THE INFRA-RED SPECTRUM OF HELIUM IN A LONG DISCHARGE TUBE.

DISSERTATION

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DEGREE OF DOCTOR OF PHILOSOPHY.

By

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THE INFRA-RED SPECTRUM OF HELIUM IN A LONG DISCHARGE TUBE.

Considering the importance of helium in the theories of atomic structure, relatively little study has been given to its infra-red spectrum. The spectra of helium are a line spectrum due to neutral helium, a line spectrum due to ionized helium, and a band spectrum.

The spectrum of neutral helium consists of a system of doublet series and a system of singlet series. Each of these systems is made up of four chief series. These are given in modern notation by

Principal Series .... $\nu = 2s - mp$ .... $m = 2,3,4,5...$

Diffuse series .... $\nu = 2p - md$ ...... $m = 3,4,5$ ....

Sharp series .... $\nu = 2p - ms$ ...... $m = 2,3,4,5....$

Bergmann, or Fundamental Series .... $\nu = 3d - mb$ ...... $m = 4,5,6$

where ν is the wave number per cm. ($= 10^8/\lambda$)

s, p, d and b are constants.

Capital letters are used when referring to the singlet system.

Some of these series are filled to as high as the eighteenth number without omission. This is the result principally of the observations by Paschen and Runge [1], Merrill [2], and Schniederjost [3]. Several com-

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(1) Astrophys. Jl. 3, 4 (1896); Ann. d. Phys. 27, 537 (1908); 29, 628,(1909

(2) " " 4, 357, 1917.

(3) Zeit. f. Wiss. Phot. 2, 265, 1904.

bination series have been observed by Koch[4], Merton[5], Stark[6] and Liebert[7].

The spectrum of ionized helium consists of three series of enhanced lines represented by the formula

$$\nu = 4R\left(\frac{1}{n^2} - \frac{1}{m^2}\right)$$

where ν is the wave number per cm. ($= 10^8/\lambda$)

R is the Rydberg constant for ionized helium

n and m are integers.

This gives

Lyman's series for $n = 2$; $m = 3,4,5,6$

Fowler's[8] " " $n = 3$; $m = 4,5,6 \ldots 10$

Pickering's " " $n = 4$; $m = 5,6,7 \ldots 21$

According to the Bohr theory of the atom these series lines are produced when an electron falls into the second, third and fourth orbits respectively from the various outer orbits. All the observed lines of helium but one have been accounted for as members of these enhanced series and of those of neutral helium.

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(4) Ann. d. Phys. 48, 98, 1915.

(5) Proc. Roy. Soc. A. 95, 30, 1918.

(6) Ann.d. Phys. 56, 577, 1918.

(7) Ann. d. Phys. 56, 600, 1918.

(8) Modestly called the "4686" series by Fowler himself.

Those lines in the infra-red region are as follows:

1.0124 μ	Pickering series	(m = 5)	Intensity .....
1.0830	Principal	(2s - 2p)	200.0
1.2784	Fundamental	(3d - 5b)	1.0
1.2794	"	(3D - 5B)	.8
1.7003	Combination	(3p - 4d)	.24
1.8684	Fundamental	(3d - 4b)	3.0
1.8693	"	(3D - 4B)	2.0
1.9090	Combination	(3P - 4D)	.11
2.0582	Principal	(2S - 2P)	20.0
4.05			4.0

With the exception of the first, all of these lines have been obtained by Paschen, using a grating of 14450 lines per inch, without fore-prism, and observing "end on" the radiations from a vacuum tube, energized by a storage battery of 4000 volts. Fowler and Evans (9) have studied the visible spectrum of helium using the ordinary Plücker tube of .8 to 3.5 mm. in diameter and excited by a 20 inch induction coil.

In view of the success of Wood's long tube in bringing out the series of atomic hydrogen (10), it seemed worth while to study the infra-red

(9) Phil. Mag. 29, 284, 1915.

(10) Astrophys. Jl. 56, 154, 1922.

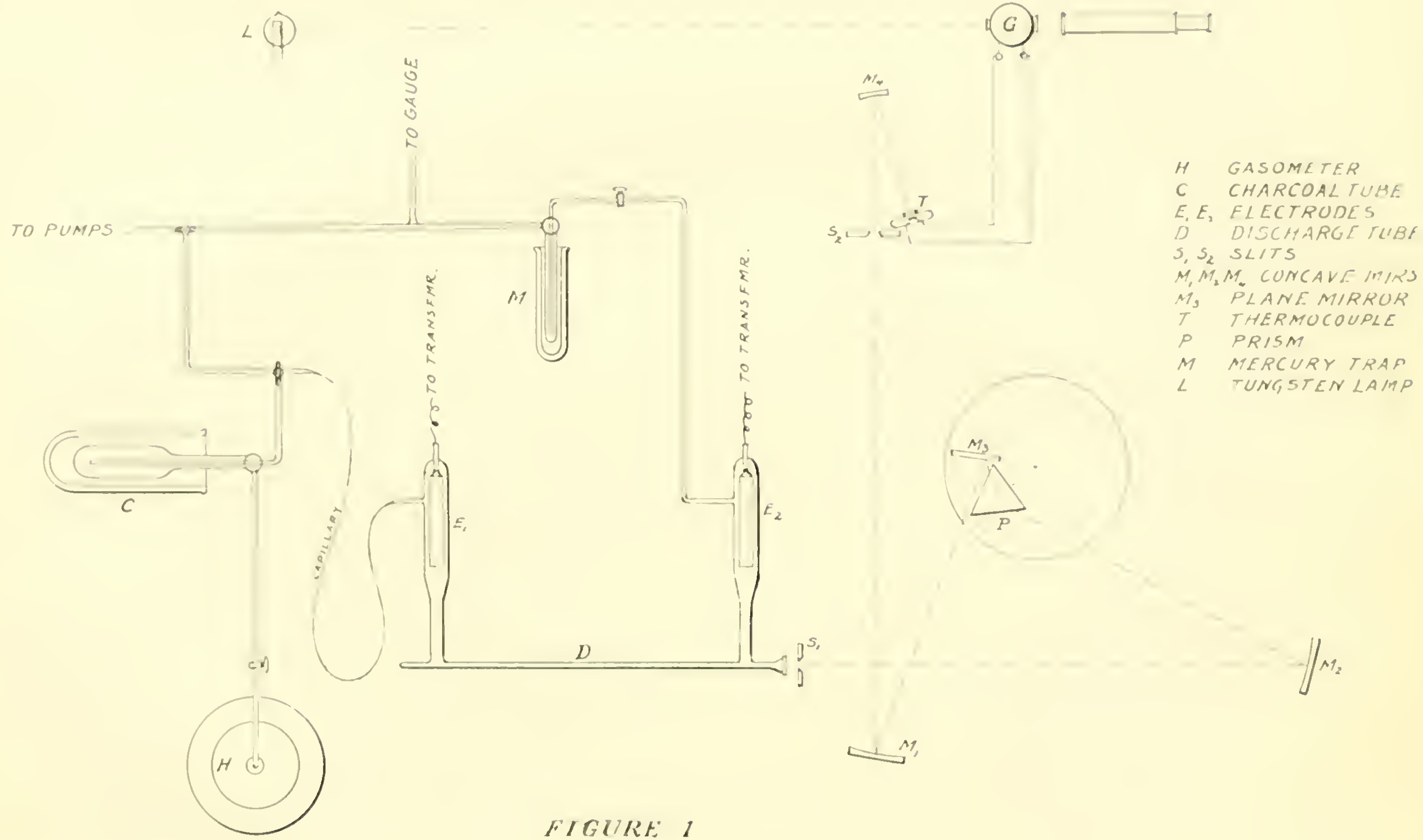
L
TO GAUGE
TO PUMPS
M
C
CAPILLARY
TO TRANSFMR.
TO TRANSFMR.
E1
E2
D
S1
S2
T
G
M1
M2
M3
M4
P
H
H GASOMETER
C CHARCOAL TUBE
E1 E2 ELECTRODES
D DISCHARGE TUBE
S1 S2 SLITS
M1 M2 M4 CONCAVE MIRS
M3 PLANE MIRROR
T THERMOCOUPLE
P PRISM
M MERCURY TRAP
L TUNGSTEN LAMP

FIGURE 1

spectrum of helium under similar conditions.

Apparatus.

Figure 1 shows diagramatically the arrangement of the apparatus. The vacuum tube, D, of pyrex glass consisted of a horizontal tube 6 mm. in diameter by 70 cm. long, in line with a projecting tube 7 cm. long and of slightly larger diameter than the main tube. A rock salt window was held on the end of this projecting tube with sealing wax. The electrodes E_1 and E_2 were cylinders of sheet aluminum 2.5 cm. in diameter by 1.5 cm. long located in larger side tubes, at right angles to the main tube.

The tube was energized from a 6600 volt transformer supplying 60 cycle current from a 110 volt primary. Voltages were controlled by rheostats in the primary circuit, and currents observed on a milliammeter in series with the tube.

The helium coming from the gasometer H, was purified by passage over phosphorous pentoxide and through a cocoanut charcoal tube, C, of large capacity, immersed in liquid air. The charcoal was relieved of the adsorbed gases by frequent heating to redness under low pressure, a by-pass to the pumps being provided for this purpose. From the charcoal tube the helium passed through a fine capillary tube into the vacuum tube. The advantage of the capillary tube was its flexibility, also the gas could be made to flow very slowly into the vacuum tube.

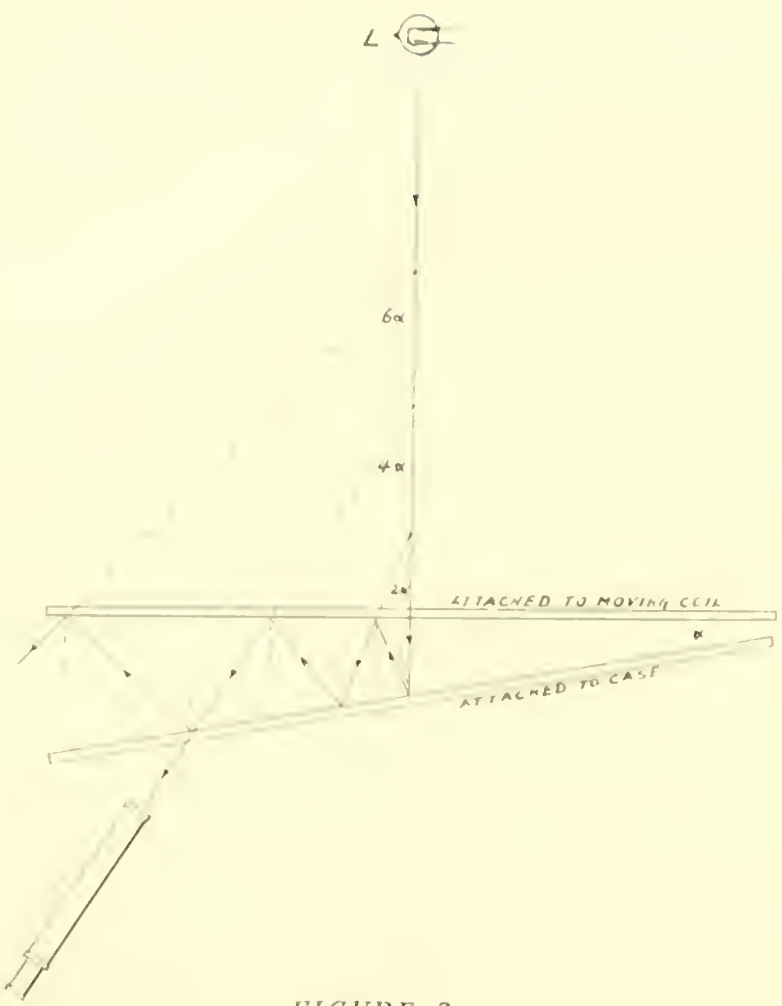

FIGURE 2

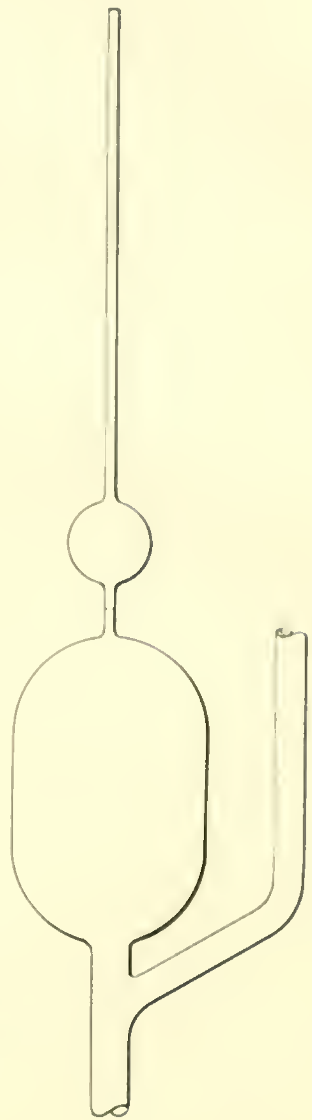

FIGURE 3

For measurement of pressures a special form of McLeod gauge was suggested by Dr. Pfund. As shown in Figure 3, this gauge has an additional bulb of about 3 cm. capacity blown in the capillary tube. By adjusting the top of the mercury column to a fiducial mark on the short portion of the capillary tube between the large and small bulbs, one secures a second scale of pressures from 0.4 mm. to 1.7 mm. which overlaps well the ordinary scale for compressions into the capillary above. Pressures above 1.7 mm. can be read with a vernier directly from the barometric column. This device in conjunction with the tungsten filament inserted in the top of the capillary as already described by Dr. Pfund [11], makes the McLeod gauge available from 10^{-10}mm of mercury up to atmospheric pressures. Therefore the whole range of pressures from 10^{-10}mm. up to atmospheric pressures may be observed with this one instrument.

A monochromator of the Wadsworth type was used (Fig. 1). This consisted of two concave mirrors M_1 and M_2 of 60 cm. focal length, and a rock salt prism of base 9 cm. and prism angle of 60°, having a plane mirror M_3 rigidly attached. The light from the spectrometer was focussed by means of a small concave mirror M_4 upon a very sensitive vacuum thermo-couple, T, constructed by Dr. Pfund. The junction was made of Antimony and Bismuth alloys, and mounted on a small strip of blackened Dutch foil on which the radiation fell. A couple mounted thus responds very quickly to the incident radia-

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(11) Phys. Rev. 15 , 536, 1920.

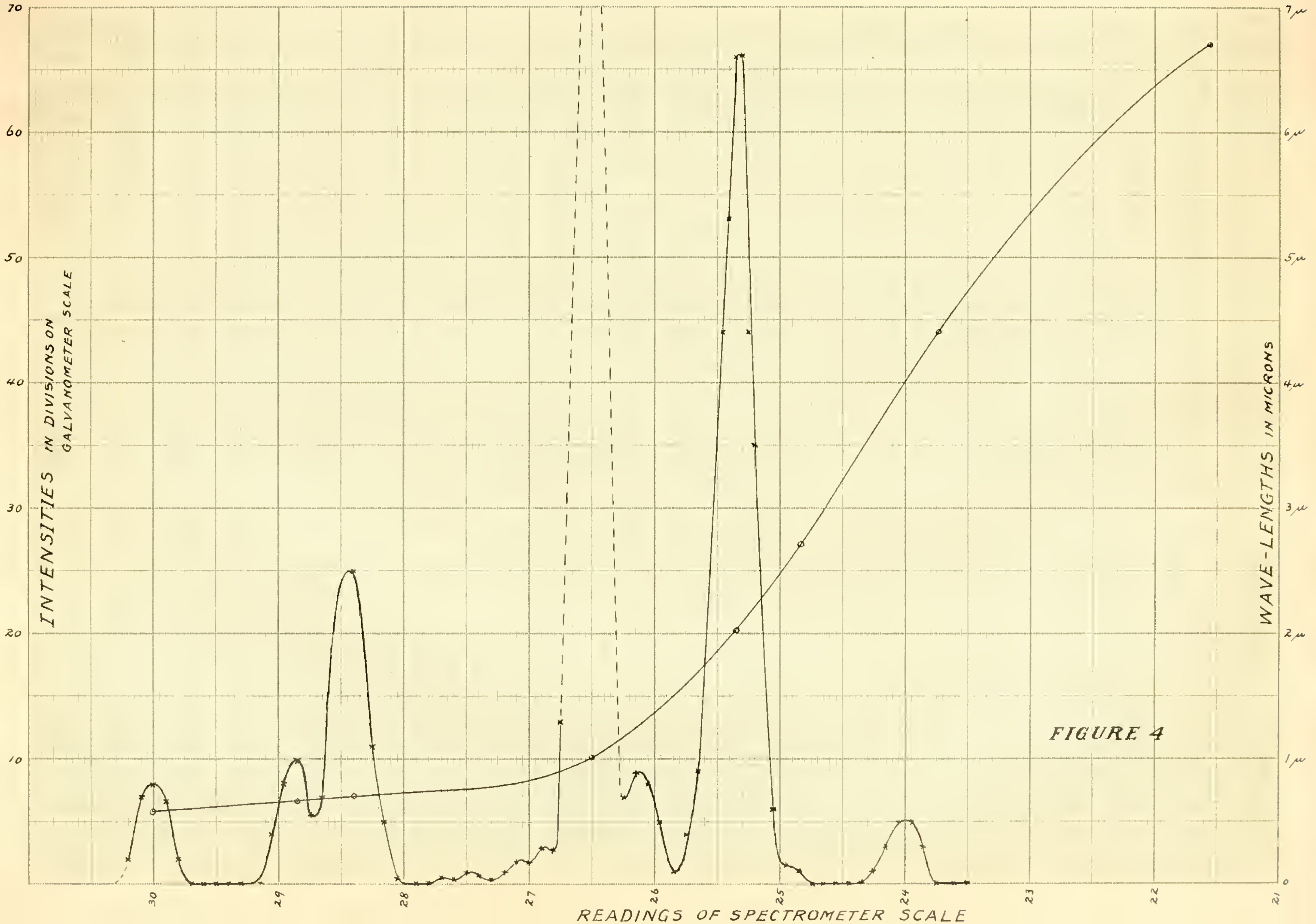
tion. Due to this fact one can easily discriminate between the radiations from the gas in the tube and the hot glass of the tube on a general drift of the galvanometer. Two junctions were mounted in series and opposing each other. The radiation in question was focussed on one. The effect of air currents and stray radiation on the thermo-couple was thus eliminated. For a thermo-couple of this type it has been shown that galvanometer deflections, if small, are proportional to intensities.

A Leeds and Northrup high sensitivity galvanometer was connected to the thermocouple. This galvanometer was reconstructed, being provided with two half silvered mirrors - one attached to the moving system, the other to the case (Fig. 2). Observations of the images of a distant tungsten lamp on a scale, ruled by Bausch & Lomb upon thin glass and placed in the position of the cross-hairs of the telescope, gave a very sensitive index as well as a convenient method of comparing the intensities of very strong and very weak lines.

Results.

1. Distribution of Intensity.

Figure 4 shows the distribution of intensity of the radiation due to Helium between the wave-lengths 0.58 μ and 5.3 μ. Intensities are plotted as ordinates. They are in divisions of the reticle which are equivalent to 3 mm. of an ordinary scale. Abscissas are readings



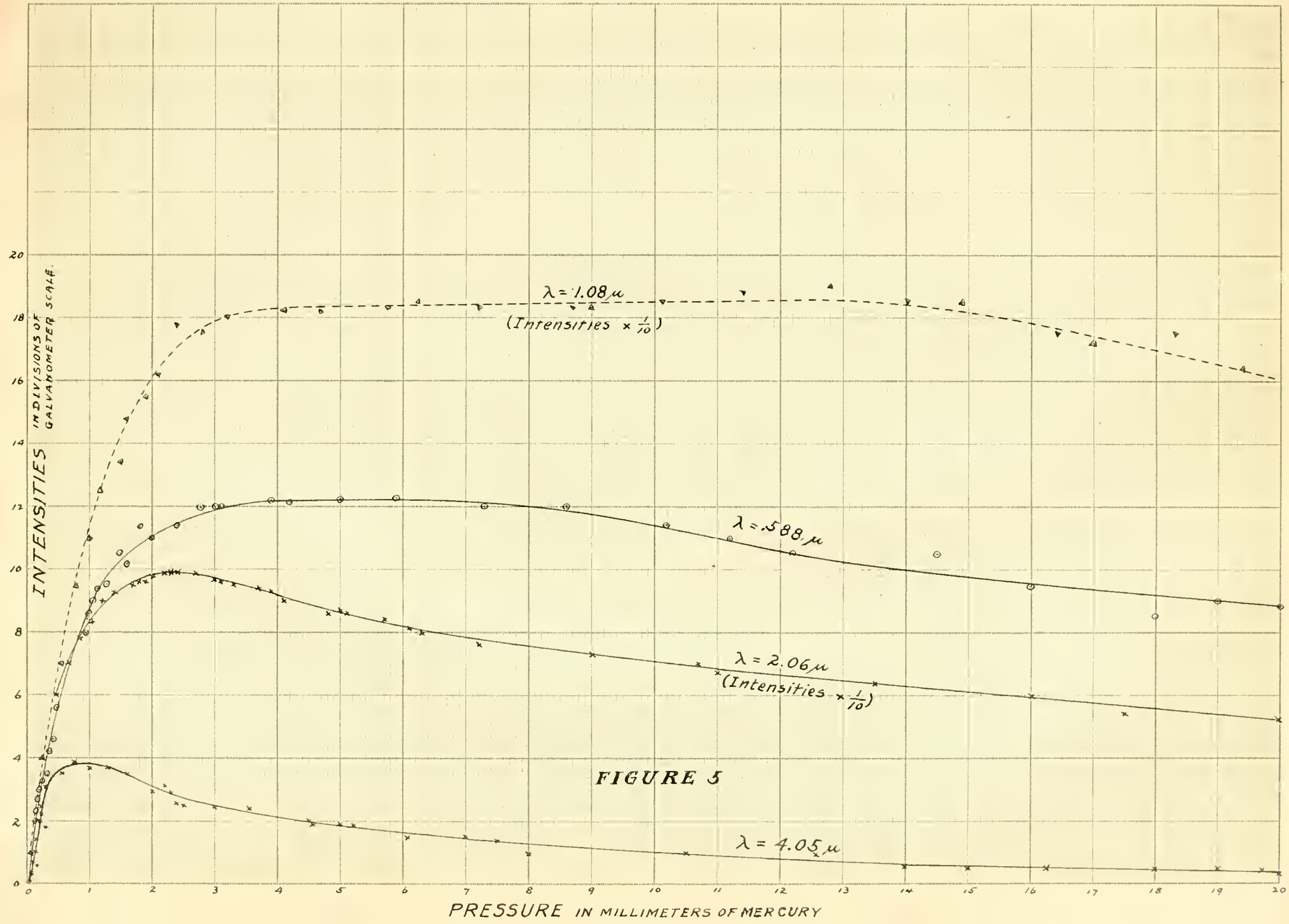
INTENSITIES IN DIVISIONS ON GALVANOMETER SCALE
WAVE-LENGTHS IN MICRONS
READINGS OF SPECTROMETER SCALE
70
60
50
40
30
20
10
7μ
6μ
5μ
4μ
3μ
2μ
1μ
0
30
29
28
27
26
25
24
23
22
21

FIGURE 4

of the micrometer of the spectrometer and are nearly proportional to the angular displacement of the prism table. Using the ~~source~~ same abscissas the dispersion curve of the monochromator has been drawn in the same figure, with its ordinates representing wave-lengths in microns shown at the right. The dispersion curve was determined from the following well known points.

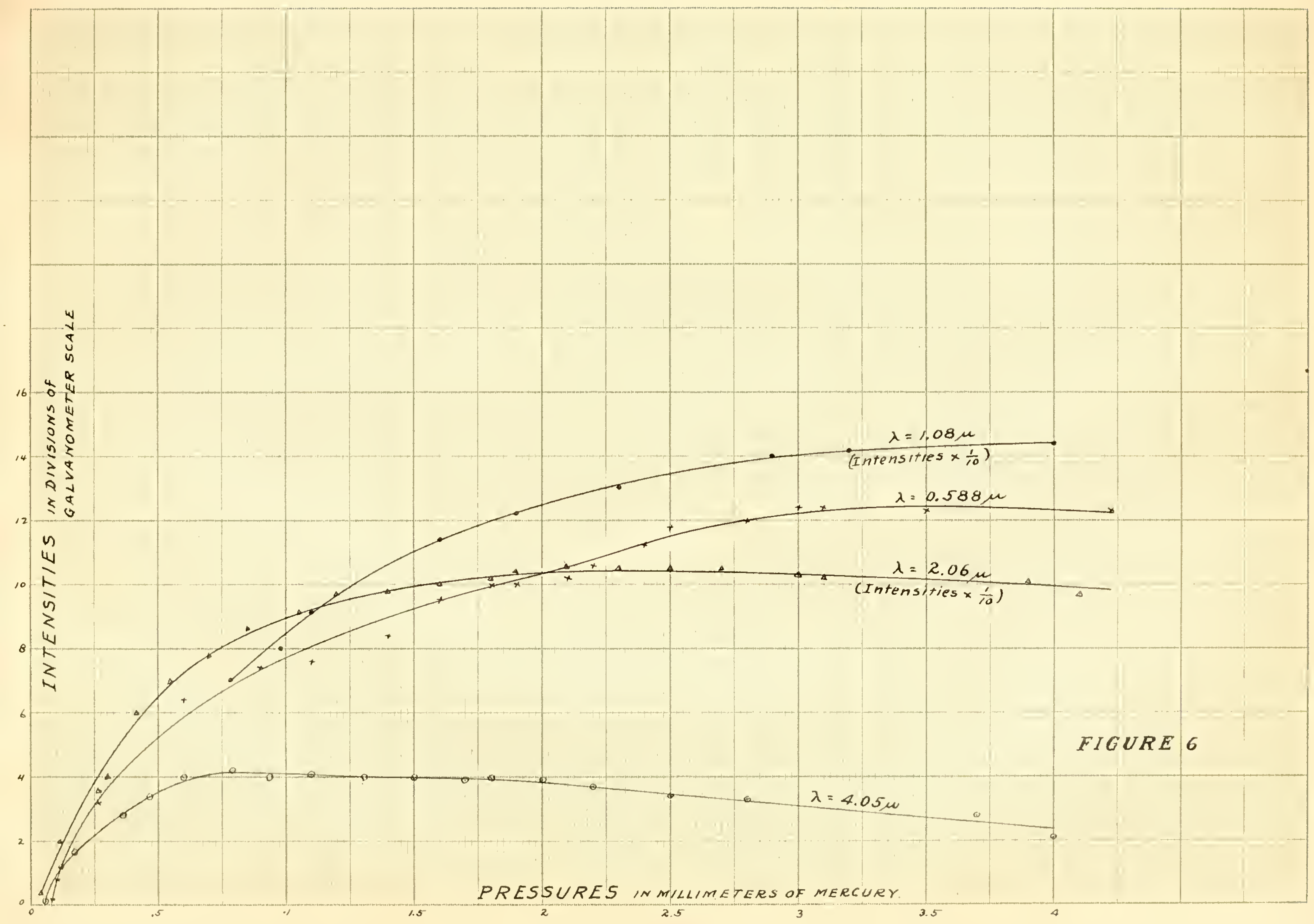
Helium	0.58 μ
"	.67 μ
"	.76 μ
"	1.08 μ
"	2.06 μ
CO_2	2.7 μ
"	4.4 μ
Residual rays of Iceland Spar	6.69 μ
" " " " "	11.41 μ
" " " quartz	8.49 μ
" " " "	9.03 μ

The accuracy with which the points of a single series of observations fall upon the intensity curve shows that the performance of the galvanometer was much more consistent than is usual with instruments of such high sensitivity. The pressure for this curve was .65 mm. The peaks represent the principal lines of neutral helium. The infra-red region was explored under various pressures as far as 11.41 μ and it seems certain that there are no new lines in this region



λ = 1.08 μ
(Intensities × 1/10)
λ = .588 μ
λ = 2.06 μ
(Intensities × 1/10)
λ = 4.05 μ
INTENSITIES IN DIVISIONS OF GALVANOMETER SCALE.
PRESSURE IN MILLIMETERS OF MERCURY

FIGURE 5



INTENSITIES IN DIVISIONS OF GALVANOMETER SCALE
PRESSURES IN MILLIMETERS OF MERCURY
λ = 1.08 μ
(Intensities × 1/10)
λ = 0.588 μ
λ = 2.06 μ
(Intensities × 1/10)
λ = 4.05 μ
0
2
4
6
8
10
12
14
16
.5
1
1.5
2
2.5
3
3.5
4

FIGURE 6

of an intensity as great as $\frac{1}{160}$ of the line 4.05 μ. The intensity of this line is given as 4 by **Paschen.**

There was a long band of radiation due to hot glass extending from 3.55 μ to 9.85 μ and having peaks at about 5.60μ and 8.55 μ.

II. Variation of Intensity with Pressure.

The relative intensity of the helium lines has been a matter of considerable uncertainty. The intensities given in tables, being those of Paschen, were determined by a grating at pressures and current densities which are only approximately known. As is well known, the distribution of energy in grating spectra is a characteristic of the grating, and varies among different gratings both with the wave-length and the order of the spectrum.

The variation of intensity with pressure is shown in the curves of Figures 5 and 6. The abscissas represent pressures in cm. of mercury; the ordinates, galvanometer deflections. The ordinates for the lines 1.08 μ and 2.06 μ are reduced to 1/10 of their actual values. The potential difference across the tube was constant at 5000 volts within the regulation of the generator. The pressure was allowed to rise slowly from .01 mm. at which the tube was non-conducting, by the influx of helium through a fine capillary. In order to show more clearly the forms of these curves at low pressures another series of observations were taken from .05 to 4 mm. These results are shown in Figure 6. At the lowest pressures the discharge was very unsteady.

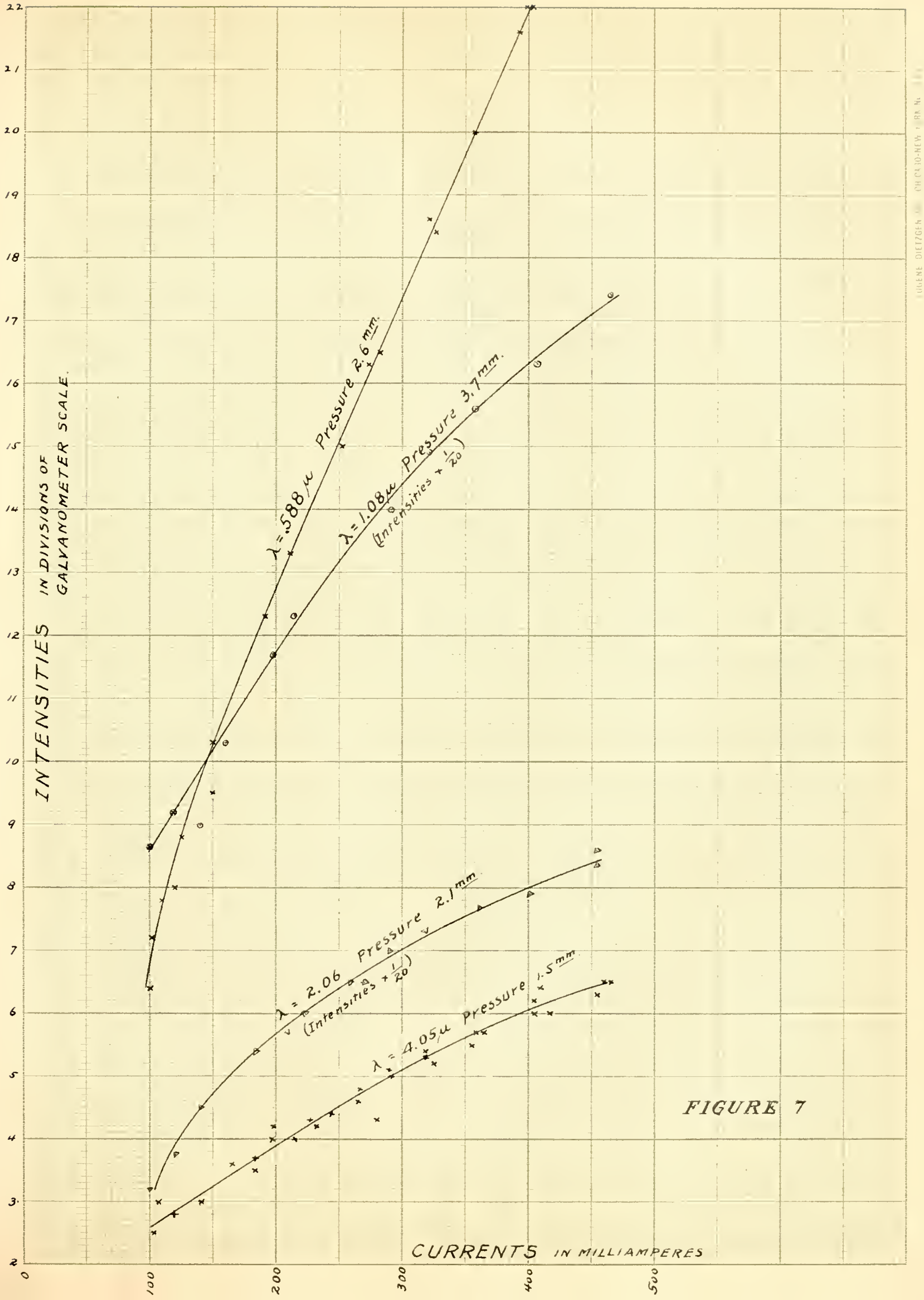

INTENSITIES IN DIVISIONS OF GALVANOMETER SCALE.
CURRENTS IN MILLIAMPERES
λ = .588 μ Pressure 2.6 mm.
λ = 1.08 μ Pressure 3.7 mm.
(Intensities ÷ 1/20)
λ = 2.06 Pressure 2.1 mm
(Intensities ÷ 1/20)
λ = 4.05 μ Pressure 1.5 mm
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
0
100
200
300
400
500

FIGURE 7

It is seen from the curves that the doublet lines 0.58 and 1.08 μ reach a maximum at much higher pressures than the singlet 2.06 μ. The behavior with pressure of the line 4.05 μ, which according to Fowler is not assigned to any series, is seen to be similar to that of 2.06 μ. This seems to indicate that the line belongs to the singlet system, and hence may be accounted for as a combination line *4B* - *5B*. It is further observed that at no pressure are the intensities of the lines 1.08 μ and 2.06 μ in the ratio of 200 to 20 as is given in the tables of spectral lines. This difference may be attributed to the afore-mentioned fact that the tabular intensities were determined with a grating.

III. Variation of Intensity with Current.

Figure 7 shows the curves for the variation of intensity with current, each taken at a pressure which gives a maximum intensity as shown in Figure 5. The abscissas are milliamperes and the ordinates are galvanometer deflections. Below 100 milliamperes the readings of the milliammeter were unreliable. The ordinates for the curves of 1.08 μ and 2.06 μ are reduced to 1/20 of their actual value. It is observed that the line 4.05 μ increases less rapidly with current than any of the others. This line, at first thought to be new, has apparently escaped the attention of Fowler and other compilers. It is not recorded in the chapter on Helium in Kayser's Handbuch der Spectroscopie, Vol. 5, but is listed under "Haupt-linien

der Elementen" in Vol. VI.

IV. New Lines:

The intensity curves show several faint lines between .706 μ and 1.08 μ, which have not been recorded in previous observations on Helium. From the dispersion curve they would have wave-lengths .76μ, .77μ, .82μ and .86μ. The first and third of these may be accounted for as ionized lines of Helium; and the second and fourth as due to traces of Oxygen. In order to determine these wave-lengths more accurately a prism spectrograph was set up and photographs of this region were made on plates super-sensitized for the infra-red with dicyanin, kindly furnished by Dr. W.F. Meggers of the Bureau of Standards. These plates on fifteen and thirty minute exposures showed faint lines at .811 μ, .818 μ, .840 μ and .847 μ. The last of these lines is probably .8446 of Oxygen as there was a trace of Oxygen and Hydrogen in the tube, but no other impurities. The lines appear as doublets on the plate and their separation can be measured much more accurately than their wave-lengths as obtained from the dispersion curve. There are no lines in the "Hauptlinien der Elementen" of Kayser's Handbuch which could account for the first three of the above lines. The line .818 obtained by this method checks with the value .82 obtained from the intensity

curve, corresponding to a line of ionized Helium. This, however, is open to question because ionized Helium was not conspicuously present in the tube. But the photographic determinations were made with a tube having only half the length and twice the cross-section of the original tube, the latter having been broken. Hence we should expect ionized Helium to be present in less amount than in the original tube. This leaves the lines .811μ and .840μ unaccounted for and probably due to combination lines of neutral Helium.

Conclusions.

The infra-red spectrum of Helium has been explored from 0.58 μ to 11.61 μ and with the exception of the new lines of wave-lengths .811μ, .818μ and .840 μ very probably no lines of intensity greater than 1/160 that of the 4.05 μ lines appear under the conditions used.

The variation of intensity with pressure and with current of the lines 0.58 μ, 1.08 μ, 2.06 μ and 4.05 μ has been studied. The relative intensities of these lines have been found to be quite different from those usually given.

A photographic study of the region at .8μ gives three new lines, one of which is found also by the thermo-couple.

Finally we wish to acknowledge our indebtedness to Dr. Pfund who proposed the problem and under whose direction the entire work was carried out; to Professor Ames for his constant interest in

the problem and for the promptness with which he placed the facilities of the laboratory at our disposal; and to Professor R.W.Wood for the loan of many pieces of apparatus and for frequent helpful suggestions.

Biographical Note.

Frank Leigh Robeson, son of George M. and Anna (McConnell) Robeson, was born at Farmville, Virginia, June 24, 1884.

He was prepared for college in the local high school, and was graduated from Virginia Polytechnic Institute in the course of Mechanical Engineering receiving the degrees of B.S. (1904) and M.E. (1905), with honors.

After three years as instructor in Mathematics at Virginia Polytechnic Institute, and one year in business, he pursued advanced work at Columbia University, obtaining the degree of A.M. in 1913, the subject of his essay being "The History and Properties of the Cycloid". Since 1913, with the exception of two years spent in graduate study at the Johns Hopkins University, he has been engaged in the teaching of Physics at Virginia Polytechnic Institute.

At the Johns Hopkins University his work has been in Physics as principal subject, Mathematics and Astronomy as subordinates. He has attended the lectures of Professor Ames and Wood, Associate Professors Pfund, Cohen and Murnaghan, and Dr. MacKenzie.

Biographical Note.

Walter White Steffey, son of Alexander M. and Dora (White) Steffey was born at Rural Retreat, Virginia, March 22, 1892.

In 1913 he graduated from Emory and Henry College, taking the A.B.degree. Two years were spent teaching in the high schools of Virginia. For four years 1915-17 and 1921-23 he has been a graduate student at the Johns Hopkins University. With the exception of one year in the U.S.Army the rest of the time has been occupied with the teaching of Physics at the Georgia School of Technology, the University of Maine and the Drexel Institute.

At the Johns Hopkins University he has taken Physics as a principal subject, and Physical Chemistry and Astronomy as subordinate subjects. He has taken lectures under Professors Ames, Wood and Patrick, Associate Professors Pfund and Cohen and Dr. MacKenzie. In 1922 he received the A.M.degree, the subject of the essay being "The Experimental Verification of the Theory of Relativity". He has held several scholarships during this time.