

THE FLUORESCENCE AND ABSORPTION SPECTRA OF SODIUM VAPOR.

By R. W. WOOD and J. H. MOORE.

THE FLUORESCENCE OF SODIUM VAPOR.

THE green fluorescence which sodium vapor exhibits when illuminated with an intense beam of white light, was first observed and studied by Wiedemann and Schmidt.¹ The method which they employed was to heat the metal in an exhausted glass bulb, concentrating a beam of sunlight on the vapor by means of a lens. A cone of green light is seen where the intense beam enters the mass of metallic vapor. Examined with the spectroscope, this light was found to consist of a band in the red, a narrower band nearly in the position of the D lines, and a broad green band which appeared to be broken up into channels or bands. The wave-lengths of some of these bands were roughly determined, but the authors do not appear to have determined exactly the relation which they bore to the absorption bands which appear in the same part of the spectrum.

Inasmuch as we have at the present time no very satisfactory theory of fluorescence, and as practically all quantitative work has been done with solutions, it seemed worth while to make a careful study of the relation between the fluorescent light emitted by sodium vapor and the light absorbed by the vapor under the same conditions. The chief points of interest which have been brought out by these investigations are the establishment of the fact that the fluorescent spectrum coincides exactly with the absorption spectrum, band for band and line for line, and a determination of the relation existing between the wave-length of the light which provokes the fluorescence and the nature of the fluorescent spectrum. The somewhat remarkable fact has been ascertained that the D line absorption

¹ *Wied. Ann.*, 57, 447, 1896.

is in no way connected with the production of the fluorescence, though the absorption at this point of the spectrum is much more intense than at any other.

By means of improved apparatus we have not only been able to photograph the fluorescent spectrum by means of a concave grating, but have been able to observe by means of a grating the fluorescent spectrum when provoked by approximately monochromatic light obtained with the Fuess monochromatic illuminator. The results of the work throw a great deal of light on the mechanics of the sodium molecule, and will doubtless prove of considerable value in the development of the theory of fluorescence.

APPARATUS EMPLOYED.

The fluorescence as observed in exhausted glass bulbs is never very intense, and the experiments can be continued only for a few moments owing to the speedy corrosion of the glass surface. Moreover, it is not possible to make use of very dense vapor, the generation of which requires a high temperature, owing to its action on glass. The form of tube which was employed by one of us in a previous investigation on the subject¹ enables vapor of great density to be obtained, but owing to the rapid distillation to colder parts of the tube, the experiment cannot be continued long enough for satisfactory photographic records. It is important not only to have a very dense vapor, but also to have the vapor confined within a small region and sharply bounded, in order that the light may not be weakened by absorption before it reaches the denser portions. To meet these requirements a new form of tube was designed and constructed which gave admirable results. With it a fluorescence ten or fifteen times as bright as anything that can be secured with glass bulbs was obtained and maintained continuously for five or six hours without recharging the tube. This tube we have had in action for fully forty hours, and it is only just beginning to show signs of leakage around the brazed joints, due to the action of sodium at a red heat on the silver, with which the joints were brazed. The tube can be very easily constructed, and when

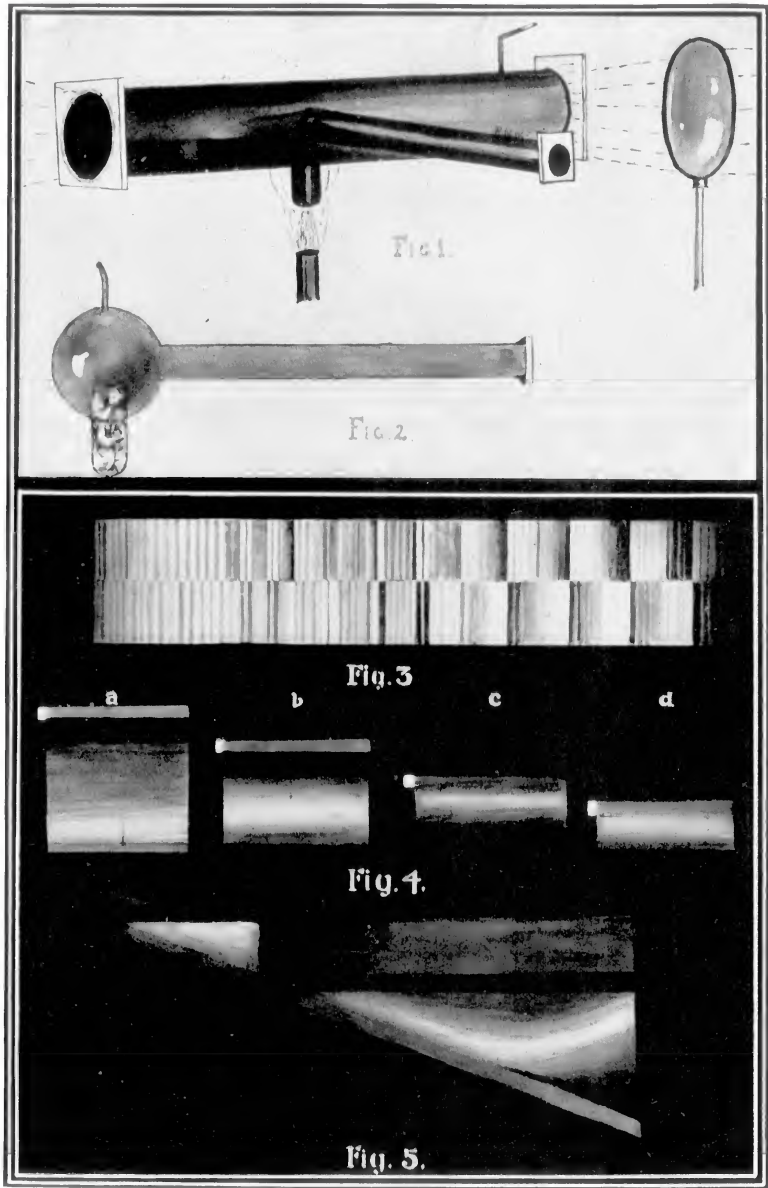
¹ R. W. WOOD, *Proc. R. S.*, **69**, 157; also *Phil. Mag.*, (6) **3**, 141, 1902.

once charged can be used over and over again without any preparation whatever, for the exhibition of this most beautiful example of fluorescence. Its general form is shown in Plate II, Fig. 1. The large tube was a piece of three-inch (sixteen gauge) Shelby seamless steel tubing, two feet in length. A ten-inch piece of thin three-fourths inch steel tubing was brazed with silver into the large tube at the center, making a right angle with it. (Fig. 2, is a cross section of tube.)

Immediately below this tube, and at a right angles to both, a small iron crucible was brazed into the larger tube, projecting into its interior to such a distance that its rim was visible through the side tube. This crucible was made by boring out a three-fourths-inch iron cylinder. A small piece of brass tubing was also brazed into the large tube near one end, through which the whole could be exhausted. The crucible was filled with lumps of sodium, and the ends of the large tube closed with plate glass, carefully cemented on with sealing wax. The side tube was then closed in the same manner, and the whole exhausted to a pressure of about a millimeter, by means of a mercurial pump. The tube was then sealed off from the pump, a small piece of glass tubing having been cemented into the brass tube and drawn down into a capillary.

The tube was now mounted in a horizontal position and a large Bunsen burner placed beneath the crucible, which was soon raised to a red heat. The dense sodium vapor poured out of the mouth of the crucible and gradually condensed on the cooler portions of the tube. Sunlight from a heliostat was sent down the large tube, a lens placed close to the glass window forming an image of the Sun immediately above the neck of the crucible. On looking down the side tube an intensely brilliant green cone of light was seen, many times brighter than anything that has ever been obtained with glass bulbs. The floating specks of oxide which appear when the tube is first heated, and which shine with a dazzling white light, soon disappear and leave the fluorescence entirely uncontaminated. It is apparent that with this arrangement light enters at once into the densest vapor without suffering previous loss by absorption in vapor of less density.

PLATE II.



Red
Orange
Yellow
Green

Gr.-Blue

Blue

Red
Yellow
D₁ D₂

Green blue

Blue

Moreover, the fluorescent light passes down the observation tube without having to traverse more than a very thin layer of the vapor, a matter of considerable importance, as we wish to examine the fluorescent light unmodified by subsequent absorption. The large amount of sodium which could be stored in the crucible enables us to deliver a dense stream of vapor in front of the observation tube for a very long time, which is absolutely essential if photographic records are to be obtained.

SPECTRUM OF THE FLUORESCENT LIGHT.

The spectrum of the fluorescent light was first examined with a two-prism Steinheil spectroscope. The spectrum consisted of a red band and a green band, the latter appearing distinctly fluted. No trace of any bright line or band at or near the position of the D lines has ever been seen in any of our experiments. Its presence in the spectrum described by Wiedemann and Schmidt, and also by one of us, may possibly have been due to the fact that in both of these cases the vapor was contained in a glass bulb heated by a Bunsen burner. This flame, colored by the sodium of the glass, may have been responsible for the appearance of a bright line in the place mentioned; a matter which can be very easily settled by repeating the experiments with the bulbs.

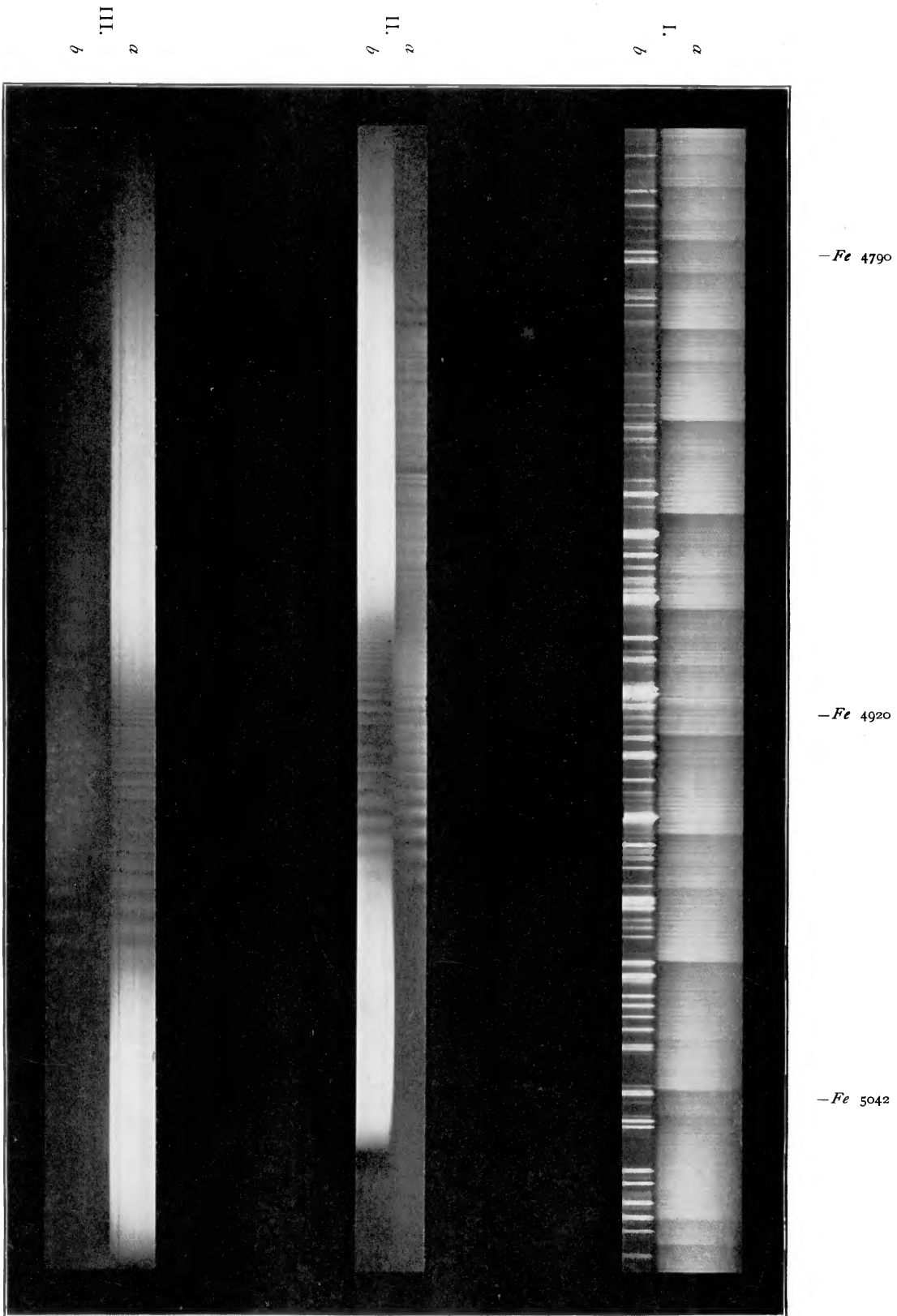
The marked resemblance which the fluted spectrum bears to the absorption at once suggests that it may be due to the fact that the fluorescent light has to pass through a certain amount of vapor before reaching the spectroscope; in other words, that it does not belong to the fluorescent spectrum at all, but is the result of absorption. To determine whether or not this was the case, an absorption comparison spectrum was formed by throwing some of the light which had passed through the tube into the instrument by means of a couple of mirrors and a small right-angled prism. It was at once apparent that the bright lines and bands of the fluorescent spectrum were exactly out of step with those of the absorption spectrum. To secure a fixed record of this fact, a camera was attached to the spectroscope and the two spectra photographed. The spectrogram confirmed the

visual observations in every respect, but the dispersion was too small to make the pictures very satisfactory.

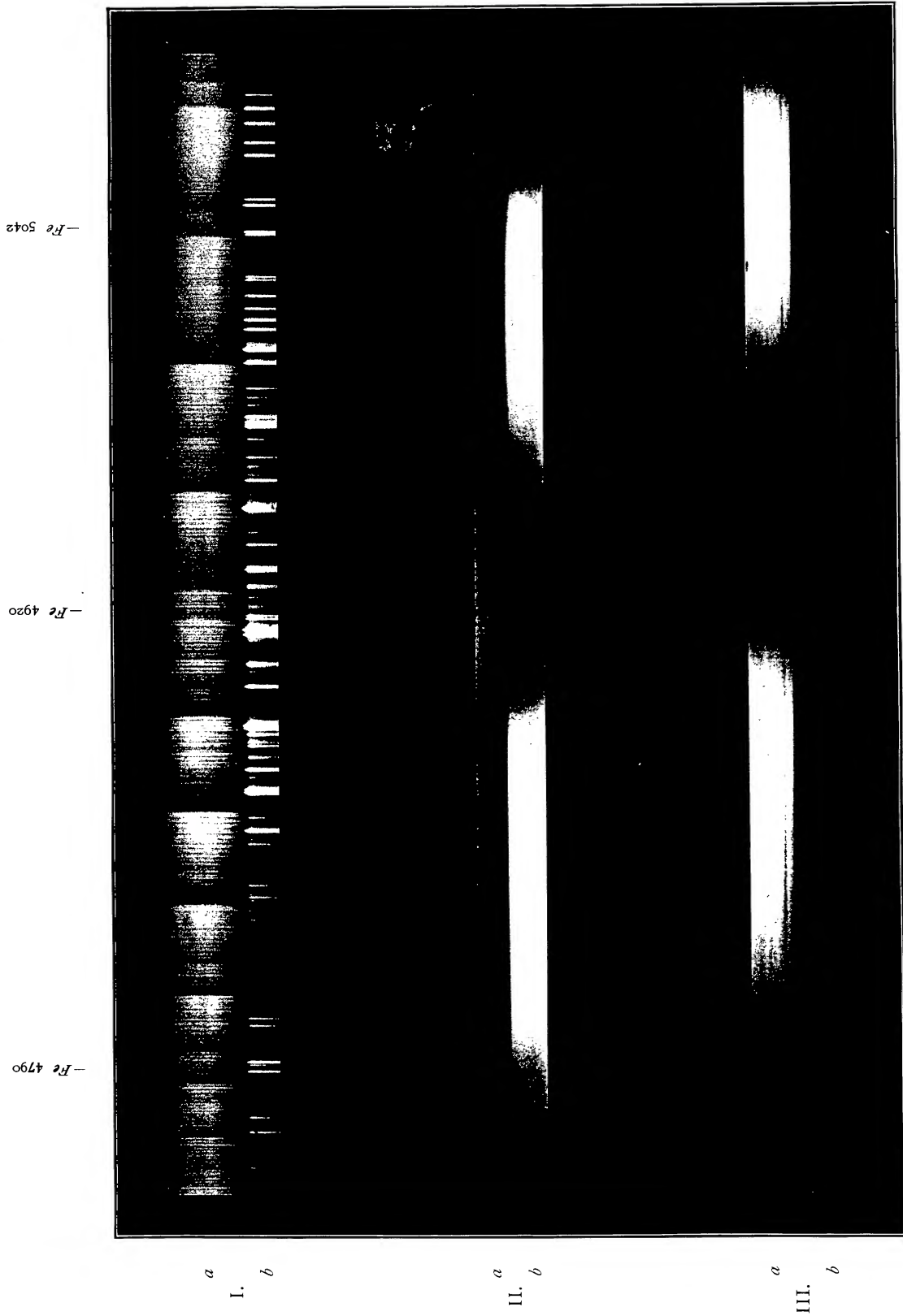
A Rowland concave grating with 15,000 lines to the inch, of one meter radius, was then used in place of the spectroscope, and some excellent photographs were obtained with an exposure of less than an hour. The fluorescent spectrum was found to extend from wave-length 5340 to wave-length 4600 in the green and blue region. All of the photographs show in addition a faint solar spectrum extending from the end of the fluorescent spectrum down to the H and K lines. This is due to a small amount of white light which is scattered by occasional specks of oxide, or perhaps reflected from the wall of the tube. So far as we have been able to determine, the fluorescent spectrum is not contaminated with solar lines, since it is located in a less actinic region, and the scattered light is not of sufficient intensity to leave any appreciable record in this region.

These photographs brought out the remarkable fact that the fluorescent spectrum is the exact complement of the absorption spectrum. The two spectra were photographed in contact on the same film, and either one might have been a contact print taken from the other. In the upper spectrum, for example, there were two broad light bands with a fine dark line down the center, while in the lower spectrum occurred two broad dark bands with bright lines down the center. This same thing was true for all of the irregularities of shading in the very complicated fluted spectrum. A number of these photographs are reproduced in Plate III, Figs. 2 and 3. As most of the fine detail will doubtless be lost in the process of reproduction, a very careful drawing of the two spectra has been prepared from the original negative, which is reproduced with the direct records. (Plate II, Fig. 3. Absorption spectrum above, fluorescent spectrum below.)

The fluorescent spectrum in the green-blue region may be divided into three groups of bands: (1) those from λ 5340 to λ 5080, consisting of six broad hazy bands, which correspond in position to the fluted bands of the absorption spectrum; higher dispersion would doubtless resolve them into lines; (2) those



I (a). Absorption spectrum of sodium vapor. (Region from $\lambda 4750$ to $\lambda 5100$.)
 (b). Corresponding comparison spectrum of iron.
 II (a). Fluorescent spectrum. (The solar spectrum showing at the left half of the plate is due to diffuse light.)
 (b). Absorption spectrum, taken with same grating.
 III (a). Absorption spectrum, (b) fluorescent spectrum, showing their complementary character.



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from $\lambda 5080$ to $\lambda 4865$, a group of irregularly fluted bands, the heads of which point toward the red; *i. e.*, they are strongest on the less refrangible side and shade off on the side of the shorter wave-lengths; (3) those from $\lambda 4865$ to $\lambda 4600$ which appear, under the dispersion used, as uniform narrow bands. The spectrum is the exact complement of the absorption spectrum taken with the same instrument, and further work with the concave grating of fourteen feet radius will show whether all of the very minute and narrow lines in the flutings of the latter spectrum are present in the former. We feel sure that the spectrum can be photographed with the large grating without difficulty.

Visual observations have shown that the red fluorescence is also fluted, though the flutings are only to be seen when the vapor is very dense and the illumination very intense. It has not yet been definitely proven whether this fluting belongs properly to the fluorescent spectrum or is the result of absorption. A new form of tube has been designed which, it is believed, will give a much denser vapor and make the settlement of this question possible.

The complementary nature of the photographs of the fluorescent and absorption spectra might lead one to suppose that the wave-length absorbed was re-emitted without change of wave-length. To test whether or not this was the case, it was necessary to illuminate the vapor with monochromatic light.

The Fuess monochromatic illuminator, which enables one to cut out a region of any width from a very intense solar spectrum and focus this light at a definite point in space, was arranged so as to send a cone of violet light down the tube, the rays meeting just above the mouth of the crucible. No fluorescence was detected. On gradually increasing the wave-length of the light, by turning the graduated screw which rotated the prisms of the instrument, it was found that the fluorescence appeared when wave-length 4600 was reached. On looking into the end of the large tube a very beautiful phenomenon was seen. The cone of deep-blue monochromatic light was distinctly visible, owing to

traces of oxide floating about, while at the point where the rays met in the dense sodium vapor there appeared a brilliant spot of *green* fluorescent light. As the wave-length was further increased, this spot increased in brilliancy, still remaining green, passed through a maximum, and then gradually faded away, disappearing entirely when the illuminating light became yellow. The vapor remained dark until the wave-length of the light exceeded that of the D lines, when the red fluorescence gradually developed, passing through a maximum in the same manner and then fading away.

The fluorescence of the vapor produced in this way was much less brilliant than in the former experiment, since the total radiant energy thrown into the vapor was very much less than when direct sunlight was employed; still the light sent down the lateral tube was intense enough to give a spectrum when the Steinheil spectroscope was directed down the tube. This spectrum was very feeble, however, and it was only with great difficulty that the changes could be followed which took place when the wave-length of the illuminating beam was changed. When blue light was employed, the complete green fluorescent spectrum seemed to be present with a maximum intensity at the yellow end. As the wave-length of the light was increased, the point of maximum intensity in the fluorescent spectrum moved toward the blue.

The important bearing which the phenomenon has on the theory of fluorescence made a more careful study of the relation between the wave-lengths of the absorbed and emitted light very desirable. To accomplish this, the arrangement of the apparatus was changed in the following manner: the monochromatic illuminator was rotated through a right angle, so that its emitting slit was horizontal, instead of vertical. The dense sodium vapor above the mouth of the crucible was now illuminated with a thin horizontal sheet of monochromatic light (the image of the horizontal slit of the illuminator projected in space by a lens). This arrangement, of course, limits the fluorescence to a thin horizontal layer of vapor, which, when viewed through the lateral tube, appears as a narrow line of bright green light. By viewing the

sheet of vapor edgewise we get a much more intense light, and since its width is small, we can dispense with a spectroscope entirely, simply viewing it through a prism or grating.

A small transmission grating of 14,480 lines to the inch, which gives a first-order spectrum nearly as bright as a 60° flint prism, was mounted in front of the lateral tube, and the line of fluorescent light viewed through it, the head being covered with a black cloth to cut out all extraneous light. It was found that by slightly inclining the large tube to the illuminating beam, it was possible to illuminate a minute projection on the inside edge of the lateral tube with the monochromatic light which caused the fluorescence; in other words, the near end of the horizontal image of the slit was brought upon this projection. The line of fluorescent light was thus tipped at one end with a small point of light similar to the light which produced the fluorescence. The spectrum of this small illuminated spot, which was of course a narrow band, fell alongside of the fluorescent spectrum, enabling a comparison to be made at once. Any exception to Stokes's law would make itself evident as an extension of the fluorescent spectrum on the more refrangible side of the position occupied by the small spot of illuminating light.

Some very remarkable and significant results were obtained with this disposition of the apparatus. Starting with violet illumination, there appeared through the grating only the small comparison spot of light which moved along as the wave-length was increased. As soon as wave-length 4600 was reached, the fluorescent spectrum appeared. Its appearance is indicated in Plate II, Fig. 4*a*. A strip of blue fluorescent light continuous with the reference spot showed that light of the same wave-length as the absorbed light was being emitted by the vapor. A region of darkness occurred on the less refrangible side (usual sense of the term), and then came a broad green band with a maximum of intensity on the end toward the yellow. Then came another gap extending considerably above the D lines, followed by a *very faint* trace of the red fluorescent band (not shown). On gradually increasing the wave-length of the light the following changes were noted. The spot of reference light, accompanied

by its fluorescent prolongation, moved up the spectrum, pushing the dark region before it, while the point of maximum fluorescence in the wide green band moved down the spectrum to meet the advancing spot. These changes are represented in Fig. 4 *b*, *c*, *d*, the point of maximum fluorescence nearly coinciding in position with the reference spot in *d*. On still further increasing the wave-length, the fluorescence became very faint, and appeared to extend a little farther down the spectrum than the position occupied by the small spot of light. This means an exception to Stokes's law when the wave-length of the illuminating light (green) has the maximum value which still yields fluorescence.

In Plate II, Fig. 5, an attempt has been made to represent these changes in the conventional way.¹ Everything shown in this diagram is, however, due to fluorescence, the deviated continuous spectrum of the light exciting fluorescence having been omitted. It will be seen that there is an emission of fluorescent light of the same wave-length as that of the exciting light, which gives the diagram an appearance not unlike the diagrams where the deviated continuous spectrum is shown. To make this diagram exhibit the changes just described, one has only to move a narrow vertical slit across it from right to left.

It was impossible to tell whether flutings were present in any portion of the fluorescent spectrum or not, owing to the comparatively wide source, and small dispersion employed. There is no reason for believing that they are not, but it does not seem safe to assume that the spectra are identical when the fluorescence is produced by white light and monochromatic blue light. The extent of the spectrum, and the distribution of the intensity in it, have been shown to be different in the two cases, and the flutings, say in the green, which are present when white light is used, may be absent when the fluorescence is produced by light of much shorter wave-length. To test this the spectrum will have to be photographed when the tube is illuminated with monochromatic blue light. To accomplish this with the present apparatus would probably require an exposure of six or eight

¹MÜLLER-POUILLET, *Lehrbuch der Physik*, II, I, 368.

hours. More favorable conditions are expected with a new form of tube now under construction, and it seems probable that we shall eventually learn a good deal about the dynamics of the sodium molecule. The results already obtained apparently prove that the light of longer wave-length emitted when the vapor is fluorescing is not the result of damping of the vibration, as assumed in Lommel's theory, but an emission resulting from the fact that the ions of longer free period are set in vibration either by the waves of shorter period or by the ions of short period which are thrown into vibration by these waves. It is not worth while to speculate about this, however, until the fluorescent spectrum produced by monochromatic blue light has been photographed.

In general, the fluorescence of a substance has its maximum intensity when the wave-length of the light is that of the light most strongly absorbed. Sodium vapor is an exception to this rule, for the D line absorption, which is far more intense than the fluted absorption, has nothing to do with the fluorescence. On Lommel's theory of fluorescence, the absence of any lateral emission of light by an absorbing medium is explained in one of two ways: either the absorption is of waves of different period (an octave below, for example) from the free period of the ions, or else the damping factor is so large that the emitted light lies in the infra-red region. In the case of sodium vapor, neither explanation is sufficient to account for the absence of fluorescence when the wave-length of the exciting light is that of the D lines, for, since Kirchhoff's law is obeyed in this case, the absorbed waves and emitted waves have the same period, and the absorption is a resonance phenomenon; moreover, the damping factor must be very small, since we have interference with large path-difference in the case of sodium light. The non-luminous vapor employed in these experiments may, of course, be in a different state from the vapor in a sodium flame, but even if this be the case, it does not seem justifiable to assume a large amount of damping, for this should cause a displacement of the absorption lines with reference to the position which they occupy in the case of absorption by a sodium flame.

It is worthy of note that lines corresponding in position to the fluted bands are absent in the emission spectrum of sodium vapor, except perhaps in the case of the temperature emission studied by Evershed, which does not appear to have been studied under high dispersion.

There seems to be no way of explaining the emission of the green light when the vapor is illuminated with blue light. It cannot be the result of the damping of the ions, whose free period is that of the blue light, for it is in all probability a discontinuous spectrum complementary to the fluted absorption spectrum.

It will be interesting to see whether the absorption of the vapor is directly affected by the circumstance that it is fluorescing at the same time. This was found to be the case in some experiments made by Burke upon uranium glass. It is also important to determine in what way the absorption and fluorescence are influenced by pressure. These matters will be investigated in the near future.

The statement that, when the wave-length of the exciting light is that of the D lines, no fluorescence is produced, requires modification. Strictly speaking, this is not true, though it is almost certain that the D line absorption is in no way responsible. This is due to the fact that the beam from the monochromatic illuminator is not strictly monochromatic, being in fact a band varying from ten to twenty Ångström units in width. As we shall show in the part of this paper dealing with the fluted absorption of the vapor, the fine lines can be traced up to the very edges of the broad band produced by the widening of the D lines when the vapor is very dense. It is unquestionably the absorption at these lines which gives rise to the very feeble reddish fluorescence which can be seen when the light furnished by the monochromatic illuminator is symmetrical about the D lines. Strictly monochromatic light of the wave-lengths of D_1 and D_2 , no matter how intense, we feel sure would produce no fluorescence, unless the flutings actually cross this region, which is very likely the case. The only light which produces no fluorescence is green light in the vicinity of $\lambda 5530$ and the violet

below λ 4600, which, as we have shown, is all that is transmitted by the vapor when it is very dense.

THE ABSORPTION SPECTRUM OF SODIUM VAPOR.

The fluted absorption spectrum of sodium vapor was first observed and studied by Roscoe and Schuster in 1874. Subsequent investigations were made by Liveing and Dewar in connection with their work on the reversal of the lines of metallic vapors, and also by one of the writers.

Previous experiments by one of us having shown that it was impossible to secure photographs of the fluted spectrum with the concave grating, using the arc as a source of light, that were not contaminated by bright lines from the vapor of the lamp, it was necessary to find a source of light of great intensity and having a continuous spectrum. After experimenting with various sources of light, we finally adopted the Nernst lamp, which was found to fulfil the conditions specified.

In the first series of experiments the sodium was vaporized in an atmosphere of hydrogen, generated by electrolysis, and dried by passage over calcium chloride and phosphorus pentoxide. In order to remove traces of oxygen which caused the tube to smoke, the gas was finally passed over red-hot copper gauze. The metal was heated in tubes of thin steel, the ends of which were closed with plate glass. In the later experiments the tubes were exhausted with a mercury pump, and the metal volatilized in a vacuum. The latter method was found to be most satisfactory. The spectra were found to be identical in the two cases.

The tubes were either heated by means of Bunsen burners, or by a coil of No. 20 iron wire, insulated from the tube by a thin layer of asbestos board. The vapor is more uniform when the tube is heated electrically, for if the upper side of the tube is colder than the lower, a non-homogeneous medium results, the density being greatest along the floor of the tube. A Bunsen burner is better, however, for some experiments, where a very dense vapor is required. With it the metal does not distil so rapidly to the colder parts of the tube, and, with careful reg-

ulation of the flow of gas to the burner, it was used very successfully in many of the experiments.

The absorption spectrum was photographed with a fourteen-foot concave grating in the first order, the time of exposure varying from twenty minutes to an hour, according to the density of the vapor. The second-order spectrum was observed from time to time during the exposure, in order to keep the density of the vapor properly regulated.

It was found that the best results were obtained with a slit-width of 0.065 mm. The width of the slit for the iron comparison spectrum was 0.030 mm. In order to eliminate any errors due to changing the width of the slit, photographs were taken of both spectra with a slit-width of 0.030 mm, and the measurements made with the two sets of plates compared. The plates were measured on the dividing engine of the laboratory, and the measurements can be considered accurate to within 0.05 of an Ångström unit. The ultra-violet region was explored in the same manner, using a tube closed with quartz plates. No traces of any flutings were found, but the lines of the principal series were strongly reversed.

The fluted absorption spectrum makes its first appearance when the D lines are two or three Ångström units in width. It begins as nine bands, the heads of which point toward the violet end of the spectrum, *i. e.*, in each band the absorption decreases from the head toward the longer wave-lengths. The heads of the bands as they first appear are:

I. 4783.35	VI. 4932.97
II. 4809.92	VII. 4962.96
III. 4837.72	VIII. 5001.94
IV. 4865.60	IX. 5040.71
V. 4894.94	

There is also evidence of absorption lines in the first seven bands. These lines, however, do not come out strong at this stage, but appear as a slight shading on the bright background. In Band I can be seen the line $\lambda 4793.10$; in Band II, line $\lambda 4820.72$; in Band IX, $\lambda 5053.50$, and in Band VII, $\lambda 4979.28$, which appear as fainter heads of small bands into which the

others break up. Bands V and VI are about the center of the region of absorption.

A very slight increase in the density of the vapor is sufficient to bring out the heads of the bands as strong dark lines, as well as the fainter heads in the bands themselves. The bands are now seen to be made up of an immense number of lines, some of which are broad and some exceedingly fine, and in some of the bands there is an appearance as if two series were superposed.

At this time the region of absorption extends from about $\lambda 4600$ to $\lambda 5200$, a series of three bands, the more refrangible edges of which are broken up into smaller bands, appearing between $\lambda 5079$ and $\lambda 5200$, and a series of twelve bands, each of which is divided into smaller bands coming into view between $\lambda 4780$ and $\lambda 4600$. The wave-lengths of the principal lines in the fluted spectrum have been carefully measured by comparing them with standard lines in the iron spectrum.

A fluted absorption spectrum makes its appearance in the red and orange portion, when the density of the vapor is such as to give the green-blue flutings at their best. This spectrum has not been photographed and measured at the present, owing to the difficulty of getting plates sufficiently sensitive to the red. The Erythro plates, which were used by one of us in securing photographs of this region with a fourteen-foot grating some years ago, are no longer on the market, and the few experiments which we have made in sensitizing our own plates have been only partially successful. This region will be studied as soon as suitable plates can be obtained.

As the density of the vapor is further increased, the greenish-blue region disappears entirely, and the fine lines can be traced nearly up to wave-length 5400 from the blue end of the spectrum, and from the red end they are seen to fill the spectrum quite up to the broad D line absorption, which is now forty Ångström units in width. On crossing this broad black band the fine lines make their appearance again, which makes it seem probable that the red fluted spectrum crosses the region occupied by the D lines. A further increase in the density results in blotting

out the red, orange, and yellow completely, leaving only a rather narrow green region, the center of which is at wave-length 5530, and the violet below $\lambda 4600$. The color of the transmitted light is now a very deep violet. The fine lines can be pushed into the green band from its opposite edges, and traces of them have been found all through it. Finally a very black broad band appears at the center of the green strip, which in a spectroscope of small dispersion appears as a rather narrow line. The center of this band is at wave-length 5530, approximately. We have not been able to photograph it with the grating, owing to the feebleness of the light, and the difficulty of keeping the vapor at this great density for a sufficient length of time; but its position was determined visually with a grating of about eight feet radius. This band has been seen by previous observers (Liveing and Dewar) and is described as persisting until the last traces of the fluted spectrum disappeared, as the vapor cooled off. We cannot understand this, for we have found it only when the vapor had the maximum density attainable, namely, when the blast-lamp played directly against the bottom of the tube, raising it to a bright red heat.

In order to see if an increase in the length of the absorbing column of the vapor produced the same effect as increasing the density of a short column, a steel tube five feet in length was used. In this were placed eight lumps of sodium of the same size, at intervals of about six inches. Eight Bunsen burners were regulated so that when one of them was placed under a lump of sodium the D lines were strongly reversed, but no trace of the fluted spectrum appeared. On adding burner after burner, exactly the same sequence of events were observed as in the previous experiments, where the density of the vapor was increased by raising the temperature of the tube. Though this was to be expected, it seemed worth while to try the experiment.

We have measured the wave-lengths of about 460 of the strongest lines between wave-lengths 4616 and 5738, which are given in the following tables :

WAVE-LENGTHS OF THE PRINCIPAL LINES AND BANDS IN THE ABSORPTION SPECTRUM.

GROUP A. λ 4600-5200.

Wave-Length	Character	Wave-Length	Character	Wave-Length	Character	Wave-Length	Character
4616.42	f	4815.84	8 b	4858.05	7 fine	4889.84	8
52.04	f	16.49	6 fine	58.75	8	90.75	7
52.18	b.h.	17.14	7 fine	59.67	7	91.52	9
59.60	b.h.	17.64	8 fine	60.41	8	92.43	7 fine
84.69	fine	18.57	8 b	60.99	fine	93.28	10 b
92.89	7	19.64	8	61.52	fine	94.13	6 fine
4704.36	I	20.72	7	61.78	fine	95.00	H 0.7
07.09	7	21.88	8	62.21	9		wide
09.72	I	23.15	7 fine	63.02	fine	96.06	4
18.29	7	23.82	8	63.78	6 b.h.	97.02	8
21.33	8	24.46	8 fine	64.45	fine	97.92	6
24.42	8	25.81	7 fine	64.88	7 fine	98.96	7 b.h.
28.82	8	26.58	8 fine	65.67	H broad	99.99	6
32.77	6	27.27	7 fine		0.4 wide	4900.94	9
35.78	6 b	27.99	8 fine	66.64	7	01.86	8
36.67	8	28.66	9 fine	67.44	7	02.64	4 fine
40.95	8 fine	30.28	8 b.h.	68.53	7	04.96	6
47.56	8 fine	32.83	8	69.54	8	05.79	7 fine
58.55	7 b.h.	33.47	9 b	70.01	10 b.h. Hs	06.43	4
51.96	8.5	35.36	fine	70.44	7 fine	07.16	7 b.h.
53.83	8.5	36.10	fine	71.33	8 b	08.22	9
58.68	9	36.51	7	72.05	fine	08.84	fine
60.85	7 fine	36.93	7	72.59	fine	09.47	9
61.86	7 fine	37.71	H	73.01	fine	10.12	fine
63.05	8 fine		<i>broad head</i>	73.50	fine	10.73	8
64.98	9 b	38.92	9 b.h.	73.93	fine	11.41	6
66.88	9 fine Hs	39.88	8 b.h.	74.46	fine	12.88	7
66.99	6 fine Hs	40.86	9	74.93	8	13.57	7
70.45	7 b	41.60	9	75.55	fine	14.26	8
71.47	7	42.40	8 b	75.95	fine	15.09	fine
77.63	8 fine Hs	43.14	9 fine	76.55	7	15.90	9
81.43	10	44.01	9 fine	77.11	8	16.62	6 fine
82.32	8 b	44.92	9	77.77	7 fine	17.52	7 fine
83.35	H 10 b	45.83	8 fine	78.31	8	18.27	7
89.83	9 fine	46.84	10	78.93	8 fine	19.10	4
90.84	9 fine	47.98	7 fine	79.52	9	19.99	8 fine
93.00	10 fine Hs	49.12	7	80.16	8.5	21.66	6 b.h.
95.30	10 b	49.75	fine	80.80	9.5	22.52	6
99.30	10 fine	50.39	9	81.51	7 fine	23.40	2
4800.74	8 fine	51.00	fine	82.22	10	24.33	7
02.86	8 fine	51.61	9	82.93	7 fine	25.28	7
04.62	10	52.27	fine	83.63	10	27.11	faint
05.77	9	52.89	9	84.33	7 fine	28.14	7
06.46	6 fine	53.65	fine	85.17	8	29.13	7
07.20	9 b	54.35	9	85.88	8	31.22	7 fine
07.90	7 b	55.06	fine	86.59	8	32.20	7 fine
09.93	H 8 b.h.	55.74	9	87.42	7 fine	33.03	H 0.7
10.68	10	56.54	7 fine	88.18	9		wide
13.68	7 fine	57.32	7 b.h.	89.06	7	33.70	fine

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WAVE-LENGTHS OF THE PRINCIPAL LINES AND BANDS IN THE
 ABSORPTION SPECTRUM—*Continued.*
GROUP A. λ 4600-5200.

Wave- Length	Character	Wave- Length	Character	Wave- Length	Character	Wave- Length	Character
4934.27	7	4970.74	8 fine	5002.55	7 fine	5034.36	fine
35.22	9	71.21	fine	06.31	fine	35.38	7 b
36.04	7	71.68	8 fine	06.90	7 fine	36.33	5 b
37.00	fine	72.09	fine	07.62	7 fine	37.34	8 fine
37.61	7 b.h.	72.61	8 fine	08.38	fine	38.17	fine
38.80	6	73.16	fine	08.78	7 fine	39.52	fine
39.54	7	73.70	7 fine	09.26	fine	40.02	fine
40.26	fine	74.28	fine	09.76	7 fine	40.94	H. b. o.9
40.74	fine	74.40	8	10.24	7 fine		wide
41.29	fine	75.41	fine	10.68	7 fine	42.58	7
42.23	6 fine	75.98	8	11.26	7 fine	43.44	fine
43.16	7	76.61	7	11.77	7 fine	44.93	fine
43.82	fine	77.17	9	12.36	7 fine	44.59	fine
44.37	8	77.85	fine	12.83	7 fine	48.81	6
44.97	7	78.45	8	13.38	7 fine	53.39	6 Hs
45.53	fine	79.20	4	13.99	7 fine	53.49	10 Hs
46.10	7	79.91	6	14.50	7 fine	54.46	8 b.h.
46.72	7	80.56	7	15.13	7 fine	56.96	8 b.h.
47.49	7 fine	81.26	8	15.77	7 fine	58.34	7
48.07	7 fine	82.00	6	16.47	7 fine	58.97	7
49.24	8	82.65	7	17.06	7 fine	61.07	7
50.08	8	84.08	8	17.77	7 fine	62.79	7
50.83	fine	86.52	6	18.38	7 fine	63.38	8
51.50	8	87.18	6 fine	19.05	7 fine	64.11	fine
52.23	2 fine	88.19	6	19.68	6 fine	64.84	h
52.97	2 fine	88.98	10 b	20.42	8	66.69	7
54.39	10 b	90.90	5	21.14	6 fine	67.37	7
56.86	2	91.52	fine	21.89	8	68.29	b
57.70	2 fine	92.56	9 b	22.61	6	69.08	6 b
59.43	8	93.34	fine	23.37	7	69.82	7 b
60.15	fine	94.18	5 b.h.	24.18	6 fine	80.38	H 10 fine
61.06	6	95.15	4 fine	24.99	7	87.37	H 7 b
62.13	fine	96.11	fine	25.77	5	95.89	9 H
63.02	H	96.53	fine	26.33	7	5118.78	Hs b
63.80	f.h.	97.29	3 b	27.37	fine	26.84	b
64.88	10 b.h.	98.05	8 b	28.21	8	33.80	Hs b
66.81	fine	99.25	8	28.98	7 fine	41.27	Hs b
67.37	fine	5000.09	6 b	29.99	8		
68.79	8 b.h.	00.86	6	30.73	7 fine		
69.31	fine	01.84	H 0.7 wide	31.76	8		
69.77	7 fine		wide	32.53	6		
70.23	fine	02.17	fine	33.47	5		

ABSORPTION SPECTRUM OF SODIUM VAPOR 111

GROUP C. λ 5300-5700.

The lines of this group are all of about the same intensity and very faint. Only the strong lines of intensity 8 or greater are marked.

Wave-Length	Character	Wave-Length	Character	Wave-Length	Character	Wave-Length	Character
5269.38		5409.78		5572.53		5651.94	broad and strong 8
75.34		14.96		74.82			
79.58		16.52		75.90		52.80	strong
5305.68		18.90		76.81		54.27	strong
11.47		25.42		81.86		55.83	
17.65		26.20		83.07		59.97	strong
25.64		32.68		84.59		64.12	
30.61		33.63		93.45	strong 8	65.63	broad
34.85		39.25		94.87	strong 8	71.25	
37.70		40.33		5602.04	broad	72.68	strong 8
43.66		41.36		03.34	broad	79.03	strong 8
46.47		48.20		07.60		83.01	strong 8
49.67		52.94		12.31		84.30	
52.44		58.09		13.78		89.70	
58.36		63.11		19.09	strong 8	97.87	strong and broad 9
65.31		82.21		20.56	strong 8		
66.09		96.99		26.31	strong 8	5706.08	strong and broad 9
70.28		5502.48		28.13	strong 8		
71.23		23.48		32.79		10.84	strong 8
78.19		28.58		36.90		12.48	
82.12		30.44		38.02		13.56	
83.38		33.16		41.18		14.72	
84.33		35.89		42.26		17.23	
90.46		40.03		43.55	broad	18.05	
91.41		59.52		45.37	broad	20.82	
97.77		62.85		46.92	broad	34.78	
98.46		64.28		48.78		36.89	
5402.61		65.70		49.60		38.32	
03.90							

JOHNS HOPKINS UNIVERSITY,
Baltimore, June 1903.