m,d	15	3

Lines of the helium and parhelium series further in the violet than λ4472 could not be seen in either case, though photographs of the spectrum of the luminosity maintained below 20·4 volts, but before the minimum value of the potential difference was reached, showed that lines further in the violet were present. A photographic comparison of the more violet part of the spectrum in the two cases for which a comparison of the visible part of the spectrum is given in Table III, could not be obtained, because owing to the high temperature at which the filament had to be maintained in order to attain a potential difference of 19·0 volts after passing the minimum value, the discharge could not be left running continuously for the time of exposure necessary to obtain a photograph.

Since the lowest potential difference at which the helium and parhelium series were ever excited (as distinct from maintained) was 20·4 volts, the maintenance of the lines below 20·4 volts must be due to the presence of atoms which are in an abnormal, (more easily ionisable), condition. The number of atoms which are in this condition must remain constant for no new ions or abnormal atoms can be produced from normal helium by electron bombardment below 20·4 volts, and the fact that the luminous discharge was maintained for long periods, at voltages below 20·4 volts, shows that there was no gradual reduction in the number of ionisable atoms present. Therefore when the lines are maintained at low voltages, the frequency of electron collisions with helium atoms must be such that, on recombination occurring, the returning electron is unable to fall right back to the normal orbit before being ejected again by another impact. The current through the discharge tube must in these cases be carried entirely by electrons, for if any of it were carried by helium ions, the number of these would diminish with time and the glow would not be maintained. The electron current measured in these circumstances is not, however, the value of the electron emission which would normally be obtained for the given values of the heating current and the potential difference, because though none of the current is carried by positive ions, there must always be a certain number of positive ions present and these will suffice to neutralise the space charge of the emitted electrons. As the heating current is increased, the electron current may continue to increase up to a certain stage, and the potential difference to decrease, but this will not continue indefinitely. A limit will be imposed by the fact that the greater the electron emission, the more frequent the encounters between positive ions and electrons become, and therefore the shorter the interval between ionisation and recombination becomes. This reduction in the period of existence of the positive ions ~~as such~~ may ultimately reduce their efficiency in neutralising the space charge of the emitted electrons, and may result in a reduction of the current through the discharge tube and consequently in an increase of the potential difference across it. This explanation accounts not only for the variation in the current-potential difference relations with increase of heating current, when the luminous discharge is maintained below 20.4 volts, but also for the fact that those changes are reversible.

When the reduction of the potential difference across the discharge tube is effected by increasing the series resistance, there is a simultaneous reduction in the current through the circuit without a corresponding reduction in the emission from the filament, so long as the temperature of this is constant. Therefore the density of the cloud of electrons round the filament increases as the series resistance is increased, whereas the number of positive ions does not increase. Moreover the frequency of encounters between positive ions and electrons, in the neighbourhood of the filament, increases as the density of the cloud increases, and ultimately the efficiency of the positive ions in neutralising the space charge is reduced as in the other case, and the resistance of the discharge, and therefore the potential difference across the tube, begin to increase.

Since, on these views, the fact that the lines can be maintained below 20.4 volts indicates that it is possible to prevent the abnormal atoms from reverting to the normal condition, by sufficiently increasing the frequency of their encounters with electrons, it might be expected that by increasing the frequency of bombardment still more, electrons would not only be unable to return to the normal orbit, but would also be prevented from returning to the 20.4 volts orbit and the 21.2 volts orbit. If this stage were reached and electrons could not fall back to either the 20.4 volts orbit or the 21.2 volts orbit, the helium and parhelium principal series lines would disappear from the spectrum, and only the 1st and 2nd helium and parhelium subordinate series would remain. The fact that the line λ 5016 of the parhelium principal series, appears in the spectrum of the luminosity for both the cases given in Table III, shows that the stage when the electrons are prevented from returning to the 21.2 volts orbit, had not been reached in the case when the potential difference had been increased to 19.0 volts after passing the minimum value. (13.5 volts). None of the lines of the helium principal series are in the region of the spectrum in which they could be detected visually if they were of feeble intensity. The first line of this series, λ 10830, is in the infra red region, and the second line, ~~is~~ λ 3889, is a little too far in the violet to be of great visibility. Therefore, as it was not possible to obtain photographs after passing the minimum value of the potential difference in any series of observations, no definite statement regarding the disappearance of the helium principal series lines can be made.

There seems to be no reason for regarding 13 - 14 volts as a definite minimum potential difference for the maintenance of lines of the helium and parhelium series. This value was the lowest obtained in the present research, but as a knowledge of the ultimate minimum was not thought to be an essential for the objects of the present investigation, no special efforts to maintain the lines at still lower voltages were made.

THE MINIMUM EXCITATION VOLTAGE FOR THE LINE λ4686, OF THE ENHANCED SERIES, UNDER DIFFERENT CONDITIONS.

Under different sets of conditions three distinct different limits were found for the minimum voltage at which λ 4686 could be obtained. These limits corresponded to the three different critical voltages 80 volts, 54·16 volts, and 50·8 volts. The first of these is the potential difference through which an electron must have fallen to acquire the energy which is necessary to enable it to remove both electrons simultaneously from a helium atom, on collision with it. The second is the potential difference corresponding to the removal of the remaining electron from a helium atom which has lost one electron by a previous collision, while the third critical voltage corresponds to the energy which must be imparted to such a helium atom to remove the remaining electron to orbit 4, i.e. the orbit from which it has to fall to cause the emission of the line λ 4686.

A value at about 80 volts as the limit for which λ 4686 could be detected visually or photographically, was obtained when the pressure of helium was about 1 or 2 mm. At rather higher pressures, a limit at 80 volts for the appearance of λ4686 was only obtained if the electron current density were not too high. With intense electron streams at these pressures, λ 4686 could be detected down to a voltage as low as 54 - 55, and in such a case, the potential difference across the discharge tube could not be increased to 80 volts or beyond without endangering the life of the filament. When the conditions of pressure and electron current density were such as to make it possible to detect λ4686 at voltages in the neighbourhood of 55, the lines of the helium band spectrum were always visible, whereas under the circumstances in which 80 volts was obtained as a lower limit for which this line was excited, these lines were faint and in some instances were definitely not detectable at all. The photographs in Plates II and III illustrate this difference in the appearance of the spectrum in the two cases. Both of these photographs were taken using the platinum filament apparatus. In the case of Plate II the potential difference across the discharge tube was 96 volts and the current carried varied from 2 milliamperes to 5 milliamperes during the exposure. λ4686 could not be seen below 80 volts under these conditions. In the case of Plate III the potential difference varied from 55 volts to 60 volts during the exposure of the plate, and the current across the discharge tube varied from 25 - 35 milliamperes. The line λ4686 can be detected in both of these photographs, though in Plate III it is not quite so readily seen as in Plate II owing to the presence of the band lines. One of the lines in the tail of one of the bands is at λ4685, but as the part of the field of view in which the band spectrum was brightest was not the part of the field of view in which the enhanced line λ4686 showed up most plainly, it was possible to distinguish the enhanced line λ4686 from the band line λ 4685. This is illustrated by Plates III and IV the latter of which is a photograph with only 42 - 46 volts across the discharge tube. In Plate III λ 4686 stands out well from among the band lines in the part of the photograph in which these are least intense, while in the corresponding part of the photograph in Plate IV there is no line in this position standing out from among the others. Plates II and IV were both taken in helium at a pressure of about 5 mm. of mercury and the time of exposure was 20 minutes in each case, the difference being that in obtaining the photograph in Plate IV the filament was at a considerably higher temperature than in obtaining that of Plate II. The current through the discharge tube in the case of Plate IV was 33 milliamperes, i.e. six and a half times the maximum current in the case of Plate II. The difference in these two photographs, and also the difference between Plates II and III, corresponds to a definite difference in the current-potential difference conditions with respect to a discontinuity in the current-potential difference curve, which can best be explained by reference to the curve given in Fig.6. This curve, whose two sections are drawn on different scales, shows two discontinuities, one between 22 and 23 volts, at which stage the helium and parhelium series lines made their appearance, and another between 44 and 45 volts. It was at this second discontinuity that the band lines appeared prominently. There was also a marked change in the appearance of the luminosity, observed directly, when this second discontinuity took place, the glow assuming the form of a brilliant arc and becoming more purple in colour.

The increase in the current through the discharge tube, and the decrease in the potential difference across it, were sometimes even more marked than in the case given in Fig.6. The voltage at which the second discontinuity occurred did not have any fixed value but depended upon the pressure of helium and on the intensity of the electron stream, being higher at low pressures and for less intense bombarding streams. At the highest pressures used, 25 mm. to 36 mm., it occurred at the same potential difference as the first discontinuity, and the line spectrum and the band spectrum then made their appearance together. The photograph shown in Plate II was taken when only a small second discontinuity in the current-voltage relations had occurred, while the photograph shown in Plate IV was taken after a marked discontinuity had occurred. The change from the conditions of Plate II to those of Plate IV was effected by increasing the temperature of the filament while the E.M.F. in the circuit remained constant. At a certain stage, as the temperature was raised, the potential difference across the arc dropped abruptly by about 40 volts and on further increasing the heating current, it fell a little more but ultimately reached a minimum.

In a large number of visual observations under conditions similar to those in which Plates III and IV were taken, the potential difference at which λ4686 was first seen to stand out from among the band lines, in the manner shown in Plate III, was found to be between 54 volts and 55 volts, indicating a limit at the critical voltage for the further ionisation of the helium positive ion. Attempts were made to obtain a photographic record of this value as a limit for the excitation of λ 4686, by taking a series of photographs at intervals of 1 volt from 51 volts up to about 58 volts, but owing to the difficulty of maintaining the potential difference across the discharge tube constant during the interval of exposure of the plate, such a photographic record was not obtained. It was always found that when the discharge was in a condition corresponding to some part of the current-potential difference curve, after the second discontinuity had occurred, slight fluctuations in the current and the potential difference took place if the discharge were left passing for any length of time. In all the photographs given in this paper the potential difference across the discharge tube was kept adjusted by continuous watching of the voltmeter and adjustment of the heating current, and when fluctuations could not be avoided the highest reading of the voltmeter during the taking of the photograph is recorded. Plate V is one of the same series of photographs as Plate III in one of the attempts. During the exposure for this photograph the potential difference was for the greater part of the time between 51 volts and 53 volts but once or twice it flashed up to 55 volts for a second or two. A comparison of these two photographs shows that the line λ 4686 was definitely present in the case where the potential difference was above 55 volts throughout, while the line was very much fainter, if indeed it was present at all, in the circumstances of the other photograph.

At still higher pressures and with intense electron streams, λ4686 could first be seen to stand out from the band lines when the potential difference across the discharge tube was adjusted to about 51 volts. In these cases the band lines were even more intense relatively to the helium and parhelium series lines than in the photographs given. It was found however, that for both increasing and decreasing adjustments of the potential difference, λ 4686 could be seen to stand out distinctly from the others, as in Plate III, when the potential difference was above 50.8 volts. The difficulty lies rather in deciding whether λ 4686 was ever present below 50·8 volts or not, than in detecting its presence in certain instances at this voltage, for of its presence at 50.8 volts, and above, there was no doubt. All that can be said is that attempts to see λ 4686 below 50.8 volts were unsuccessful. At the highest pressures tried, i.e. from about 20 mm. to 36 mm., the enhanced line λ 4686 was never observed at all. At these pressures it was generally found that if the temperature of the filament were such as to make it possible for a discontinuity in the current-voltage relations to occur at all, the drop in the potential difference across the discharge tube was so large as to make it impossible to raise the potential difference across the discharge to more than 40 volts, at least for more than a second. The effect of altering the various possible adjustments, in an attepmt to increase the potential difference to 51 volts, was either to vary the current without appreciably altering the potential difference, or to cause the discharge to change its character and to revert to a stage corresponding to a point in the curve before the discontinuity had occurred. In the few instances, at these high pressures, in which the potential difference was maintained at about 55 volts for a second or two, λ4686 was not seen. This result is in accord with that of Compton, Lilly, and Olmstead[18] who failed to excite the enhanced lines at any voltage used at pressures above 10 mm.

If 50·8 volts is a genuihe limit for the excitation of λ4686, it may be concluded that the line can be stimulated without further ionisation of the helium positive ion taking place. If, however, λ4686 ~~could~~ can be obtained for voltages lower than 50·8, this conclusion is not justified. It has been shown in the case of the lines of the helium and the parhelium series that these can be excited at voltages intermediate to the ionisation voltage, 25·2 volts, and the minimum radiation voltage, 20·4 volts, this latter value being a limit for their excitation. The corresponding theoretical value in the case of the enhanced lines would be 40·62 volts, as this value corresponds to the energy necessary to produce the fundamental displacement of the remaining electron in an already ionised helium atom, i.e. it is the voltage corresponding to the frequency given by $\nu = 4N\left(\frac{1}{1^2} - \frac{1}{2^2}\right)$. Therefore if λ 4686 could be detected at voltages between 50.8 and 40·62, it would be concluded that ionisation of the helium positive ion was occurring as the result of cumulative effects. It has already been stated that no evidence of the presence of λ 4686 below 50·8 volts was obtained, so that the results of the present research indicate that the detection of λ 4686 between 55 volts and 50·8 volts does not result from ionisation of the helium positive ion by cumulative effects, but from single electron impacts on helium positive ions without the occurrence of further ionisation.

Since the helium positive ion can be stimulated to the emission of the line λ 4686 in this way, it would be expected that when the second electron within a helium atom is disturbed by the same impact as that which removes the outer electron from the atom, λ 4686 could still be excited without the further ionisation of the atom, i.e. that it might be excited at voltages between 76 and 80, when it could not be stimulated at lower voltages. This question was investigated, but it was found extremely difficult to arrive at any final conclusion because, in the instances when λ 4686 was observed below 80 volts, the possibility that its presence was due to the further ionisation of a helium positive ion, by a 54·2 volts electron collision, could not be ruled out. Attempts were made to obtain a series of photographs, at intervals of 1 volt, from 71 volts up to about 78 volts, but here again the question of fluctuations was a difficulty, because when λ4686 could be seen between 70 and 80 volts, the discharge was always in the stage immediately preceding the large second discontinuity in the current-potential difference relations, and frequent changes in the current and potential difference occurred.

THE MINIMUM EXCITATION VOLTAGE FOR THE LINES OF THE HELIUM BAND SPECTRUM.

Some reference has already been made in the last section to the presence of the band spectrum of helium in certain circumstances. A more complete account of the conditions under which it was seen is given in the present section. The helium band spectrum was not always excited when the lines of the ordinary helium and parhelium series were stimulated, though the minimum voltage at which lines of these series were ever excited, 20.4 volts, was identical with the minimum voltage at which lines of the helium band spectrum were first seen as the potential difference was gradually increased. Moreover, in the instances when it was found possible to lower the potential difference across the discharge tube to between 13 volts and 14 volts, and yet to maintain the helium and parhelium series lines, the brightest lines of the band spectrum could also be seen down to the same voltage. Photographs showing the presence of the band spectrum at low voltages are given in Plate VI. A and B were taken on a Wellington Speedy plate, the time of exposure being 65 minutes for A and 80 minutes for B. C and D in Plate VI were taken under conditions were identical with those for A and B respectively, but on a Wratten Panchromatic plate, the times of exposure being the same as for A and B respectively. The potentential difference across the discharge tube for the photographs A and C was 21 volts, and for B and D it was 14 volts, with an occasional fluttuation up to 16 volts. An immediate readjustment to 14 volts was made every time a fluctuation occurred. The photographs show the bands in the blue and green regions of the spectrum quite distinctly, even when the potential difference across the tube was only 14 volts. The bands in the red and yellow however, though they are shown clearly in the photograph at the higher voltage, are not so distinct in the photograph, D, at 14 volts.

It has already been pointed out that the bands were always very prominent under conditions which corresponded to any point on the current-potential difference curve after a second marked discontinuity had occurred. In fact, the indications were that the helium band spectrum was not present at all until this discontinuity in the current-potential difference relations had taken place. The abrupt increase of current, and the simultaneous fall in the potential difference, which constitute the discontinuity, can be brought about by gradually increasing the temperature of the filament, if the potential difference is sufficiently high. The value of the potential difference across the discharge tube before the discontinuous change, affects the final potential difference after the change very little, but it does affect the current through the discharge, the increase of current being greater the higher the initial potential difference. The photograph in Plate II was taken after the occurrence of a discontinuity in the current-potential difference relations, in which the fall in the voltage and the accompanying increase of current were very small, and it will be seen that the helium band lines were not very bright in this case.

At each pressure there was a limit below which the final potential difference after the discontinuity could not be made to go, however the filament temperature, E.M.F. in the circuit, and the resistance of the circuit, were varied. In the case of the tungsten filament apparatus with the adjustable anode, this limit was affected to a certain extent by the distance of the anode from the filament. As the result of several series of observations of the variation of the final potential difference after the discontinuity in the current-voltage relations, and the distance apart of the two electrodes, this distance was fixed at 2 mm. as this value was found to give the lowest value of the potential difference across the discharge tube. As the pressure of helium in the apparatus was increased, the limiting value of the final potential difference after the discontinuity, decreased. The lowest value ever obtained in the present research was 13.5 volts, but there seems to be no reason for supposing that this is an ultimate limit. At any given value of the pressure of helium in the apparatus, the value of the final potential difference, after the discontinuity in the current-voltage relations, depended upon the form of apparatus used, for it was found to be very different in the apparatus shown in Fig 2, from in that of Fig 1. With the tungsten filament apparatus, Fig 2, the limit for the final potential difference at pressures ranging from about 6 mm. to 9 mm. was between 70 and 80 volts. At about 16 mm pressure the limiting value was about 45 volts, from which it was gradually reduced to 13.5 volts at 36 mm. pressure. In this same apparatus, at pressures below about 4 mm. the filament had to be made extremely hot and the potential difference increased to 150 volts before the voltage drop took place, the minimum final potential difference being 80 volts. At these pressures it was observed that after once obtaining the bright luminous discharge which accompanied the discontinuity, under any given set of conditions, the change took place less and less readily for subsequent repetitions of those conditions, and the current and potential difference changes at the discontinuity decreased in magnitude at each occurrence.

Lines of the helium band spectrum could always be seen at the final potential difference after the discontinuity, and the limits for its detection varied with the pressure of helium in the apparatus, in the same way as the limits for the final potential difference after the discontinuity in the particular form of apparatus used. The minimum initial voltage (i.e. voltage just before the occurrence of the discontinuity in the current-voltage relations) at which the changes could be made to take place, and at which the band lines were first seen, was the minimum radiation voltage 20.4. At high pressures the helium band spectrum, and the series spectrum, came in simultaneously at this voltage. The band spectrum was never under any circumstances seen without the helium and parhelium series lines being seen also, and at the higher pressures it was relatively more intense with respect to the ordinary series lines than at low pressures.

In the band spectrum obtained in these experiments the first doublet of the main series, and the first doublet of the second series, discovered by Fowler,[26] were identified visually. The heads in the first main series doublet are at λ 4625.4 and λ 4648.5, and the heads in the first doublet of the second series are at λ 5133.3 and λ 5108.2. The details of the first main series doublet, given by Fowler, were clearly recognisable visually and can be seen in some of the photographs given. The line λ4685 already referred to in connection with the investigation of the limits for the appearance of λ 4686, the enhanced line, is given by Fowler as one of the lines in the chief series in the tail of this doublet.

In addition to these doublets, the prominent single headed fluting at λ 5733, degrading towards the violet, recorded by Curtis[27] and by Fowler, was seen. All the heads down to λ4546, recorded by Curtis, were also observed visually. Of

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26. A. Fowler, Proc. Roy. Soc. A XCI p.208 (1915)

27. W.E.Curtis. Proc. Roy. Soc. A. LXXXIX p.146 (1913)

these the heads at λ5733 and λ6399 were the most prominent. λ5733 is marked on the photograph C of Plate VI. When the external conditions controlling the discharge were varied in such a way as to make the band spectrum fade in brightness, λ5733 was one of the last lines to disappear, as judged by visual observations.

The results stated in this section show that the only limit which can be definitely associated with the helium band spectrum is the minimum radiation potential difference, 20.4 volts, and that this is only associated with it in that it has not been found possible to <u>excite</u> (as distinct from to <u>maintain</u>) the band spectrum of helium below this voltage. At high pressures the systems which give rise to the band spectrum of helium can be produced, and receive the excitation necessary for the emission of the band spectrum, at any voltage above 20.4 volts. From this fact, and from the fact that the band spectrum was never observed in the absence of the line spectrum, it appears that some circumstance attending the presence of the line spectrum is essential either for the production of the systems from which the band spectrum arises, or for the excitation of these systems, or for both of these purposes. From the way in which the relative intensities of the band spectrum and the line series spectrum varied with change in the pressure of the helium, it may be concluded that the actual production of the systems which give rise to the helium bands is dependent upon this circumstance attending the presence of the line spectrum. The view that the systems which give rise to the helium band spectrum are molecules formed by the combination of abnormal helium atoms therefore obtains support from the results of the present investigation, although this affords no evidence as to the particular nature of the abnormal helium atoms concerned.

It follows from this view that when the band spectrum is maintained below 20.4 volts, the number of helium molecules present cannot be increased without causing a reduction in the number of abnormal atoms present. The band spectrum of helium, like the line spectrum, has been maintained for prolonged periods below 20.4 volts, so that the number of molecules which are capable of giving rise to the band spectrum at these voltages, whether they are normal molecules or molecules maintained in some abnormal condition, must remain constant in these circumstances.

Though the helium band spectrum was maintained down to the same limit as the helium and parhelium series lines, it was not present in the spectrum of the discharge when the minimum potential difference in the current-voltage relations had been passed, and the voltage was increasing again in spite of all attempts to reduce it still further. As the potential difference was being gradually reduced to the minimum value, both the line spectrum and the band spectrum diminished in intensity, the latter at a more rapid rate than the former. Sometimes only the heads of the bands, and not the detail, could be seen when the minimum value was reached. After passing the minimum value of the potential difference, the band spectrum had completely disappeared and the mercury line λ5461 stood out clearly, although it was much fainter than the helium and parhelium series lines. On further increasing the potential difference across the discharge, this line increased in intensity, reached a maximum brightness, and ultimately faded out entirely. The hydrogen line H_β, like the helium band lines, was not visible after passing the minimum value of the potential difference.

In an investigation of the effect of mercury vapour on the spectrum of helium, Collie[28] found, in 1902, that the presence of mercury vapour caused a great simplification of the spectrum of the negative glow of helium. He found that all the band lines, and in addition the series lines λ7066, λ4713, and λ4472, disappeared, while the yellow line λ5876 was very much reduced in intensity when mercury vapour was admitted. In the present research, the superseding of the helium band spectrum by the mercury line λ5461, is not an analogous effect because no variation occurs in the amount of mercury vapour present in the tube.

In one or two instances, in the present research, the mercury line λ5461 was in turn superseded by other lines as the potential difference was increased after the minimum stage was passed. The wave lengths of two of these lines in the

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28. J.N.Collie. Proc. Roy.Soc. LXXI. p.25 (1902)

region of the spectrum which was specially under observation were about 5512 Å and 5220 Å. These lines appeared before the mercury line λ 5461 had completely disappeared, but as they brightened, the mercury line faded and ultimately vanished. The changes in the spectrum, like the changes in the current-potential difference relations, which occur simultaneously, were found to be reversible, and after repassing the minimum potential difference on effecting the current-voltage changes in the reverse order, the helium band spectrum reappeared and the mercury line vanished. The disappearance of the band spectrum without the disappearance of the series lines, when the voltage was varied by altering the heating current or the series resistance, and its subsequent reappearance when the variations of the controlling factor were made in the opposite order, admit of explanation in two ways.

The first explanation is analogous to the explanation of the maintenance of the line series spectrum below 20.4 volts, by the presence of abnormal, and more easily ionisable, atoms. It has been suggested earlier in the paper, that the atoms were maintained in an abnormal condition because the frequency of encounters between abnormal atoms and electrons was such as to prevent the reversion of an abnormal atom to the normal state, the returning electron being always re-ejected before reaching its normal orbit. It is possible that a somewhat similar effect occurs in the case of the helium molecules, and that these are maintained in such a state of excitation by frequent electron encounters that they are prevented from making the transitions which result in the emission of the band spectrum of helium in the visible region of the spectrum. The disappearance of the hydrogen line H_β might be explained in a similar way. It would be expected that the Paschen series in hydrogen would remain after the disappearance of H_β, a Balmer series line, if the explanation suggested above were correct, for the frequencies of the Balmer series lines are given by the equation $\nu = N\left(\frac{1}{2^2} - \frac{1}{m^2}\right)$, while the lines of the Paschen series are given by $\nu = N\left(\frac{1}{3^2} - \frac{1}{m^2}\right)$, so that the latter series is associated with a more abnormal condition of the hydrogen atom, than the Balmer series. The lines of the Paschen series, however, all lie in the infra red region of the spectrum, and therefore could not be detected in the present investigation.

It seems possible that the appearance of the mercury line λ 5461, for a short stage in the current-potential difference relations, may be another manifestation of a similar occurrence. Though the amount of mercury vapour present must have been very small, since no indication of its presence was obtained in any other circumstances, the augmented electron bombardment in the circumstances under consideration must have produced sufficient ionisation, and subsequent recombination, of mercury atoms to give a detectable emission of mercury lines, for the ionisation of the mercury could not have been caused by helium radiation, because the limiting frequency in the helium spectrum, maintained below 20.4 volts, cannot exceed that corresponding to (25.2 - 20.4 =) 4.8 volts. That the line λ5461, which is in the region of the spectrum specially investigated, only became visible when a certain stage in the current-potential difference relations was reached, would be accounted for, if, at this stage, its intensity was increased due to electron transitions being limited to outer orbits of the mercury atom. Its subsequent fading and eventual disappearance would be explained if the mercury atoms were ultimately maintained in a still higher stage of abnormality, which resulted in an increase of intensity of other mercury lines (possibly in the infra red region) at the expense of λ 5461.

The second possible explanation of the disappearance of the helium band spectrum, and its subsequent reappearance on altering the current-potential difference relations in the reverse order, depends upon a particular type of abnormal atom being essential for the production of the helium molecule, for instance, the 20.4 volts coplanar atoms suggested by Franck and Knipping.[13] If the constancy of the supply of abnormal helium atoms and of helium molecules, at any given values of the heating current, and potential difference, (below 20.4 volts) were maintained by the dissociation of a certain number of molecules into abnormal atoms and the formation of an equal number of new molecules, then when the necessary type of abnormal atom was no longer produced, owing to intense electron bombardment, the formation of new molecules would cease and the helium band spectrum would disappear. Reducing the frequency of encounters between abnormal helium atoms and electrons would lead once again to the presence, in the tube, of the type of abnormal atom necessary for the production of helium molecules, and the band spectrum might reappear. This suggested explanation involves the assumption that the newly formed helium molecules can acquire the degree of excitation necessary for the emission of the helium band spectrum, at between 13 and 14 volts. If this were not the case, the band spectrum could not reappear on retracing the current-potential difference curve.

If this explanation is correct, one or more series of lines in the ordinary line spectrum of helium must disappear when the band spectrum disappears. Table III shows that none of the lines between λ7066 and λ4472 disappear under these circumstances, so that the series must be one having no lines within this region. The helium principal series is the only series which fulfils this condition, and this is the one which results from transitions involving a return of the displaced electron to the 20.4 volts orbit. It has already been mentioned that the 1st and 2nd lines of this series are in the infra red and the violet respectively, the second line λ3889 being too far in the violet for reliable results to be obtained from visual observations, while the obtaining of photographs after the disappearance of the band spectrum, proved impossible on account of the high temperature of the filament, which usually resulted in its burning out if the discharge were maintained under these conditions for any length of time. If the disappearance of the helium principal series at the same time as the helium band spectrum could be proved, evidence would be obtained not only in favour of the second explanation offered above, but also of Franck and Knipping's[13] suggestion as to the nature of the helium molecule.

C O N C L U S I O N.

It has been shown in the course of the ~~following~~ foregoing pages that none of the lines of the helium and parhelium series can be excited without all these lines being stimulated, and, moreover, that the lines generally do not appear until the ionisation potential difference for the normal helium atom is passed. When, however, the conditions are such as to make ionisation by cumulative effects possible, the lines can be excited as low as the minimum radiation potential difference, 20.4 volts. At this voltage, an electron collision with a helium atom can result in the removal of the outer electron of the helium atom to the orbit associated with the helium principal series i.e. a coplanar orbit, but it cannot remove an electron to the orbit associated with the parhelium principal series. At 20.4 volts, however, the lines of both the helium and the parhelium series are excited simultaneously, so that clearly electrons must be returning to both the crossed and the coplanar systems of orbits. Therefore the experiments show that when ionisation and subsequent recombination occur, the returning electrons fall to either system of orbits irrespective of the system from which they were removed. This fact, combined with the fact that the occurrence of ionisation is essential for the production of the series lines in helium, made it impossible to obtain any spectroscopic evidence, in the present research, in connection with Franck and Reiche's [14] theory regarding the metastable character of the abnormal atoms resulting from 20.4 volts electron collisions with helium atoms.

The present experiments do not afford any confirmation of Franck and Knipping's[13] detection of critical voltages for electrons in helium intermediate to the radiation voltages, (20.4 volts and 21.2 volts) and the ionisation voltage, 25.2 volts. On the other hand, the results of the present investigation of normal uncharged helium are in complete agreement with the results of the investigations of McLennan and Ireton[20] on the vapours of zinc, cadmium, and mercury, and of Foote and Meggers[21] on caesium vapour.

The results of the investigation of the minimum voltage for the excitation of the enhanced line λ4686 showed that this line could be excited by the displacement of the second electron within a helium positive ion, without further ionisation occurring, and they thus suggest that there is a difference in the possible methods of excitation of neutral and ionised helium atoms when submitted to electron bombardment. It would be of interest to ascertain whether such a difference occurs in other cases, for instance, in mercury, zinc, or cadmium vapours. If it does not do so, it is possible that λ4686 can be excited without further ionisation of the helium atom by virtue of the fact that the helium positive ion, which is the system from which the enhanced lines originate, is a simple system consisting only of a nucleus and a single electron.

It has been shown that the helium and parhelium series lines can be maintained at voltages below 20.4 volts, the minimum potential difference at which they can be excited, and that this can be accounted for on the view that a certain number of helium atoms are maintained in an abnormal, more easily ionisable, condition by the frequency of their encounters with electrons. Since, under such conditions, no electrons could be returning to the normal orbit, none of the extreme ultra violet series lines of helium can be present when the spectrum is maintained at voltages below 20.4.

The conditions under which the band spectrum of helium made its appearance, and those under which it could be maintained support the view that this spectrum has its origin in a helium molecule which is produced from abnormal helium atoms, and thus that it cannot be produced in normal helium for electron energies below 20.4 volts. The results of the present research afford no information regarding the energy which is necessary in order to excite the molecule to the emission of the band spectrum, beyond the fact that this energy can be acquired, under intense electron bombardment, at a potential difference of 20.4 volts. The results of the present investigation, however, considered in conjunction with the recent conclusions of Horton and Davies,[12] viz, that at 20.4 volts some system is produced in helium which can be ionised by the radiation which is produced at 21.2 volts, support the suggestion made by Franck and Knipping[13] that the coplanar atoms, resulting from 20.4 volts electron collisions with helium atoms, are capable of entering into chemical combination and forming He_2 molecules which give rise to the band spectrum of helium.

Except where the work of other investigators is definitely referred to, and where references are given, the research embodied in the Thesis is entirely the writers own work. The investigation appears to the writer to advance scientific knowledge in that it affords detailed information as to the energy required for the excitation, and for the maintenance, of the various spectra of helium under different conditions; this information enables important deductions to be drawn in connection with the nature of the systems which give rise to the band spectrum of helium and also in connection with the limitations of possible transitions of the helium atom from states of lower to states of higher potential energy.

A.C.D.

FIG I

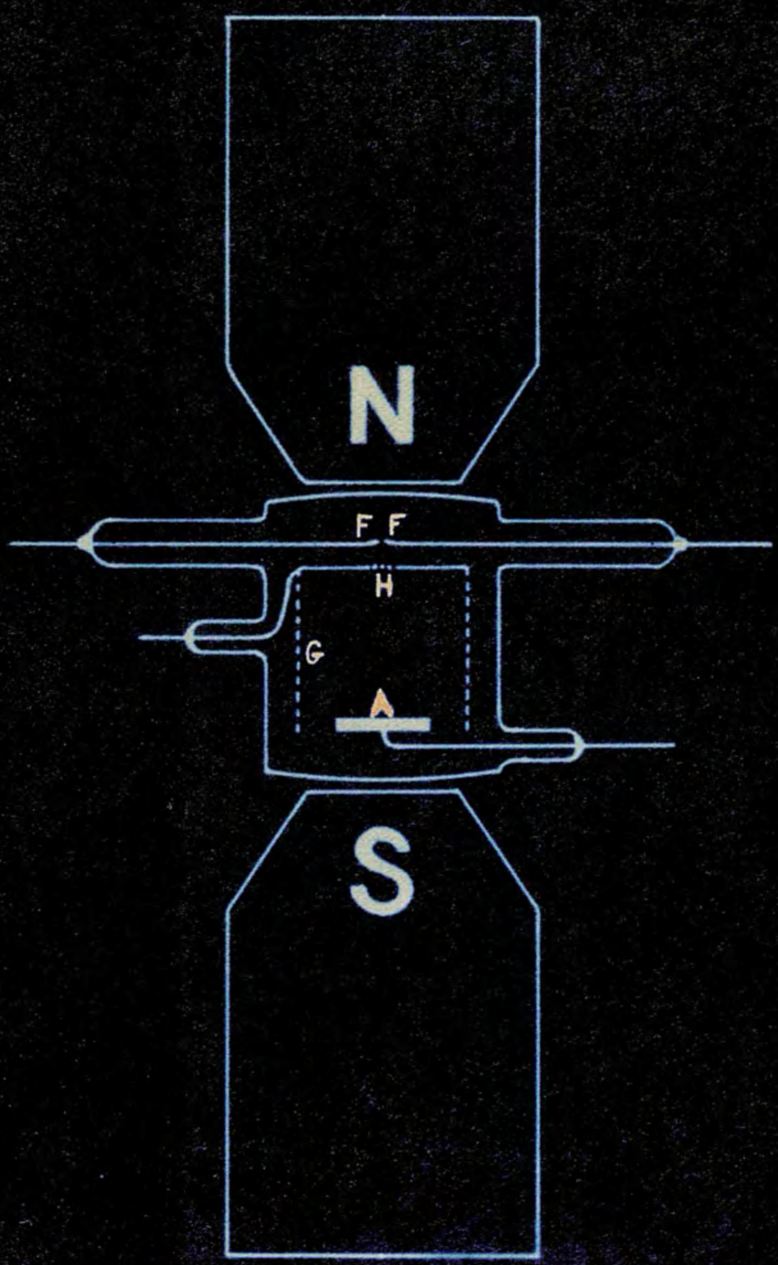


Fig 2

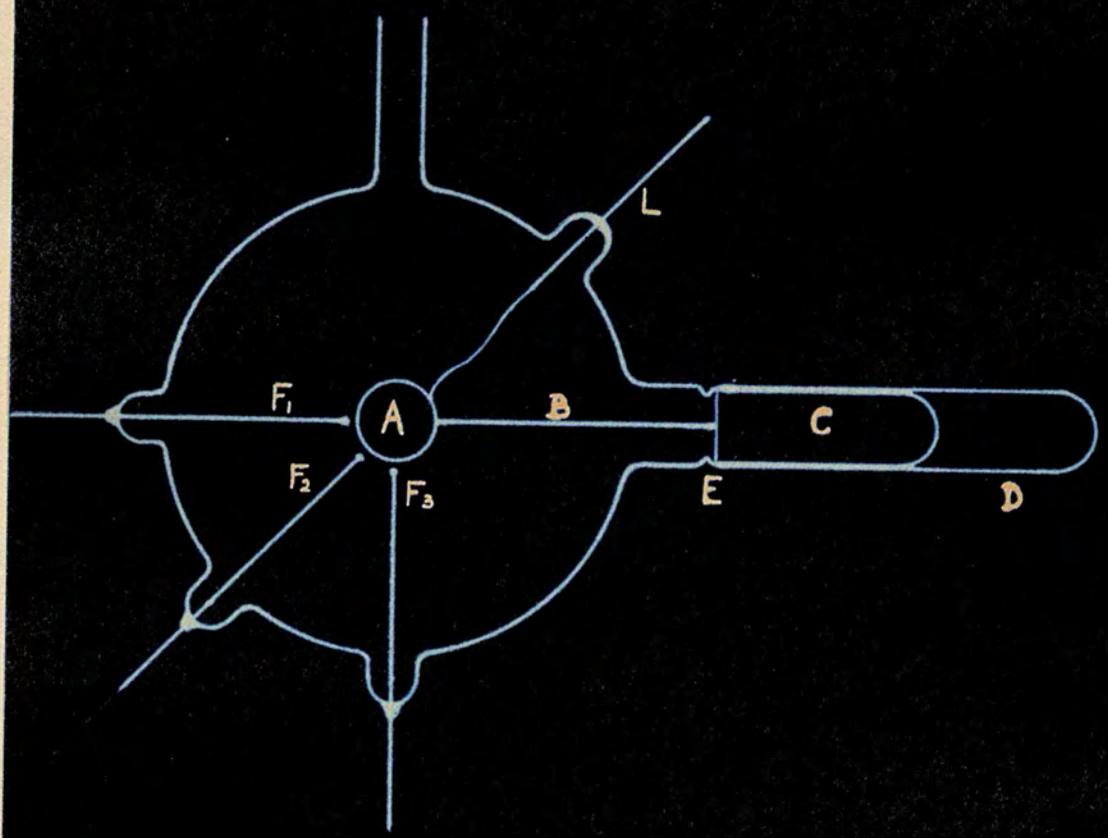


FIG 3

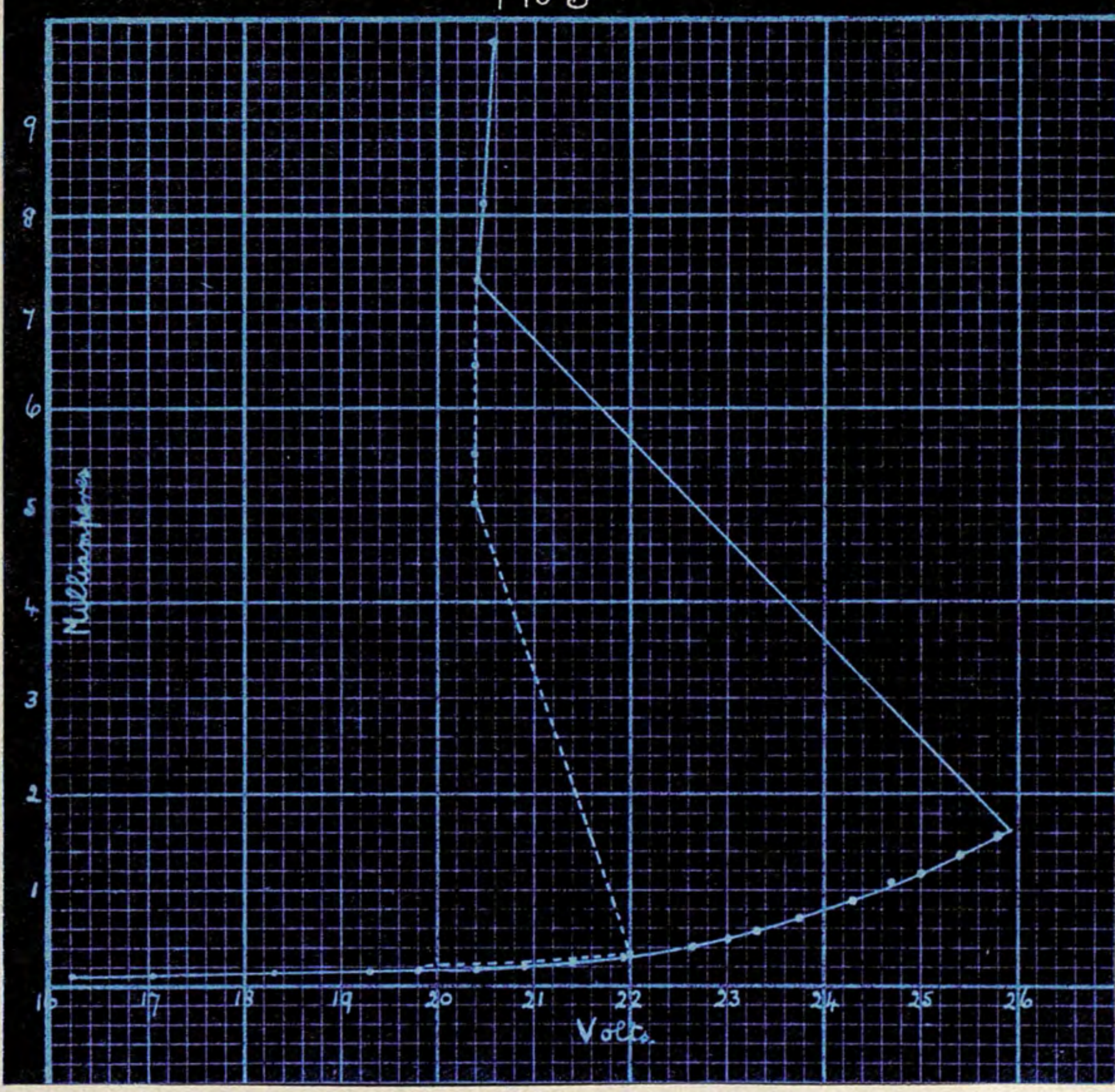


FIG 4

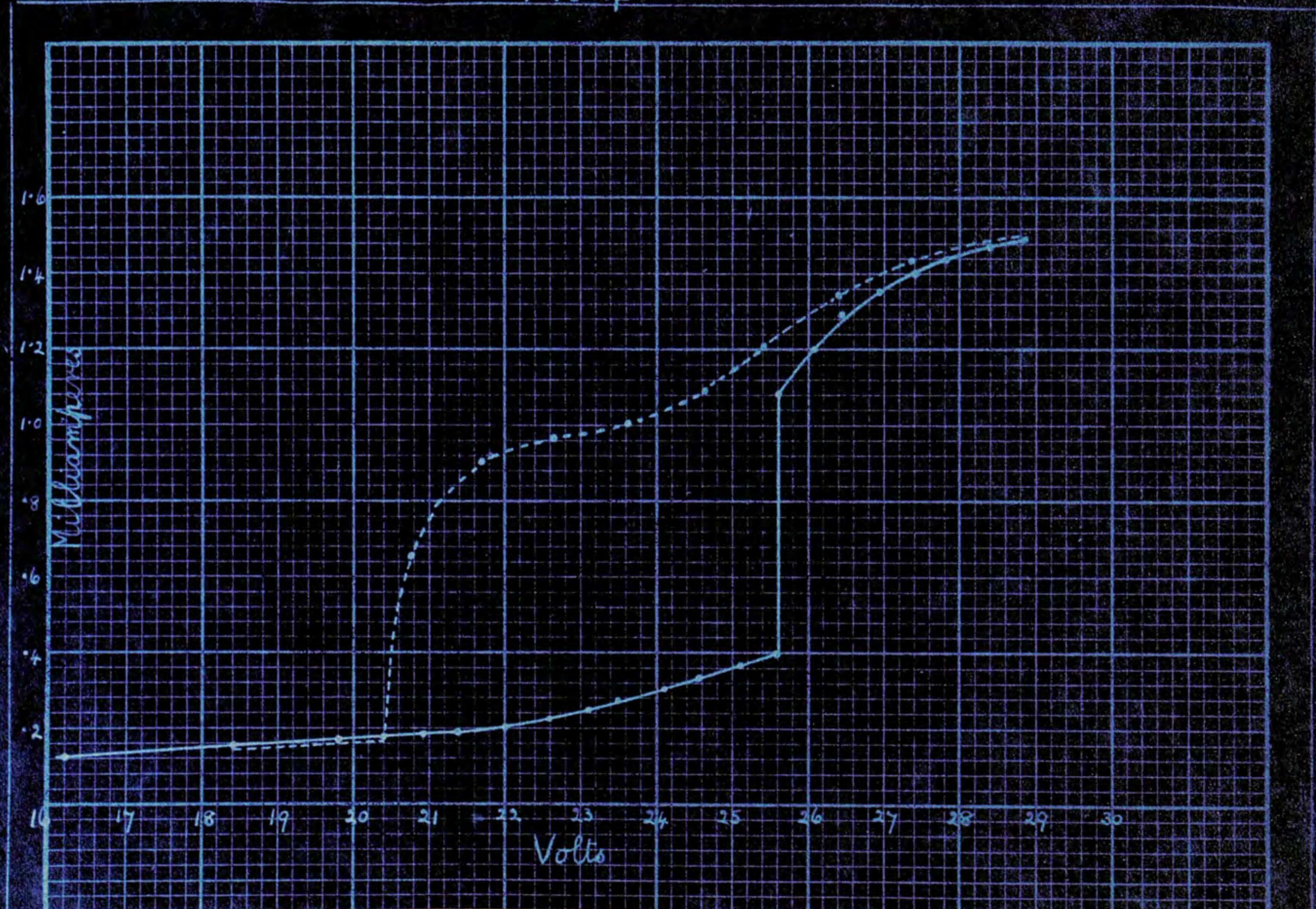
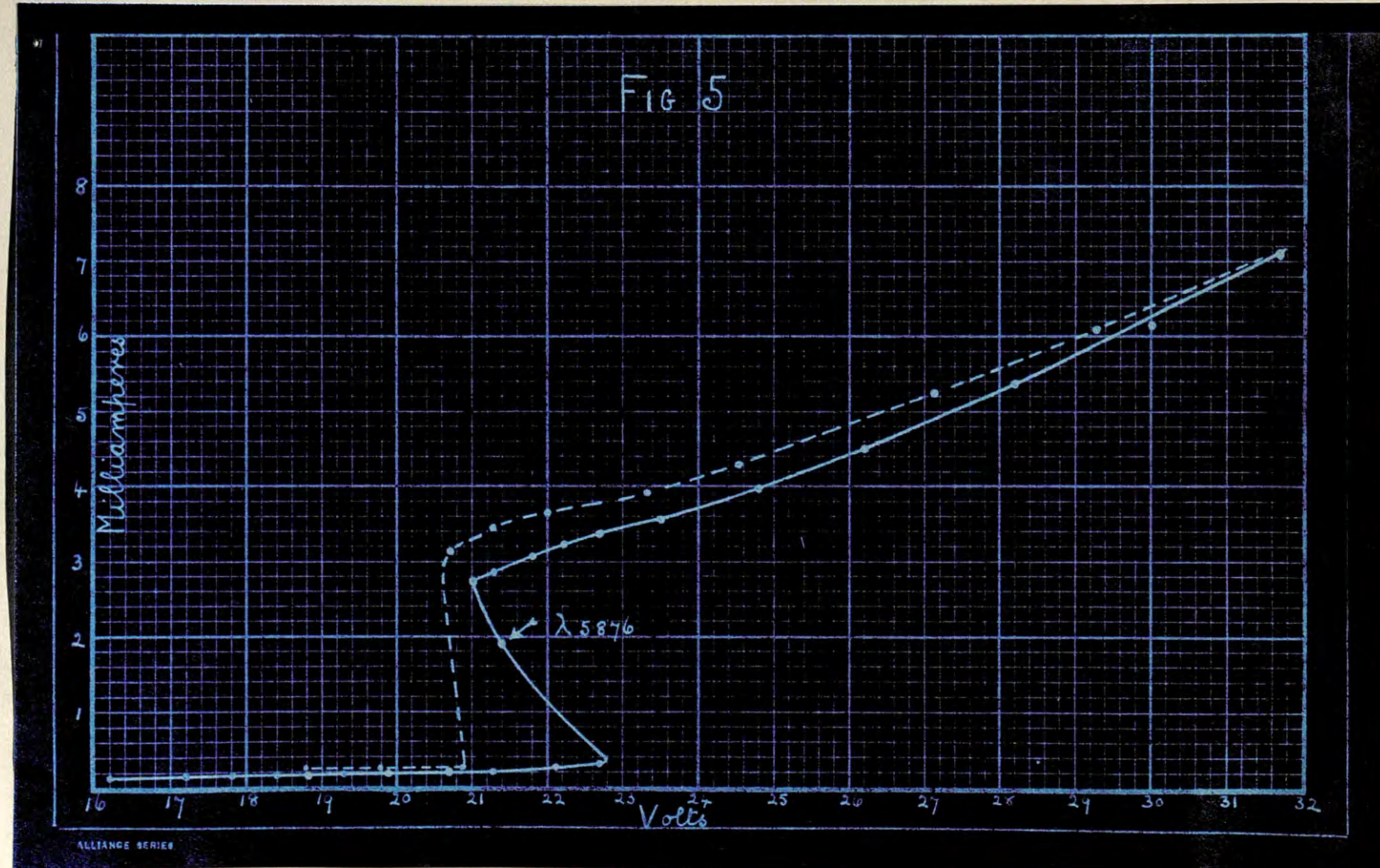
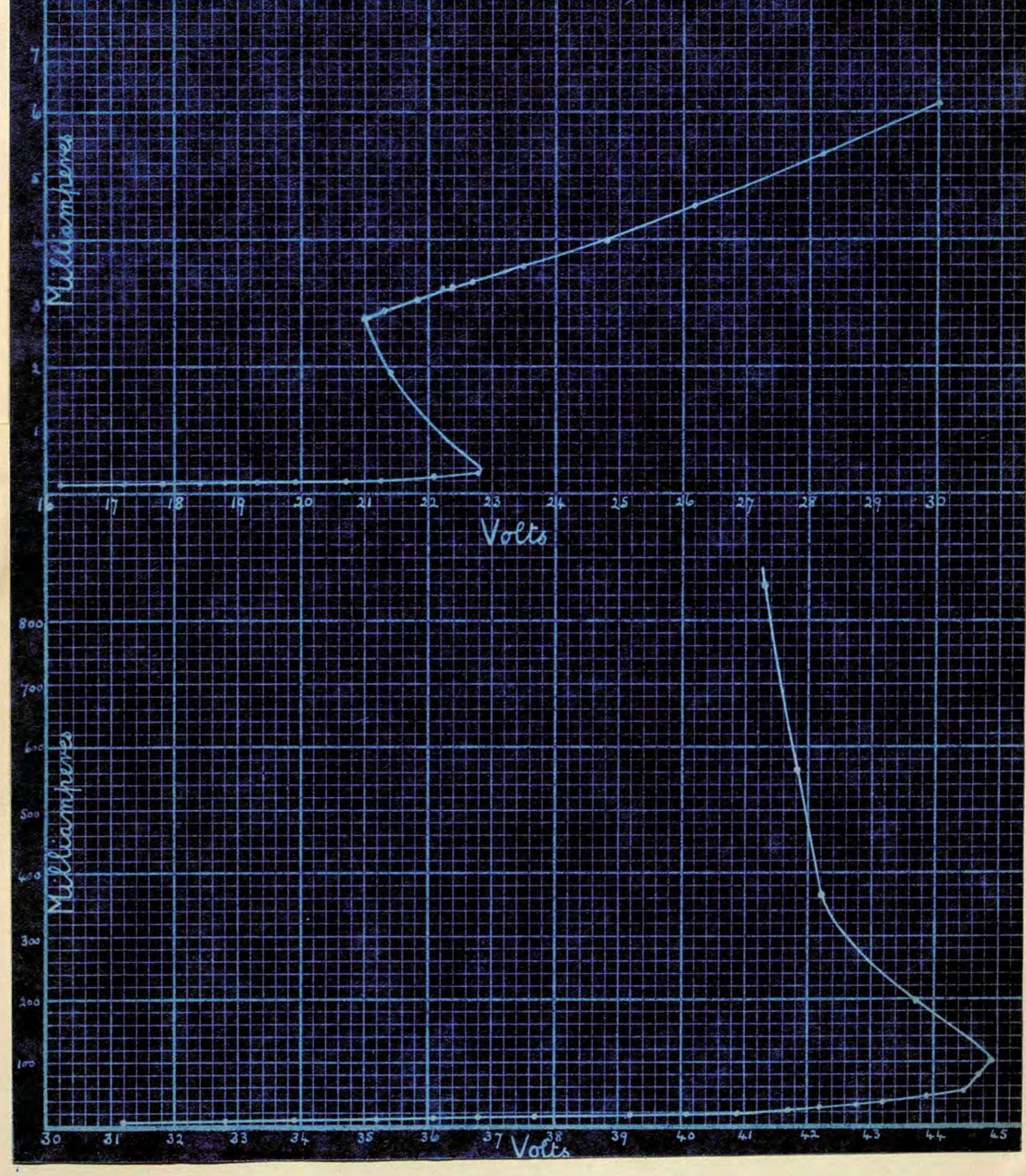

1·6
1·4
1·2
1·0
·8
·6
·4
·2
Milliamperes
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
Volts

Fig 5

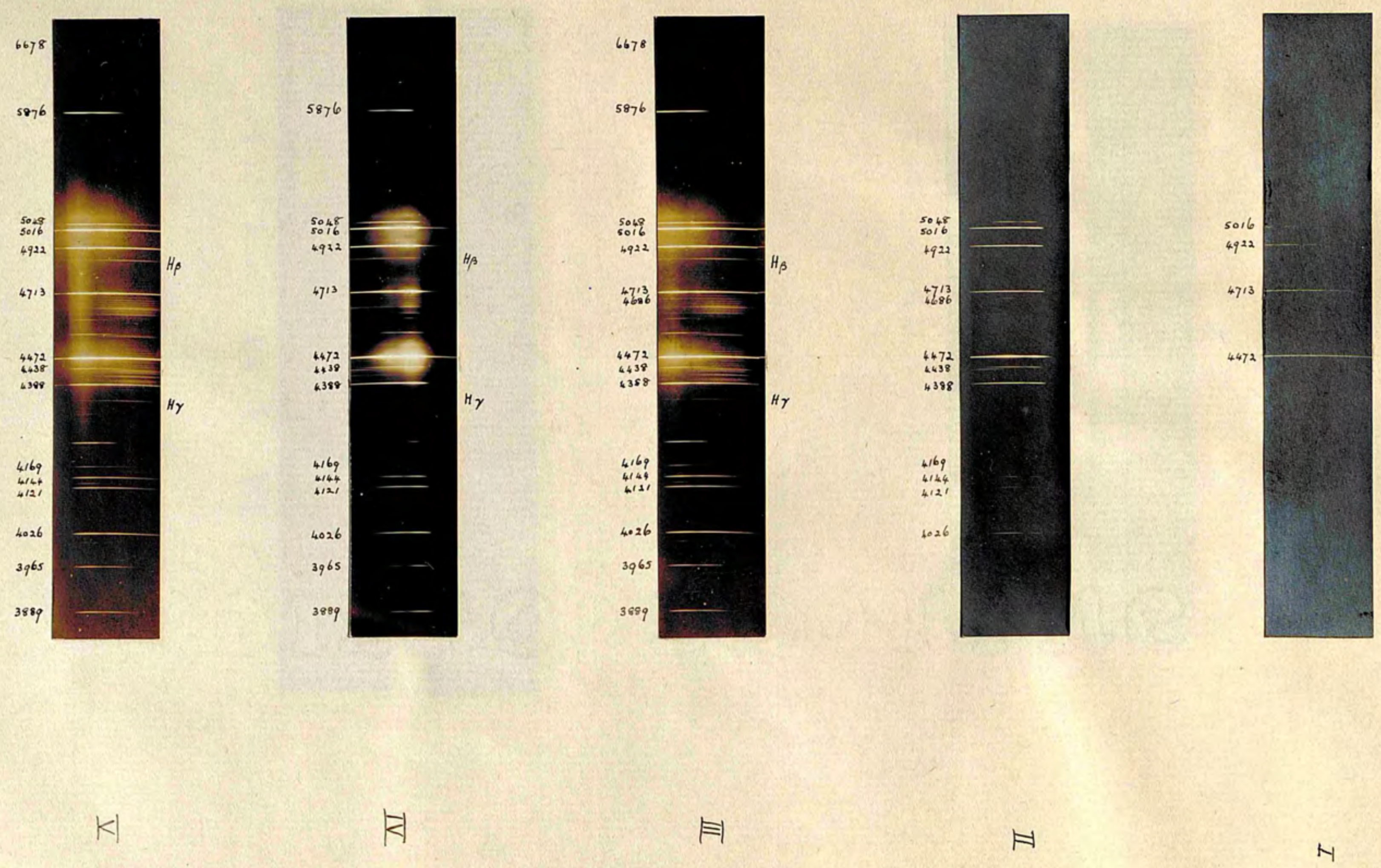


λ5876
Milliamperes
Volts
8
7
6
5
4
3
2
1
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
ALLIANCE SERIES

FIG 6

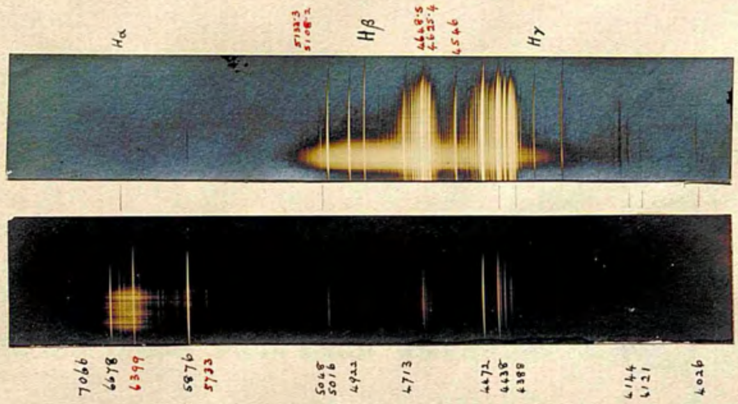


Milliamperes
7
6
5
4
3
2
1
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
Volts
Milliamperes
800
700
600
500
400
300
200
100
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
Volts



6678
5876
5048
5016
4922
Hβ
4713
4686
4472
4438
4388
4358
Hγ
4169
4144
4121
4026
3965
3889
I
II
III
IV
V

VI


Hα
Hβ
4648·5
4625·4
Hγ
7066
6678
6399
5876
5733
5048
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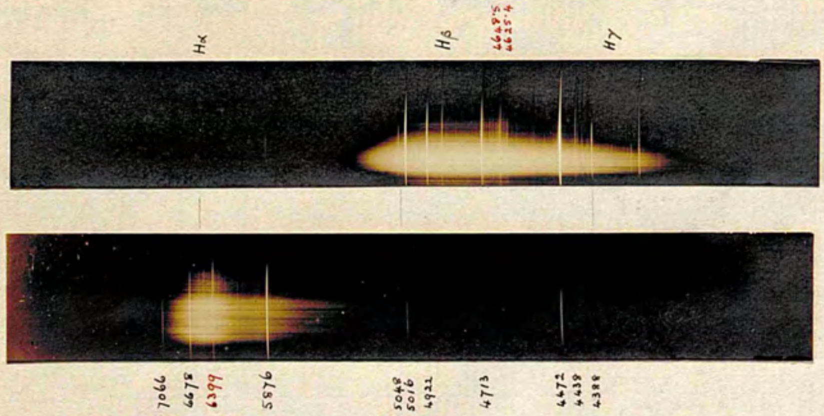
4921
4713
4472
4438
4388
4144
4121
4026

A

C


Hα
Hβ
4648·5
4625·4
Hγ
7066
6678
6399
5876
5048
5016
4921
4713
4472
4438
4388

B

D