Effect of Change in Pressure and Current Density on the Spectrum of Helium.

Thesis by

Albert Clarence Hodges

In Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy.

California Institute of Technology
Pasadena, California

1928.

ABSTRACT.

A study has been made of the intensities of the various lines of the neutral helium spectrum, with the particular view of obtaining regularities in the variation of the relative intensities with changes in current density and pressure.

The method used is a modification of that developed by Ornstein at Utrecht. A study has been made of the lines 5876, 5016, 4922, 4713, 4472, 4387, 4143, 3964, 3889 and 3819, at pressure of 27,9 and 3 mm., and currents of 64, 20, and 4 milliamperes in a capillary discharge.

The results show little variation with current density except for the trial at 3 mm pressure. At this pressure, the higher members of the series seem to be relatively stronger, and the singlet system is relatively stronger with a decrease in current density.

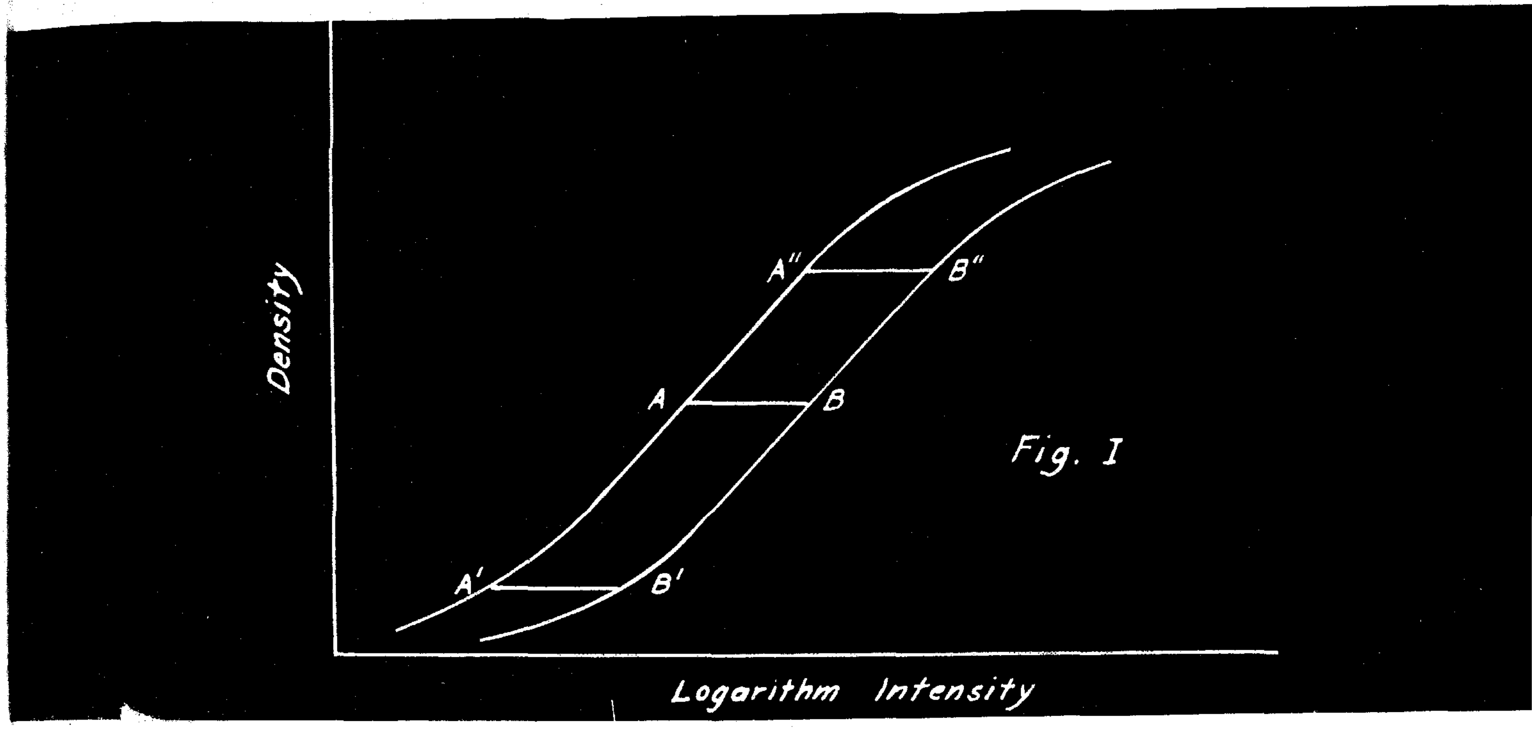
There is a very definite shift of energy into the higher members of the various series with a decrease in pressure. There does not appear to be much change in relative intensity for the two higher pressures. The singlet system is made more prominent by decreasing the pressure.

Tables are included showing the relative intensities of three members of the diffuse series of the triplet system, 2 members of the principal series of the singlet system and three members of the diffuse series of the singlet system.

INTRODUCTION.

Theoretical investigation by Bohr, Sommerfeld, Lande', and others, have shown interesting regularities in the line spectra of elements. These were first concerned with frequency relations, but soon regularities in intensity ratios in multiplets were noted. This scheme of the relative intensity of components of multiplets has been fully discussed by Sommerfeld (1) and has led to the formulation of a number of rules known as Summation Rules. Measurements made by Dorgelo, (2) using a method developed by Ornstein (3) at Utrecht completely confirmed these rules for multiplets of the sharp and diffuse series of the alkalis and alkaline earths, and the fundamental series of the earth-alkalis, and for several systems of higher multiplicity. Similar investigations, made by Frerichs (4) using a slightly different method, completely confirmed the measurements made by Dorgelo. A number of later investigations have shown, however, a considerable deviation from the 2:1 ratio for CS doublet 4555Å, 4593Å. (5) (6) This difference may be explained by the excess absorption of one of the lines by other excited atoms.

Any photographic method of determining relative intensity depends on the characteristics of the photographic plate. If we define as the density of the photographic deposit, the logarithm of ratio of the light transmitted by the unexposed to the light transmitted by the blackened portion of the film, the well known H and D curve results.



The middle portion of this curve can be represented by the equation

$$D = \gamma \log I t^{p} + a$$

where $D = \log_{10} \frac{U_o}{U}$

$I =$ intensity of incident light.

$t =$ time of exposure.

$\gamma =$ slope of the straight part of the curve.

$p =$ Schwartzschild constant.

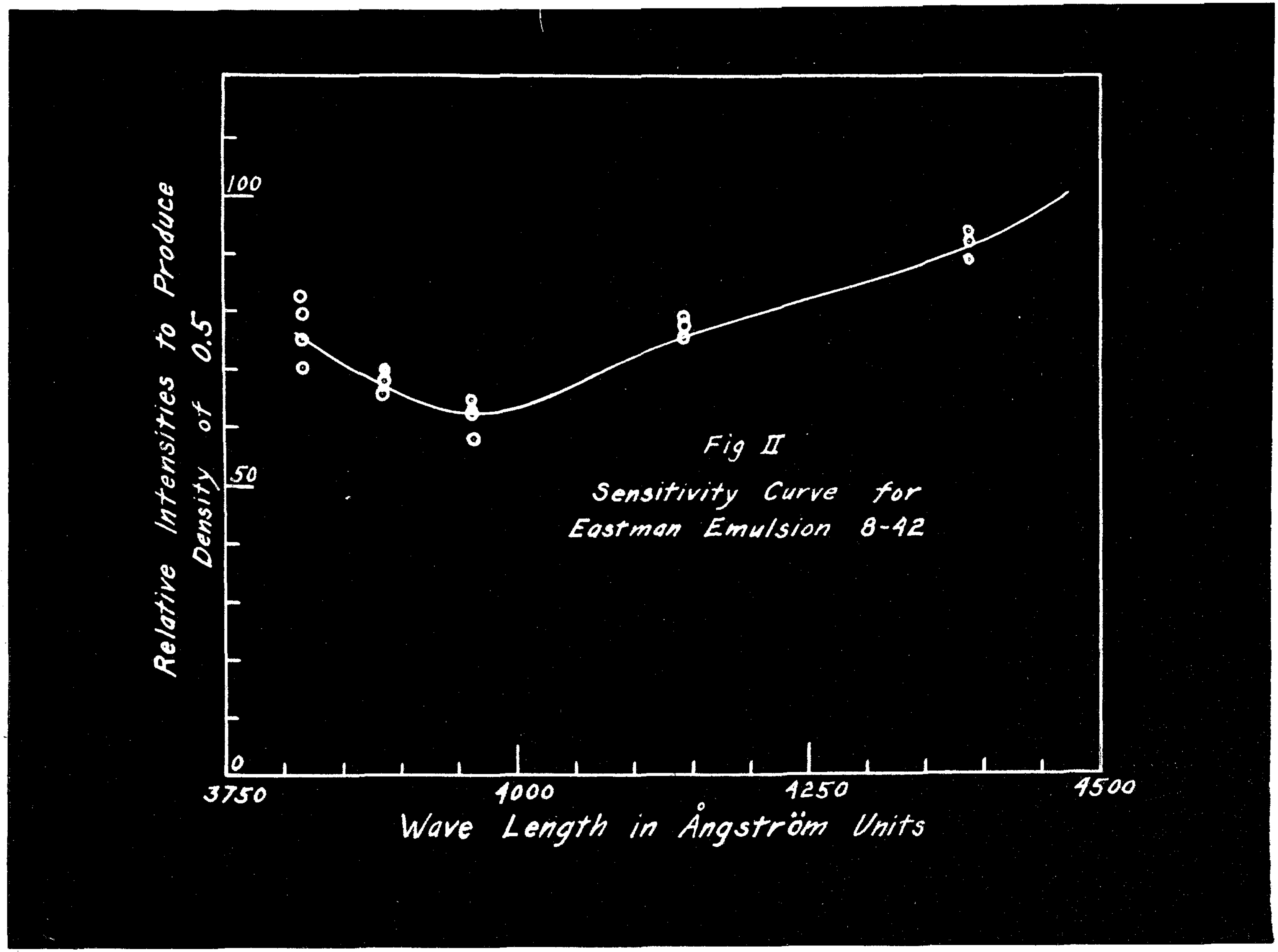
For a given plate, γ and p may depend on both the wave length, and the kind and duration of the development. Usually γ is larger for the longer wave lengths, altho for some emulsions it is nearly constant for wave lengths lying between 4500Å and 3800Å.

It can be seen from figure 1, that for two sources of the same wave length, and the same time of exposure, photographed on the same plate, and hence having the same development, will be separated along the log I axis by a constant distance AB = A'B' = A"B". This separation holds for the curved part of the curve as well as for the straight part of the curve. Thus the intensity ratio is determined by the distance AB. The form of the H and D curve can be used to determine the ratio of two sources, even though only a few points are used to determine each curve. The degree to which two such curves may be shifted is also a measure of the accuracy of the intensity ratio. It is therefore good practice to draw the curves with a constant displacement, since this really increases the number of points which fix each curve.

Except for a very small region, the sensitivity of the plate may vary greatly with the wave lengths of light striking it.

Figure II. shows the sensitivity of the films used in this work, for the region from 3800Å to 4500Å. In plotting this curve, the intensity of the light of wave length 4472 was taken as 100%. The points are shown for five films. These films were exposed, developed and photometered in the same manner as other films used.

This shows the necessity of comparing each wave length, of the source to be investigated, directly with some standard source. If, however, γ is the same for a group of lines, as has been shown to be the case from 4500Å to 3800Å (7) the lines may be compared with each other and the plate calibrated over this range. This method was used for some of


Relative Intensities to Produce
Density of 0.5
100
50
0
3750
4000
4250
4500
Wave Length in Ångström Units
Fig II
Sensitivity Curve for
Eastman Emulsion 8-42

the lines of shorter wave length because of the low intensity of the standard source in this region. If, however, the time of development is too long, this cannot be done.

It is essential, if intensities are to be compared directly with a standardized lamp, that the time of exposure be the same for both exposures, otherwise a separate determination of the Schwartzschild constant must be made and while Schwartzschild's constant is not strictly constant for large differences in wave length, it may be assumed as constant for small differences, certainly, for lines of low intensity, the error involved is not larger than the error introduced by direct comparison. For long exposures neutral absorbing filters were placed in the path of the incident light from the standard lamp. These filters were the same as those used for reducers, hence the transmission for each wave length has been determined. It would have been better to reduce the intensity from the standard lamp by narrowing the slit of the spectroscope; but this would have required a better slit than the one used.

THE STANDARD SOURCE.

The standard source was an incandescent, ribbon filament lamp. The filament is 3.5 cm long and 2 mm wide, and was burned at constant current. The filament was aged by running it for several hours with a current of 23 - 24 amperes, and about 24 hours with a current of 20 amperes. Such a lamp has been shown by Worthing, and Forsythe (8) to radiate as a "gray" body. The emissivity of tungsten at various temperatures has been carefully determined by them for two wave lengths, and it has been shown that the emissivity varies linearly with the wave length in the visible spectrum.

The intensity distribution can be calculated from Wien's equation for the visible spectrum, if a factor is introduced to take care of the emissivity of tungsten. Wien's Equation, thus modified, takes the form

$$I_\lambda = c_1 \varepsilon_\lambda \lambda^{-5} e^{-\frac{c_2}{\lambda T}}$$

The temperature of the filament at various currents was measured by Dr. C. H. Prescott, National Research Fellow in Chemistry, with a disappearing filament type of radiation pyrometer. These temperatures are correct to within 1°C or 2°C.

In calculating the relative distribution of energy, the constant c_1, drops out and the value of c2 was taken as 14330 (1) μ degrees, as determined by Forsythe and Worthing. The relative distribution of intensity for the various temperatures at which the lamp was operated are shown in Table I. These were calculated from Wien's equation, after applying the factor for emissivity from the data of Worthing and Forsythe.

TABLE I.

Wave Length	16 amp T = 2175°K	16 amp T = 2014°K	15 amp T = 1914°K
	I_{2175}	I_{2014}	$I_{1914°}$
5876	100	41.30	22.10
.5016	33.4	11.8	5.63
4922	28.6	9.87	4.67
4713	19.8	6.5	2.98
4472	12.8	4.00	1.74
4387	10.0	3.05	1.26
4143	5.61	1.59	.520
3965	3.47	.93	.385
3889	2.42	.63	.245
3819	2.22	.58	.137

THE OPTICAL ARRANGEMENT.

If one is to plot a density - intensity curve similar to the one in Figure I, it is necessary to have light of various intensities incident on the film. This can be best done by passing the light through a series of reducers, each of which transmits a certain fraction of the light. In this work a Rowland mounting was used with a Wallace Replica Grating of 25,000 lines to the inch. The Rowland mounting is astigmatic, vertical lines at the slit being in focus at the plate, whereas horizontal lines on a tangent to the plate are in focus.

The reducer was made of neutral gelatine filter, and was divided into six parts, which were numbered consecutively from 1 to 6. Sections 1 and 6 were left open, while in openings 2,3,4,5, were placed, 1,2,3, and 4 filters.

Openings numbers 1 and 6 were taken as 100% intensity, while the transmissions of the others were measured with a thermocouple and galvanometer for 5876Å, 5016Å, 4922Å, 4713Å, 4387Å. For wave lengths below 4387Å, the light was too weak to get good measurements. These reducers were calibrated in place with the Rowland grating. The transmissions for the other wave lengths were measured photographically. Since the approximate transmissions were known, the H and D curves were drawn so as to make the slopes of all curves from 4472Å to 3889Å the same. This was done for a large number of photographs so the final average values cannot be far wrong.

Table II. gives some idea of the accuracy of the measurements. Each value of the transmission is the result of averaging over several thermocouple readings.

TABLE II.

Wave Length	Reducer No.	Ratios of Transmission				Mean
	2 - 1	46.7	47.3	47.3		47.1
5876	3 - 2	45.1	47.2	42.7	44.1	44.8
	4 - 3	42.5	44.2	47.6	44.8	44.8
	5 - 4	38.4	38.6	38.4		38.5
	2 - 1	44.5	44.1	44.5		44.4
5016	3 - 2	43.1	44.2	41.2	45.5	43.5
	4 - 3	40.2	42.2	41.3	40.8	41.2
	5 - 4	40.7	44.7	42.7	44.4	43.1
	2 - 1	42.7	44.0	43.8		43.5
4713	3 - 2	45.8	47.8	44.8		46.2
	4 - 3	45.2	42.0	43.1	44.5	43.7
	2 - 1	45.5	43.8	41.8		43.7
4472	3 - 2	42.7	45.7	44.7		44.4
	4 - 3	38.7	38.0	42.1		36.7

TABLE III.

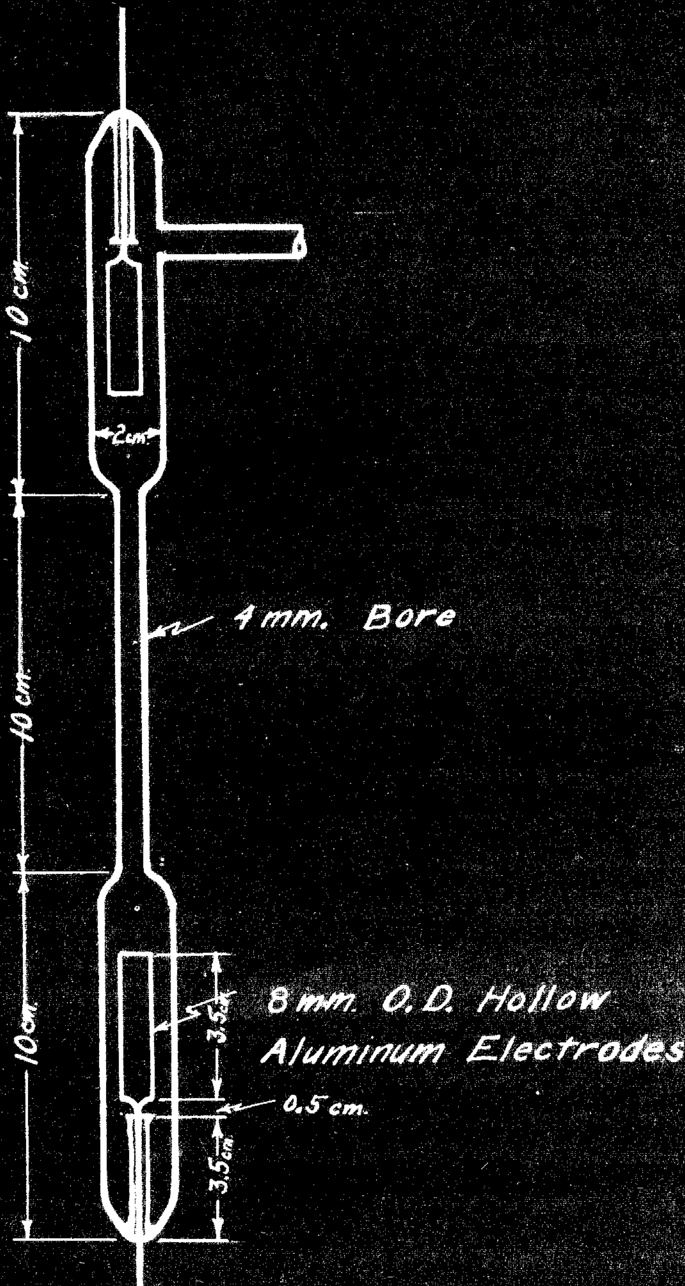
Comparative transmission in per cent.

Wave Length	Screen No. 1	2	3	4	5
5876	100	47.1	21.1	9.45	3.64
5016	100	44.4	19.3	7.97	3.44
4713	100	43.5	20.1	8.80	
4472	100	43.7	19.4	7.30	

It is quite difficult to get a source of light which will remain constant over the time required for calibration and yet have sufficient intensity to make the observation for high reduction for shorter wave lengths. A 400 W mazda lamp, with a water filter, was used and the variations in transmission were due to a large extent to the variations in the radiation from this lamp.

Figure III. shows the discharge tube used, with its dimensions. The arc spectrum was excited with a 10,000 volt, 1/2 KVA Thordorson transformer. The power was supplied from the municipal power circuit at 50 cycles. The voltage across the tube was approximately 575 volts. The volume of gas, not included in the tube, was approximately 4.5 times the volume of the tube. The tube was connected with a charcoal trap which was always immersed in liquid air.

The helium used was practically free from impurities, as no lines due to impurities showed on the plate.



DISCHARGE TUBE

Fig. III

THE PHOTOMETER.

The density of a photographic deposit has been defined as $\log_{10} \frac{I_o}{I}$, in which I_o is the light that is transmitted by the exposed part of the film. If the films or plates are photometered with a Hartmann[9] or Fabry and Buisson,[10] type of photometer the ratio $\frac{I_o}{I}$ may be measured directly. On the other hand, if an instrument of the type of the Moll,[11] or Koch[12] microphotometer is used, the ratio of $\frac{I_o}{I}$ is given by the ratio of the galvanometer deflections, and is equal to $\frac{U_o}{U}$, where U_o is the deflection when light is transmitted by the clear part, and U is the deflection caused by light transmitted by the blackened part of the film.

In the present case, there is little difference between the two types of methods, optical or thermocouple, as far as the required accuracy is concerned. Either type of instrument will give results which are more accurate than the determination of the characteristics of the photographic plate. In this work, a thermocouple and high sensitivity galvanometer were used. The filament of a tungsten incandescent lamp was brought to a focus on the film at the spot to be investigated. Behind the film a slit, .5 mm x 3 mm, was placed and this slit was brought to a focus on one junction of a bismuth, bismuth-tin thermocouple. The deflections of the galvanometer were read visually.

METHODS OF DETERMINING RELATIVE INTENSITIES.

As shown in Figure I, the relative intensity between two sources can be obtained by the method of displacing one of the curves until it coincides with the other. The amount of this shifting is a measure of the intensity ratio of the two sources. It is obvious that one may plot $\frac{U}{U_o}$, or some other function of $\frac{U}{U_o}$ as ordinates, and obtain the same intensity ratio.

This method will be illustrated in Figures IV, V, VII. From Figure 3, one observes that the ratio between 4472 and 3964 is given by the distance along the log I axis. This ratio is

$$I_{4472} : I_{3964} = 13:1$$

but this does not take account of the condition that the sensitivity of the film is different for light of different wave lengths.

From Figure II, we can see that, for light of a given intensity, 62.5% of the light of wave-length 3964Å will cause the same photographic density as 100% of the light of wave length 4472Å. Hence the relative intensity is

$$I_{4472} : I_{3964} = 13: .63$$

Or, since the intensity of the 4472 line is 15.6 on an arbitrary scale, then the intensity of the line 3964Å is

$$\frac{1}{13} \times 15.6 \times \frac{62.5}{100} = .74$$

Further, we can see, at once, from Figure 4, that, for the trial with a pressure of 3 mm. of mercury, for the wave length 5016Å

$$I_{cont} : I_{He} = 100 : 87$$

Since these curves are for the same wave length, same time of exposure, and the same development no factor of adjustment is needed.

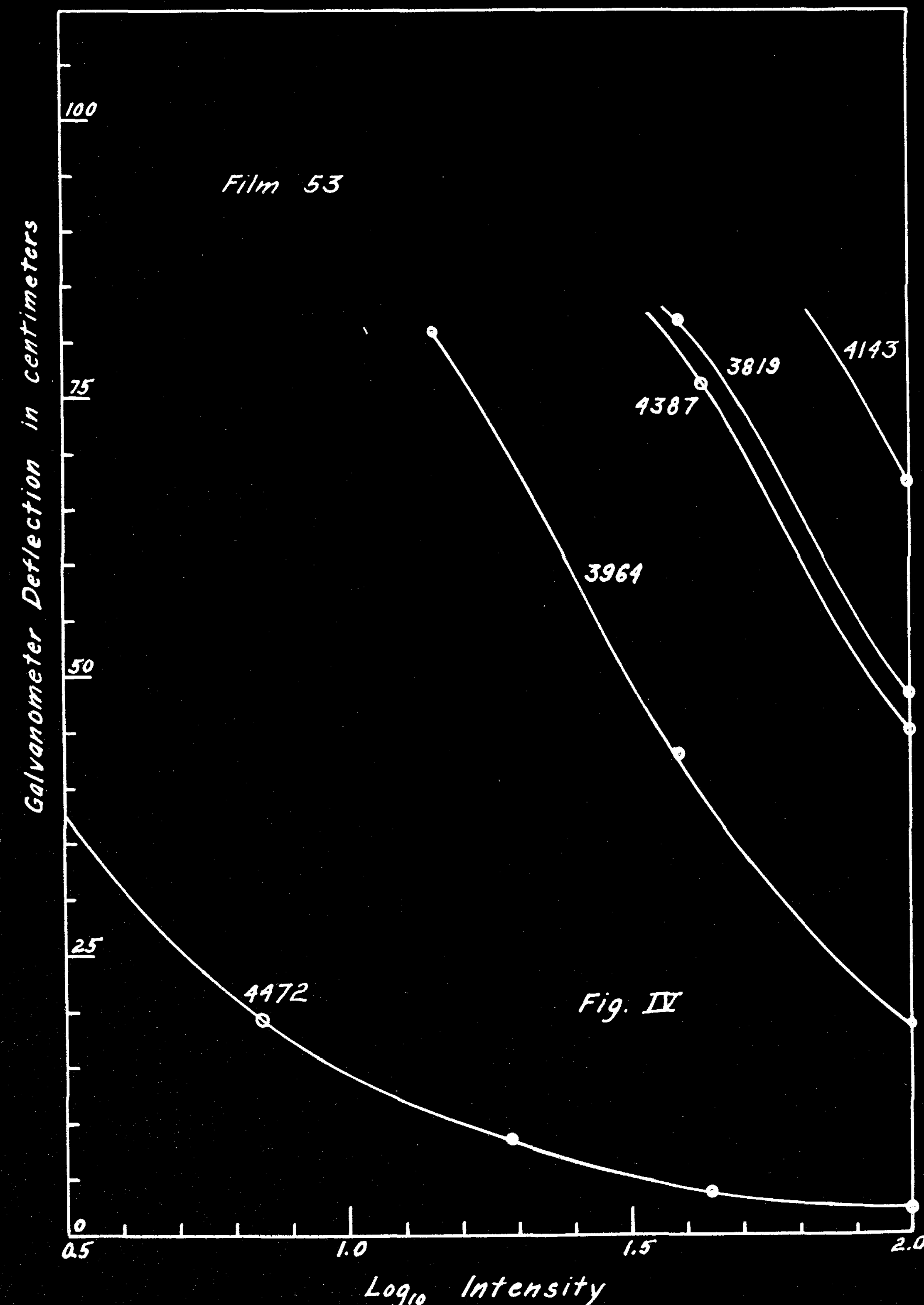
The following data and the corresponding curves are submitted as a fair test of the degree of exactness to which the photographic plate can be applied to the measurement of relative intensities. The curve in figure VI, is given to show that the method of shifting can be used, even for very small photographic deposits. This film, 67, was exceptionally good, however, and this method could not always be used.

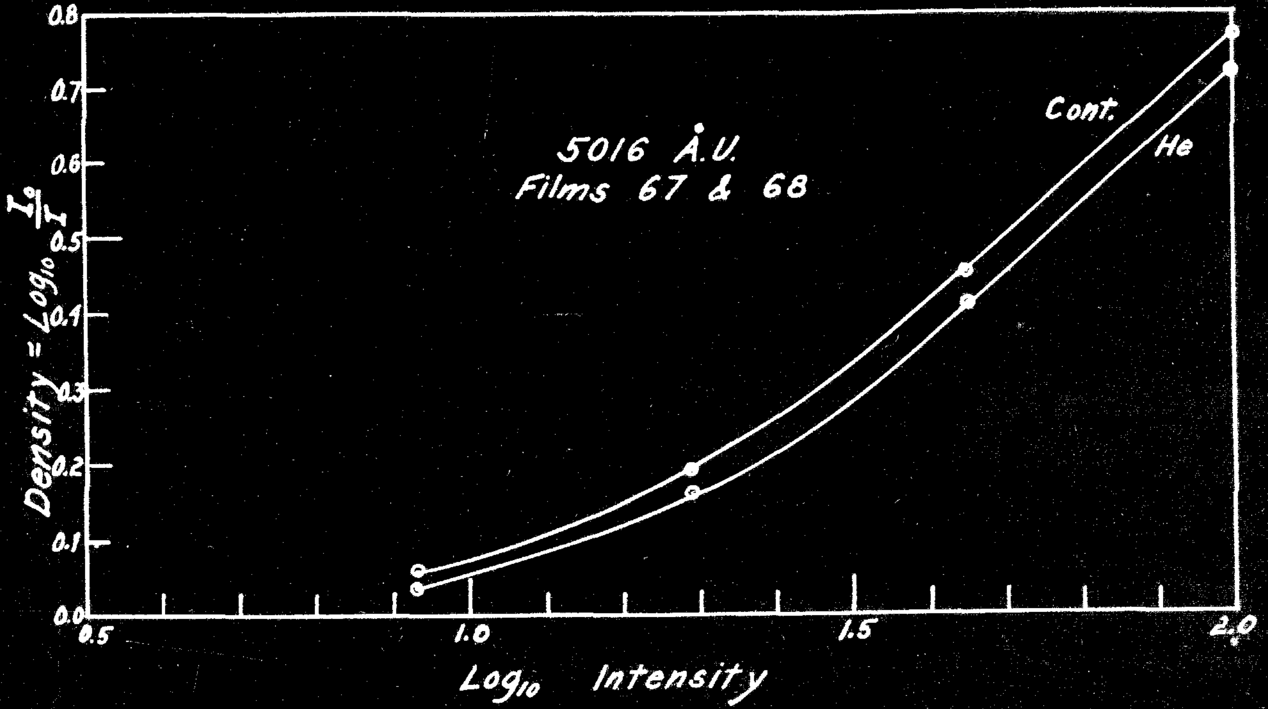
TABLE IV.

Film	Source	Wave Length	Reducer	Defl.	Density	$\frac{U}{U_o}$
53	He	4473	1	1.04		.021
			2	1.90		.039
			3	4.02		.082
			4	9.30		.191
			5	21.80		.424
			Clear	48.80		
		4387	1	22.30		.451
			2	37.65		.761
			Clear	49.50		
		3964	1	9.45		.188
			2	23.95		.478
			3	40.60		.811
			Clear			
67	Cont	5016	1	8.60	.761	
			2	17.55	.448	
			3	32.20	.187	
			4	43.05	.060	
			5	46.80	.024	
			Cl	49.50		
68	He	5016	1	9.65	.715	
			2	19.70	.405	
			3	34.90	.157	
			4	46.10	.035	
			Cl.	50.00		

TABLE IV. (Cont'd.)

Film	Source	Wave Length	Reducer	Defl.	Density	$\frac{U}{U_o}$
67	Cont	3819	1	29.65	.215	
			2	44.75	.037	
			3	47.55	.01	
			Cl	48.70		
68	He	3819	1	19.80	.403	
			2	37.15	.128	
			3	46.80	.028	
			Cl	49.90		


Film 53
Galvanometer Deflection in centimeters
Log10 Intensity
100
75
50
25
0
0.5
1.0
1.5
2.0
4143
3819
4387
3964
4472
Fig. IV


5016 Å.U.
Films 67 & 68
Cont.
He
Density = $Log_{10} \frac{I_o}{I}$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.5
1.0
1.5
2.0
Log_{10} Intensity

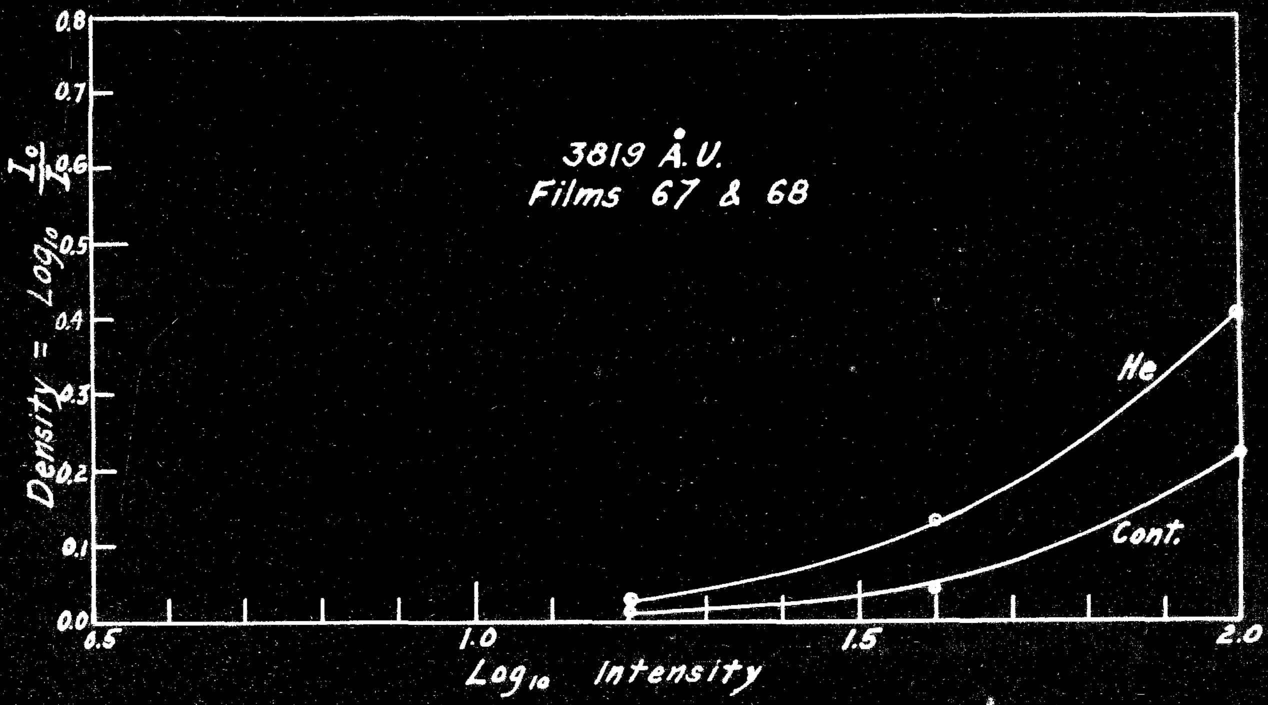

3819 Å.U.
Films 67 & 68
He
Cont.
Density = $Log_{10} \frac{I_o}{I}$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.5
1.0
1.5
2.0
Log_{10} Intensity

Fig. V & VI

TABLE V.

Wave Length		Current = 65 ma. Pressure 27 mm.	9 mm.	3 mm.	Current = 20 ma. Pressure 27 mm.	9 mm.	3 mm.	Current = 4 ma. Pressure 27 mm.	9 mm.	3 mm.
5876	2^3P-3^3D	100	100*	100	100	100	100	100	100	100
4472	2^3P-4^3D	11.5	9.	14.3	6.3	6.5	18.3	7.05	7.4	29.0
3819	2^3P-6^3D	.22	.17	.44	.19	.18	.88	.20	.24	1.61
4713	2^3P-4^3S	1.3	1.5	2.7	1.8	1.0	3.4		1.5	7.9
3889	2^3S-3^3D	28.7	20.6	36.8	19.6	19.1	25.2	26	22.2	44.5
5016	2'S-3'P	9.8 (100)	7.2 (100)	9.3(100)	6.8(100)	5.6 (100)	10.6 (100)	7.0(100	5.6 (100	25.6 (100)
3964	2'S-4'P	.54 (5.5)	.42 (5.9)	1.2(12.9)	.30 (4.4)	.37 (6.4)	1.1 (10.3)	.38(5.4)	.34(6.1)	1.52(6.3)
4922	2'P-4'D	2.0 (100)	2.0 (100)	4.0(100)	2.6 (100)	1.9 (100)	4.0 (100)			7.9 (100)
4388	2'P-5'D	.29 (14.5)	.26 (13.0)	.69 (17.3)	.38 (14.6)	.22 (11.5)	.70 (17.5)	.25	.28	2.1 (26.4)
4143	2'P-6'D	.13 (6.5)	.12 (6.0)	.39 (9.7)	.20 (7.7)	.14 (7.4)	.53 (13.3)	.20	.24	1.35(17.2)

* This value is probably 10% to 15% too high.

TABLE VI.

Wave Length		Pressure = 27 mm. Current 65 ma.	20 ma.	4 ma.	Pressure = 9 mm. Current 65 ma.	20 ma.	4 ma.	Pressure = 3 mm. Current 65 ma.	20 ma.	4 ma.
5876	2^3P-3^3D	100	100	100	100	100	100	100	100	100
4472	2^3P-4^3D	11.5	6.3	7.05	9.0	6.5	7.4	14.3	18.3	29.0
3819	2^3P-6^3D	.22	.19	.20	.17	.18	.24	.44	.88	1.61
4713	2^3P-4^3S	1.3	1.8		1.5	1.0	1.5	2.7	3.4	7.9
3889	2^3S-3^3D	28.7	19.6	26	20.6	19.1	22.2	36.8	25.2	44.5
5016	2'S-3'P	9.8 (100)	6.8 (100)	7.0 (100)	7.2(100)	5.6 (100)	5.6 (100)	9.3 (100)	10.6 (100)	25.6(100)
3964	2'S-4'P	.54 (5.5)	.30 (4.5)	.38 (5.5)	.42 (5.8)	.37 (6.6)	.34 (6.2)	1.2 (12.9)	1.1 (10.5)	1.52(6.6)
4922	2'P-4'D	2.0 (100)	2.6 (100)		2.0 (100)	1.9 (100)		4.0 (100)	4.0 (100)	7.9 (100)
4388	2'P-5'D	.29 (14.5)	.38 (14.6)	.25	.26 (13.0)	.22 (11.5)	.28	.69 (17.3)	.70 (17.5)	2.1 (26.4)
4143	2'P-6'D	.13 (6.7)	.20 (7.7)	.20	.12 (6.0)	.14 (7.4)	.24	.39 (9.7)	.53 (13.3)	1.35 (17.2)

TABLE VII.

Current = 65 ma.

Wave Length	27 mm.	9 mm.
5876	870	1120
4472	100	100
3819	19	18.7
4713	11.5	
3889	250	230
5016	87 (100)	81 (100)
3964	4.75 (5.5)	4.7 (5.8)
4922	17.8 (100)	22.4 (100)
4388	2.54 (14.3)	2.86 (12.8)
4143	1.13 (6.3)	1.31 (5.9)

RESULTS.

The relative intensities of the neutral helium discharge were obtained for three pressures 27 mm, 9 mm, and 3 mm, and for currents of 65 ma., 20 ma., and 4 ma., in a capillary discharge. The relative intensities are tabulated for three lines of the diffuse series of the triplet system, for 2 lines of the principal series of the singlet system, and for three lines of the diffuse series of the singlet system. In addition, there are values, relative to 5876, for the lines 4713Å, and 3889Å, of the triplet system.

These intensity relations as depending on pressure and temperature are tabulated in Tables V and VI. In arranging these tables, the intensity of the line 5876Å, is taken as 100 arbitrary units. The figures in parentheses give the relative intensity of the members in the corresponding series, based on 100 for the strongest line.

Table VII gives the relative intensities for the trials at 27 mm., and 65 ma., and 9 mm., and 65 ma. These intensity ratios are secured by taking the line 4472Å as standard. This is justifiable because this line has been taken as a reference line to connect up the two films, the one film on which the stronger lines were photographed, and the second film, on which the weaker lines were photographed, and which had a much longer exposure. When the line 4472Å is taken as the standard, columns 1 and 2 of Table V become almost identical, except for the line 5876. This indicates a fairly large error in determining the intensity of this line. Examination of the H and D curve for this line shows a fairly large irregularity, so this error is, no doubt, due to some non-uniformity in that particular film.

The above correction would apply equally well to the corresponding columns in Table VI, although the error is not so noticeable there.

A decided increase in the intensity of the higher members of all series measured with a decrease in pressure can be observed. This is not surprising for the decrease in the number of impacts per second would result in a decrease in the probability of inelastic impact, and the transfer of energy without radiation. This effect is particularly noticeable at the lowest pressure used, 3 mm., and might lead one to suspect that the work was discontinued at the most interesting point. There is not any great difference between the relative intensities for the two higher pressures. The experimental error is fairly large, when applied to lines of low intensities.

It also appears that the singlet system gains in prominence, slightly with a decrease in current, and considerably with a decrease in pressure.

There does not appear to be any large change in relative intensity due to changing the current through the tube, except for the trials at 3 mm., pressure, for which there appears to be a shifting of intensity to the higher members of the series for both the triplet and singlet systems. The sharp series of the singlet systems seems to be the exception.

COMMENTS ON THE METHOD.

The method is straightforward and can be made to yield results approaching an accuracy of about 4%. That is, any intensity could be expressed as a fraction of a standard and the error should not be greater than 4% of the strongest line. There are a number of rather perplexing details to master, but once mastered, the method is fairly rapid.

A replica grating is not best suited for this type of work; ghosts are too prominent, and there is too much light scattered from the grating. However, the error involved here is not large, provided that there is a sufficiently large area on the grating to receive all the light that enters the spectroscope.

It has not been practicable to get both spectra on the same film, but a few preliminary tests have indicated that there is as much variation between the two ends of a $2\frac{1}{4}$" x 10" film as there is between two films from the same box. It seems to be recognized that films are not as satisfactory as plates.

The process of photometring the films is not a difficult one, and really does not contribute so much to the uncertainties of measurement. If films of large grain size are used, the beam of light in the photometer, or the photometer slit should not be too narrow.

It was very difficult at first, to so arrange conditions that the curves representing the continuous and helium spectrum could be displaced. The curve for the continuous almost invariably had a slope much less than that for the helium of the same wave length. When we began to use about one-third the time of development we had no further trouble except for the line 4472 on the longer exposures. This condition seems to be due to a selective scattering of light amounting to about 4% - 5% of the total intensity.

This value for the scattering was obtained by exposing one film for about fifteen times the normal exposure and measuring the resulting density at various distances from the image on the film. When light of this amount is scattered, it does not affect the intensity of the 100% region appreciably, but it becomes quite an item where the intensity is greatly reduced. This scattering seems to be selective, and does not appear to affect other regions of the plate.

This work was undertaken as a preliminary investigation. Many refinements can, and doubtless will be made. It is proposed to continue this problem and clear up some of the apparent irregularities observed.

It is rather difficult to estimate the actual error in any of these measurements, but the few checks which have been possible indicate an error not much larger than 5% to 6%. When it is considered that the range of intensities measured runs from 1 to 500, it is obvious that errors are apt to be large.

It would be unjust not to mention the author's

appreciation to Dr. R. A. Millikan, Dr. Wm. V. Houston, Dr. I. S. Bowen and to Mr. Walter C. Michels for counsel and assistance in this research.

1. Sommerfeld, Atombau and Spectrallinien, 4th ed. Chap. VIII, Section 5.

2. Dorgelo, Tec't. of Physik, 22, 170, 1924.

3. Ornstein, Proc. of Phys. Soc. 37, 334, 1925.

4. Frericks, Zeit. f. Phys. 31, 305, 1925.

5. Filippov, Zeit. f. Phys. 42, 495, 1927.

(6) Hughes & Hagenow, Phys. Rev. 30, 284, 1927.

7. Jones, Huse & Hall, J.O.S. 12, 321, 1926.

8. Forsythe & Worthing, Astro Jour, 61, 146, 1925.

9. Hartmann, Zeit f. Instrument, 19, 97, 1899.

10. Fabry & Buisson, Journal de Physique 5, 9, 705, 1912.

11. Moll, Kon, Akad, van Wentenschappen, Amsterdam, 28,566, 1919.

12. Koch, Ann d. Phys. 39, 705, 1912.