THE LUMINOSITY OF A FLAME CONTAINING SODIUM VAPOR

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Abstract

This paper contains an account of measurements of the variation of the luminosity of a sodium flame with the thickness of the flame and the concentration of the sodium salt solution sprayed into it. The reversal of the sodium lines by the layer of cool vapor at the front of the flame was eliminated by having no sodium in the front 3 cms of the flame. An improved form of sprayer was used in which the level of the solution and its concentration remained constant. It was found that the luminosity is a function of the product of the thickness of the flame and the concentration of the sodium in it or of the mass M of sodium per square cm. This result agrees with the previous results of Gouy, H. A. Wilson and Locher but not with the recent results of C. D. Child. The function of M is proportional to M when M is very small but increases less rapidly than M when M is large. Measurements of the variation of the luminosity with the thickness at the center of one of the D lines and at its edge showed that the absorption at the center is much greater than at the edge as was to be expected.

Introduction

The first measurements of the luminosity of flames containing salt vapors were made by Gouy[1] in 1879–80, while more recent work has been done by Zahn,[2] H. A. Wilson,[3] Locher,[4] and Lundegardh.[5] Gouy, H. A. Wilson, and Locher found that the luminosity of the surface of a sodium flame is a function of the product of the flame thickness and the concentration of the sodium salt solution sprayed into the flame or a function of the mass M of sodium per square cm. This function was roughly proportional to $(M)^{1/2}$ over a considerable range provided M is not too small. Recently C. D. Child[6] has measured the luminosity of sodium flames, but his results do not show that the luminosity is a function of M. The experiments described below were undertaken to find out the reason for this discrepancy.

Experimental Methods and Results

The burner used was a horizontal fused quartz tube 25 cm long and 3 cm in diameter with a straight slot 15 cm long and 2 mm wide cut in it parallel to its axis. One end of the burner was connected to a sprayer in which natural gas and air were mixed together along with spray of a sodium

[1] Gouy, Jour. de Physique **9,** 19 (1880).
[2] Zahn, Deut. Phys. Ges. Ber. **15,** 1203 (1913).
[3] H. A. Wilson, Phil. Trans. Roy. Soc. **A216,** 63 (1916).
[4] G. L. Locher, Phys. Rev. **31,** 466 (1928).
[5] Lundegardh, Zeits. f. Physik **66,** 109 (1930).
[6] C. D. Child, Phys. Rev. **38,** 699 (1931).

chloride solution. The mixture was burned at the slot and gave a Bunsen flame 15 cm long, 6 cm high and about 1 cm thick. The inner cone was about 1 cm high. The air and gas supplies were regulated and kept at constant pressures indicated by manometers.

The burner and sprayer were similar to that described by H. A. Wilson,[7] but an improvement was introduced which prevented errors due to the gradual change in the level of the solution in the sprayer and the slow increase in its concentration due to evaporation. The sprayer was connected to a large reservoir of the salt solution, and the solution was kept circulating through the sprayer and reservoir by means of a small air aspirator.

The brightness or luminosity of the flame, along a horizontal line parallel to the slot and about one half cm above the top of the inner cone, was measured with a Nutting spectrophotometer made by Hilger. A small incandescent lamp was used for comparison and the potential difference on it was kept constant during any one set of measurements. The thickness of the flame on the line along which the luminosity was measured was varied by means of a vertical black copper plate put across the flame. This plate was carried on a graduated slide so that its distance from the front of the flame could be varied and accurately measured.

When the sodium lines from this flame were examined with a plane grating in the third order, it was found that they were strongly reversed unless the solutions used were very weak. This reversal was evidently due to the absorption of the center of the sodium lines by cool sodium vapor at the front of the flame. This effect was eliminated by having no sodium in the front part of the flame so that all the sodium vapor was at the same temperature. A thin diaphragm was cemented into the quartz burner 3 cms from the front end of the slot and a mixture of gas and air only was passed into one end of the burner and the gas, air and salt spray into the other end. In this manner a uniform flame 15 cm long was obtained with no sodium in the front 3 cm but sodium in the remaining 12 cm. With this flame there was no reversal even when strong sodium solutions were sprayed.

In previous work on the luminosity of sodium flames, the light from a row of equal flames was measured and the number of flames in the row was varied. Each flame must have had a layer of cool vapor on each side so that there must have been strong absorption of the centers of the D lines by these cool layers. The previous experiments therefore do not give the way in which the luminosity varies with the thickness and concentration for a layer *all* at the same temperature. It was found that the removal of the cool reversing layer considerably altered the variation of the luminosity.

A diaphragm of 1.5 mm in diameter was placed at a distance of 30 cm from the collimator slit so that the width of the cone of light admitted to the slit was only 2.2 mm at the back of the flame; thereby making the intensity of illumination due to the different portions of the flame independent of their distances from the spectrometer. Since C. D. Child used a Lummer-Brodhun photometer in his experiments, he had to take into consideration

[7] Electrical Conductivity of Flames, Rev. Mod. Phys. **3**, 156 (1931).

the distance of the flames from the photometer as the intensity of illumination is inversely proportional to the square of the distance. The uncertainty in the determination of the effective distance of the flames from the photometer probably accounts for his results.

In performing the experiment, the standard lamp was so adjusted for each concentration of salt solution that the photometer readings would fall symmetrically around 45° where the photometer has its maximum sensitivity. When a second solution was used, the relative intensities of the standard lamp with the two different potentials was determined so that all the intensities could be compared with one another. The data on a sample run are given in Table I which shows the variation in intensity with change in thickness of a flame sprayed with a sodium chloride solution of 40 gm per liter.

TABLE I. (*Voltage on standard lamp—3.03 volts*).

Thickness of flame				
1.6 cm	2.6 cm	4.1 cm	6.6 cm	11.1 cm
56.0°	52.8°	47.0°	45.8°	38.3°
56.6	52.0	49.8	43.0	38.5
56.3	52.9	48.3	45.2	40.8
55.0	52.0	49.0	46.5	40.9
55.8	53.3	48.8	46.5	37.3
56.5	51.2	47.9	45.0	42.5
56.0	53.4	48.4	44.5	40.0
57.2	51.8	49.0	43.5	40.0
56.6	52.8	49.5	44.1	40.7
55.8	51.8	48.5	44.7	40.0
55.0	51.2	48.2	43.0	38.5
55.5	52.0	47.0	45.8	40.9
56.5	52.8	48.8	46.6	42.5
56.3	52.9	49.8	45.2	40.2
57.2	51.6	48.5	45.0	40.6
55.5	53.3	49.0	46.5	40.9
56.3	53.4	49.0	43.5	39.3
56.0	52.4	48.4	44.5	40.9
56.3	51.6	47.8	44.7	40.2
56.0	52.4	49.5	44.1	40.8
Av. 56.1°	Av. 52.4°	Av. 48.6°	Av. 44.9°	Av. 40.2°
Intensity $(I)=1.00$	$I=1.19$	$I=1.41$	$I=1.61$	$I=1.87$

The intensities given in Table II were obtained in the same way and thus each intensity represents the average of twenty independent readings of the photometer.

When sodium carbonate solutions were used in place of sodium chloride, it was found that the luminosity due to an equal weight of sodium was the same for both salts, in keeping with the results of H. A. Wilson.

Fig. 1 shows the variation of the logarithm of intensity with the logarithm of pd where pd is varied from 4 to 83200. From this curve one concludes that the luminosity of the flame is a function of pd and is independent of the distribution of the vapor. Since the luminosity of a flame sprayed with a dilute salt solution is almost proportional to pd, there must be very little absorption under these circumstances. For a flame in which there is more sodium vapor present, the absorption becomes quite large. The square root relation be-

TABLE II. *Intensity of the D lines of sodium as compared with an incandescent lamp.*

Gm NaCl per liter	Concentration ρ in arbitrary units	Thickness d in cm	ρd	Intensity I
0.00532	1	4.1	4.1	4.83
0.00532	1	6.6	6.6	7.81
0.00532	1	11.1	11.1	12.50
0.0267	5	1.6	8.0	8.67
0.0267	5	2.6	13.0	13.5
0.0267	5	4.1	20.5	20.5
0.0267	5	6.6	33.0	28.2
0.0267	5	11.1	55.5	38.0
0.0800	15	1.6	24.0	20.7
0.0800	15	2.6	39.0	30.5
0.0800	15	4.1	61.5	41.3
0.0800	15	6.6	99.0	48.4
0.0800	15	11.1	167	64.3
0.400	75	1.6	120	55.1
0.400	75	2.6	195	68.9
0.400	75	4.1	308	82.1
0.400	75	6.6	495	99.7
0.400	75	11.1	832	128
4.00	750	1.6	1200	149
4.00	750	2.6	1950	189
4.00	750	4.1	3080	220
4.00	750	6.6	4950	265
4.00	750	11.1	8320	323
40.0	7500	1.6	12000	367
40.0	7500	2.6	19500	438
40.0	7500	4.1	30800	516
40.0	7500	6.6	49500	591
40.0	7500	11.1	83200	688

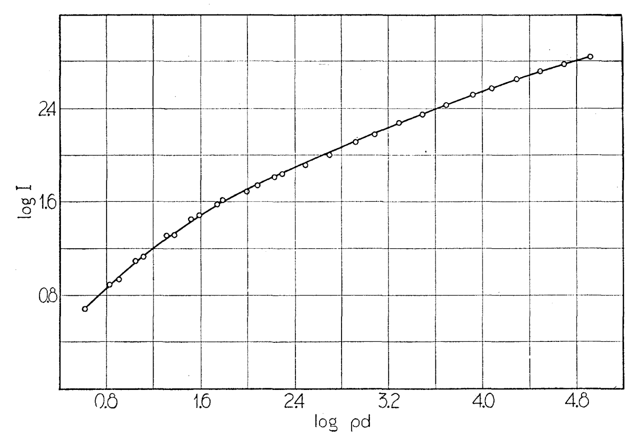

Fig. 1. Variation of the logarithm of intensity with the logarithm of ρd.

tween luminosity and ρd holds only over a limited range, and for the largest values of ρd used in these experiments the luminosity is approximately proportional to the cube root of ρd.

H. A. Wilson[8] gave the theoretical relation for the luminosity of a sodium flame

[8] H. A. Wilson, Proceedings Roy. Society **A118**, 362 (1928).

$$I = E \int_{-\infty}^{+\infty} (1 - e^{-n\gamma_0/(1+4m^2\Delta^2/k^2)}) d\Delta \tag{1}$$

where m = mass of vibrating electron; k = viscous resistance to motion at unit velocity; n = number of atoms; γ_0 = atomic absorption coefficient at the center of the line; Δ = variation in frequency from that of the center of the line; E = intensity of black body radiation at the temperature of the flame per unit range of Δ near the D lines. When $n\gamma_0$ is greater than 2 or 3, he gave the approximate value of this integral to be

$$I = Ek/m(\pi n\gamma_0)^{1/2}(1 - 1/4n\gamma_0 - 3/32n^2\gamma_0^2 - \cdots). \tag{2}$$

An exact series for this integral can be gotten by expanding the integrand into the series

$$\frac{n\gamma_0}{1 + \dfrac{4m^2\Delta^2}{k^2}} - \frac{1}{2!}\frac{n^2\gamma_0^2}{\left(1 + \dfrac{4m^2\Delta^2}{k^2}\right)^2} + \frac{1}{3!}\frac{n^3\gamma_0^3}{\left(1 + \dfrac{4m^2\Delta^2}{k^2}\right)^3} - \cdots.$$

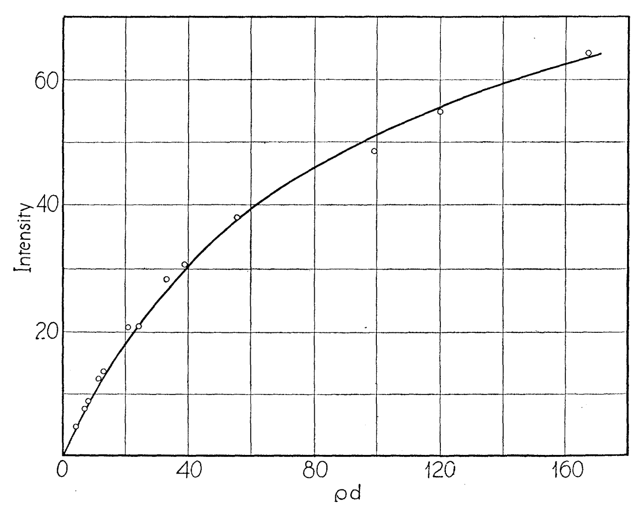

Fig. 2. Variation of luminosity for small values of ρd (circles represent experimental points).

Each term of this series can be integrated, so Eq. (1) becomes

$$I = En\pi k\gamma_0/2m(1 - n\gamma_0/4 + n^2\gamma_0^2/16 - 5n^3\gamma_0^3/384 + \cdots). \tag{3}$$

For small values of $n\gamma_0$ Eq. (3) is approximately equal to

$$I = E\frac{k\pi}{2m}\frac{n\gamma_0}{\left(1 + \dfrac{n\gamma_0}{4}\right)}. \tag{4}$$

The variation of the luminosity for small values of ρd is shown in Fig. 2. The experimental points fall approximately on the curve given by the equation $I = 1.09\rho d/(1 + 0.0112\rho d)$ which is of the same form as (4).

Since according to the theory the middle of the D lines is absorbed more than the edges, it seemed to be a good plan to test this assumption experimentally. High resolving power was obtained by viewing the D_1 line in the third order of a plane reflecting grating. Light from a standard lamp was made to fall on the upper half of the collimator slit by placing a right angle prism over this portion of the slit. The solid angle of light admitted to the spectrometer was again cut down by a diaphragm so that the illumination due to different parts of the flame would be independent of their distances. Shutters in the eyepiece were adjusted so that a narrow portion of the middle of the D_1 line was observed and the variation of the intensity of this portion

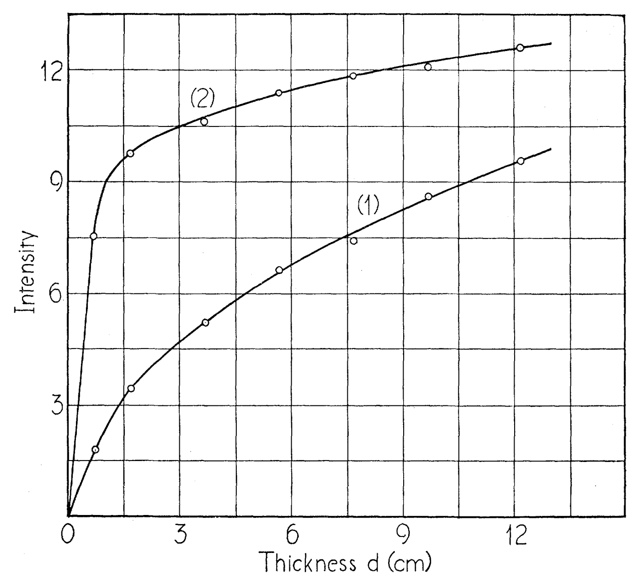

Fig. 3. Curve I shows variation of the intensity of the edge of the D_1 line; curve II that of the middle of the D_1 line with change in thickness of flame.

of the D_1 line was determined when the thickness of the flame was varied. The intensity of the light from the standard lamp was varied until it was of the same intensity as that from the flame and then the potential applied to the lamp was noted. The lamp was subsequently calibrated for the wave-length of the D_1 line for various applied potentials.

The spectrometer was then rotated through a small angle corresponding to a change of wave-length of 1.7 angstroms and the variation of the edge of the D_1 line noted for different flame thicknesses. Curve (2) of Fig. 3 shows the variation of intensity of the middle of the D_1 line with change in the thickness of the flame, while curve (1) shows the variation of the intensity of the edge of the D_1 line. The curves indicate that the middle of the line is absorbed much more than the edges in agreement with the theory.

The conclusion reached is (1) that the luminosity of a flame containing sodium vapor is a function of the mass of sodium per square cm contained in it and is independent of the distribution of the vapor, and (2) that the middle of the D_1 line of sodium is absorbed more than the edges.

In conclusion, I wish to acknowledge my indebtedness to Professor H. A. Wilson for the suggestion of this problem and my appreciation of his interest and many valuable suggestions made during the course of this work.