APRIL, 1927 *PHYSICAL REVIEW* *VOLUME 29*

THE DIFFUSION OF IMPRISONED RESONANCE RADIATION IN MERCURY VAPOR

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ABSTRACT

The rate of diffusion of imprisoned resonance radiation in mercury vapor.—The imprisonment of resonance radiation in mercury vapor was studied by measuring the rate at which resonance radiation emerged from one face of a slab of vapor after the exciting light, incident upon the other face, was cut off. The radiation was found to fall off exponentially, and the exponential constant of decay was measured for vapor densities ranging from 0.77×10^{15} atoms per cc to 29×10^{15} atoms per cc, corresponding to temperatures ranging from 60°C to 130°C. Slabs of two different thicknesses were studied, one 1.95 cm, and the other 1.30 cm. It was found that for vapor densities lower than about 4×10^{15} atoms per cc, the exponential constant varied approximately inversely as the square of the thickness of the slab, in qualitative agreement with the theory of the diffusion of imprisoned radiation as worked out by Milne.

Extension of Milne's theory: broad exciting line; collisions of second kind.—In this region of vapor densities it was found also that the exponential constant decreased with the vapor density. The failure of Milne's results to give quantitative agreement with this result is discussed and it is suggested that this discrepancy is due to the fact that the exciting light in this experiment was a very broad spectral line, and that postulated by Milne of very narrow width. A rough method of extending Milne's theory to include the absorption and imprisonment of frequencies larger and smaller than the heart of the 2536.7 line is discussed, and it is shown that the experimental results can be explained on this basis. At higher vapor densities, the decay constant increased almost linearly with the number of absorbing atoms per cc. It is shown that this result is in accordance with the theory of imprisonment when extended to include impacts of the second kind. The probability of an impact of the second kind between a normal and an excited mercury atom is calculated from the experimental data and found to be approximately 9×10^{-4}.

INTRODUCTION

IT IS well known that the fluorescence excited in some solids and liquids persists for a short time after the excitation has been cut off. Wood,[1] and later, Gottling[2] and Wawilow[3] studied the visible fluorescence excited in fluorescine, rhodamine, uranium glass, etc., and found that fluorescence persists after the cut-off of the exciting light for a time, which, in some cases, is as long as 10^{-2} secs.

Phillips[4] investigated the visible fluorescence excited in mercury vapor, and showed that it was carried by a moving column of the vapor a considerable distance past the point of excitation. Since this fluorescence, consisting of a violet and a green band, depends upon the absorption of the

[1] R. W. Wood, Proc. Roy. Soc. **A99**, 362 (1921).

[2] P. F. Gottling, Phys. Rev. **22**, 566 (1923).

[3] S. J. Wawilow and W. L. Lewschin, Zeits. f. Physik. **35**, 920 (1926).

[4] F. S. Phillips, Proc. Roy. Soc. **A89**, 39 (1913).

mercury resonance line 2536.7 this experiment implies that mercury vapor is capable of holding resonance radiation in it for a short time. It does not determine, however, whether this is accomplished by metastable atoms or by repeated atomic absorptions and re-emissions, nor is it suitable to decide this question, since the origin of the visible fluorescent bands is so much in doubt.

The most direct experiment on persistent resonance fluorescence was made by Miss Hayner,[5] who studied the actual resonance radiation emitted by mercury vapor after the excitation was cut off. Miss Hayner used a quartz mercury arc provided with a hot cathode so that it could be struck and cut off very rapidly by a commutator. Light from this arc was incident on one face of a small cylindrical quartz cell containing mercury vapor, and the rate at which the resonance radiation escaped from the other face, after the arc was cut off, was measured. She obtained the result that the resonance radiation fell off exponentially, with an exponential constant that was independent of the density of the vapor, and approximately inversely proportional to the thickness of the slab of vapor. She found also that the resonance radiation did not persist after the cut-off, if the absorption cell was sealed off after evacuation.

In 1912, Wood[6] observed that resonance radiation excited in one portion of a mass of mercury vapor spread to other portions, and, by introducing a small quartz window, established the fact that this diffusion was not due to the movement of atoms. He concluded that the resonance radiation spread by repeated atomic absorptions and re-emissions. This idea was extended by K. T. Compton[7] to explain certain peculiarities in the behavior of the arc. He suggested that resonance radiation becomes imprisoned within a mass of vapor because of the fact that a quantum of radiation is absorbed and re-emitted by many atoms before it finds its way out of the enclosing vessel. Calculations on the basis of this theory were made by Compton and by Webb[8] who used the differential equation of diffusion to calculate the number of excited atoms in a mass of vapor and the rate at which radiation arrives at one boundary.

Recently this problem has received a more rigorous solution by Milne[9] who used the Einstein radiation hypotheses to obtain the differential equation of the diffusion of imprisoned resonance radiation. Considering the vapor enclosed between two infinite planes, and monochromatic radiation incident upon one face, he obtained an exact expression for the radiation arriving at the other face after the exciting radiation was cut off. According to his result, the radiation should fall off exponentially with an exponential constant inversely proportional to: (1) The square of the number of absorbing atoms per cc; (2) The square of the thickness of the slab of vapor.

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[5] L. J. Hayner, Phys. Rev. **26**, 364 (1925).

[6] R. W. Wood, Phil. Mag. **23**, 689 (1912).

[7] K. T. Compton, Phys. Rev. **20**, 283 (1922); Phil. Mag. **45**, 752 (1923).

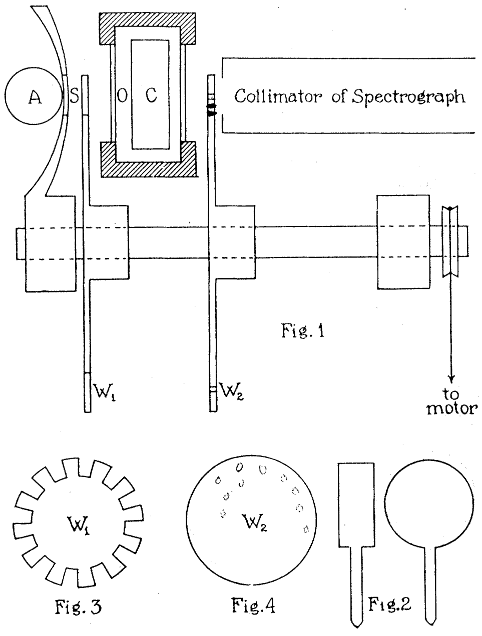
[8] H. W. Webb, Phys. Rev. **24**, 113 (1924).

[9] E. A. Milne, Journ. Lon. Math. Soc. No. 1 (1926).

This result does not agree with Miss Hayner's experimental results, nor has it been possible to account for her results on the basis of any theory. Consequently it was thought worth while to repeat her experiment under better conditions. The following paper contains a description of such experiments and a theoretical discussion of the results.

METHOD AND APPARATUS

The method was essentially the same as that used by Miss Hayner. The total radiation from a water cooled, magnetically deflected quartz mercury arc *A* (see Fig. 1) passed through a horizontal slit *S*, 0.5 mm wide, into a cylindrical cell *C* containing mercury vapor. The cell was of clear fused quartz with circular faces 5.1 cm in diameter, (see Fig. 2) which was baked out, evacuated and sealed off with a drop of mercury remaining in the stem. An electric oven *O* with quartz windows kept the faces and the stem of the cell at constant temperature. Between the oven and the slit there was a rotating wheel W_1 with twelve teeth. (see Fig. 3) The face of the wheel was very close to the slit and the edges of the teeth were parallel to the slit. This arrangement alternately transmitted the light and cut it off twelve times per revolution. Mounted on the same shaft as W_1 was a second wheel W_2 containing two sets of holes, (see Fig. 4) twelve holes in the outer set, and nine in the inner. The diameter of each hole was 0.3 mm. These holes acted as moving slits for a Hilger quartz spectrograph placed as is shown in Fig. 1, causing pairs of curved traces on the photographic



Figs. 1, 2, 3, 4

plate, each pair corresponding to one of the mercury arc lines. (see Fig. 5) The two wheels were so adjusted that, just as a tooth on W_1 was about to cover the slit S, a hole in W_2 presented itself in front of the collimator of the spectrograph. After a trace on the plate a few millimeters long (distance AB in Fig. 5) had been made, the tooth cut the exciting light off, and the persistent radiation produced a continuation of the trace (distance BC in Fig. 5). The small, rounded portion at the point B represents the interval of time required for the tooth to cover the breadth of the slit, usually about 10^{-5} secs.

The history of the radiation emitted from the cell after the exciting light was cut off was obtained by measuring the photographic density at different points along each trace; each point corresponding to a known interval of time after the cut-off. Density-time curves were plotted for both traces on the same graph. Since one trace was produced by twelve exposures per revolution and the other by nine, corresponding densities represent exposure times in the ratio of 1 to 3/4. In order to determine the intensity relation between corresponding points on the two traces, two photographs were taken on the same plate, one with the usual spectrograph diaphragm, and one with a diaphragm which cut out 1/4 of the light. The trace representing full intensity and 3/4 time, was then compared with the trace representing 3/4 intensity and full time, and it was found that the two traces were identical when the photographic densities were between 0.4 and 0.8; that is, in the linear region of the curve of blackening of the plate. Thereafter, within these limits, the trace produced by nine exposures per revolution was used as a comparison trace representing 3/4 the intensity of the other trace.

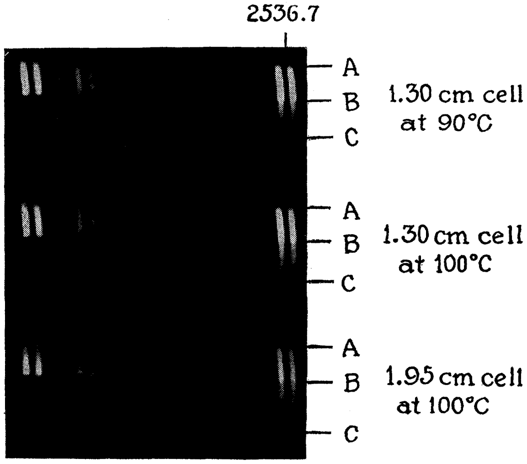


Fig. 5

On each plate three separate exposures were taken corresponding to three different sets of conditions. One of these was produced by the persistent radiation emerging from the 1.95 cm cell at 100°C. This pair of traces was used as a standard of comparison and appears as the lowest pair of traces in Fig. 5. The trace representing full intensity is on the left. From these two traces the constant of contrast of the plate, γ, and the exponential constant, $1/T$, for the persistent radiation at 100°C were obtained in the following manner:

The two traces were placed in turn over the circular slit of the densitometer and the photographic densities of all points ten minutes of arc apart were measured. Translating angular distance into time, and plotting all values of photographic density that lay between 0.4 and 0.8 against the time, two curves were obtained, one for the full intensity trace and the other for the 3/4 intensity trace. Each curve consisted of a rapidly decreasing portion, representing a small period during the cut-off of the exciting light, and a linear region representing the persistent radiation. The intersection of these two portions was taken as the instant of cut-off. Calling the density of this intersection point on the full intensity curve D, and the density of the corresponding point on the 3/4 intensity curve D', we have

$$\begin{aligned} D &= \gamma \log I + \text{const.} \qquad && (0.4 < D < 0.8) \\ D' &= \gamma \log \tfrac{3}{4} I + \text{const.} && \quad '' \end{aligned} \qquad (1)$$

Whence

$$\gamma = (D - D')/\log_{10}(4/3) = (D - D')/0.125$$

Now, let I be the intensity of the persistent radiation that gives rise to the full-intensity trace, t seconds after the cut-off of the exciting light. Then $I = I_0 e^{-t/T}$ where $1/T$ is the exponential constant to be measured. Combining this equation with Eq. (1) we obtain

$$D = -\gamma t/2.30T + \text{const.}$$

which expresses the fact that the density-time curve is a straight line, when D is between 0.4 and 0.8 with a slope S equal to $\gamma/2.30T$. The exponential constant for the persistent radiation at 100°C was then obtained from $1/T = 2.30S/\gamma$ and that corresponding to any other trace on the plate, from the relation $TS = T'S'$ where T' and S' refer to the second trace.

Procedure and Results

Before exposing the plate, the stem of the cell which contained the drop of mercury was heated to the desired temperature, and the faces to a temperature about 5°C higher. In this way condensation of mercury on the faces of the cell was avoided. The wheels rotating so close to the oven which contained the cell caused a draft which tended to cool the oven, so that, at least three-quarters of an hour had to be allowed for the whole system to attain constancy. The temperature of the stem of the cell and the speed of the wheels remained constant within two percent during an exposure which lasted in most cases about one hour.

No difficulty was found at any time in obtaining imprisonment of resonance radiation in a sealed-off cell. It was evidently not necessary to have freshly evaporating mercury present, since the liquid mercury remained in the stem of the cell throughout an exposure. Only that pair of traces corresponding to wave-length 2536.7 showed any trace on the plate *after* the cut-off of the exciting light. Although all the mercury arc lines were present in the exciting light, there was never any evidence of absorption and consequent re-emission of any wave-length other than 2536.7. It is, therefore, believed that whatever absorption of other wave-lengths occurred it played a negligible rôle in the imprisonment of the resonance radiation.

The exponential constant of decay of the persistent radiation from the 1.95 cm cell and the 1.30 cm cell at temperatures ranging from 60°C to 130°C (about a 30-fold increase in vapor density) was measured. The saturation vapor pressures of mercury at the temperatures employed were taken from Landolt and Börnstein's tables and the number of atoms per cc corresponding to the different vapor pressures calculated.

The results are presented in Table I. The first and second columns give temperatures and corresponding vapor densities respectively. The third and fourth columns give the corresponding values of the exponential constant $1/T$ and the time constant T for the cell 1.95 cms thick, and the fifth and sixth columns give the same quantities for the 1.30 cm cell. In Fig. 6 these results are plotted for both cells with the exponential constant as ordinate and the number of atoms per cc as abscissa.

TABLE I

Rate of decay of resonance radiation emerging from a slab of mercury vapor after the exciting light, incident on other face, is cut off.
T is the time constant in the equation $I=I_0e^{-t/T}$.

Temp. °C	No. of Atoms per cc $N\times10^{-15}$	1.95 cm cell $(1/T)\times10^{-3}$	1.95 cm cell $T\times10^4$	1.30 cm cell $(1/T)\times10^{-3}$	1.30 cm cell $T\times10^4$
60	0.770	26.6	0.376		
70	1.40	14.2	0.704	28.1	0.356
80	2.50	8.81	1.13	19.3	0.518
90	4.40	7.07	1.41	12.1	0.827
100	7.26	6.89	1.45	9.47	1.06
110	11.8	7.72	1.30	9.00	1.11
120	18.8	9.64	1.04	10.6	0.944
130	29.0	13.2	0.757	13.5	0.740

DISCUSSION

In Fig. 6 it is seen that the curves for the two cells are of the same general character. At low vapor densities, the exponential constant of decay of the persistent radiation decreases very rapidly with increasing vapor density; and at high vapor densities, the exponential constant rises nearly linearly with the vapor density. That is, as the number of absorbing atoms increases, the resonance radiation remains imprisoned for a longer and longer time, until a maximum time is reached, after which, any increase in the number of absorbing atoms causes a diminution in the time of imprisonment of the radiation in the vapor.

Let us compare these results with those obtained by Milne. Assuming that one face of an infinite slab of vapor perpendicular to the x axis, is exposed to radiation of very narrow spectral width, and, neglecting molecular motion and impacts, Milne finds that the number of excited atoms per cc, n_2, is given by the equation

$$\frac{\partial n_2}{\partial t} = \frac{1}{4\alpha^2 N^2 \tau}\frac{\partial^2}{\partial x^2}\left(n_2+\tau\frac{\partial n_2}{\partial t}\right) \qquad (2)$$

where τ represents the duration of the excited state produced by absorption of the radiation, N the number of atoms per cc, and α the atomic absorption coefficient for the exciting radiation. The solution of this equation yields the result that the radiation emerging from the far face of the slab after the exciting light, incident on the front face, is cut off, falls off exponentially, with a time constant T given by

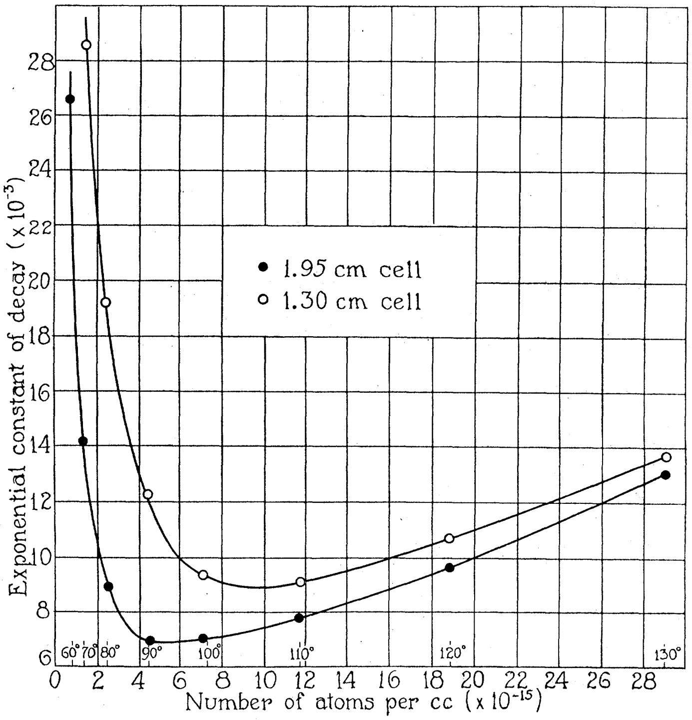


Fig. 6

$$T=\tau(1+4l^2\alpha^2N^2/\pi^2) \qquad (3)$$

where l stands for the thickness of the slab. The duration of the 2^3P_1 state ($2p_2$ state, in the old notation), τ, for mercury is known to be 10^{-7} seconds.[10]

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[10] W. Wien, Ann. d. Physik. **73**, 483 (1914); Eldridge, Phys. Rev. **23**, 772 (1924); Phys. Rev. **24**, 234 (1924); Hanle, Zeits. f. Physik. **30**, 93 (1924); Turner, Phys. Rev. **23**, 464 (1924); Tolman, Phys. Rev. **23**, 693 (1924); Breit and Ellett, Phys. Rev. **25**, 888 (1925).

Malinowski[11] and Orthmann[12] measured the absorption coefficient of mercury vapor at a density of about 3×10^{13} atoms per cc for the radiation from a mercury resonance lamp at room temperature, and found a value of approximately 3. This gives for the atomic absorption coefficient a value of approximately 10^{-13} which can be regarded as reliable in order of magnitude at least.

Since, in this experiment, N, the number of atoms per cc, ranged from 0.77×10^{15} to 29×10^{15} and l was 1.95 cm for the thicker slab, and 1.30 cm for the thinner, $4l^2\alpha^2N^2/\pi^2>>1$ and we can write Eq. (3) more simply

$$1/T=\pi^2/4\tau l^2\alpha^2N^2 \tag{4}$$

which is the expression for the exponential constant that would result if, in the original differential equation, Eq. (2), the term $\partial^3n_2/\partial x^2\partial t$ were neglected. Consequently in the region of vapor densities employed in this experiment we may neglect the last term in Eq. (2).

If now, we consider the left-hand part of the experimental curves in Fig. 6 for which $N<4\times10^{15}$ atoms per cc, we see, at first, that the way in which $1/T$ varies with l is in good agreement with Eq. (4) which requires that $1/T$ be inversely proportional to l^2. The ratio of the squares of the thicknesses of the two slabs is 2.2. At 70°C the inverse ratio of the exponential constants is 2.0, at 80°C it is 2.2 and at 90°C, 1.7.

A quantitative comparison, however, between Eq. (4) and the experimental values of the exponential constant for the thicker cell shows a large discrepancy. At 60°C for which $N=0.77\times10^{15}$ atoms per cc, Eq. (4) gives $1/T=1100$ as against the experimental value of 26600. At 70°C, Eq. (4) gives 330 whereas experiment yields 14200. At higher temperatures Eq. (4) gives values of $1/T$ that get rapidly smaller, approaching zero, whereas the experimental curve in Fig. 6 shows a minimum value for $1/T$ of about 7000 at 100°C and an almost linear increase for $1/T$ at higher temperatures.

This lack of agreement between theory and experiment leads us to seek an equation fitting the actual conditions of the experiment more closely than does that of Milne. There are certain obvious differences between the conditions assumed in Milne's development and those actually present in these tests. One of these can readily be disposed of as not materially affecting the quantity in question, $1/T$. The use of a cylindrical enclosure for the vapor instead of an infinite slab affects, for the most part, the functions which are coefficients of the exponential terms in the exact solution of the problem. A simple calculation shows that, for a cylindrical boundary the exponential constant is given by an expression the same as Eq. (4) except that instead of π^2 entering, we have approximately the value 14. This slight difference is unimportant.

Milne's equation does not take into account the gaseous diffusion of excited atoms under the concentration gradient which exists in the slab

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[11] Malinowski, Ann. d. Physik. **44,** 935 (1914).

[12] Orthmann, Ann. d. Physik. **78,** 601 (1925).

during the steady state, and the effect of dissipative impacts (impacts of the second kind). This can be done in a manner indicated by Milne in a footnote in his paper, by replacing $\partial n_2/\partial t$ of his paper, which represents the rate at which excited atoms are being formed in a unit volume due to imprisonment, by $\partial n_2/\partial t - g\partial^2 n_2/\partial x^2 + kn_2$ where $g\partial^2 n_2/\partial x^2$ represents the rate at which excited atoms are forming due to gaseous diffusion, and kn_2 represents the rate at which excited atoms are disappearing through impacts of the second kind. From the kinetic theory of gases we have $g = c/3(2)^{1/2}\pi s^2 N$, where c is the root mean square velocity, s the distance between centers at impact, and N the number of atoms per cc; and $k = (2)^{1/2}\pi b s^2 c N$, where b is the probability that an impact between a normal mercury atom and an excited one is of the second kind.

The outstanding discrepancy between Milne's theory and the conditions actually present in this experiment, however, cannot be handled so easily, i.e. the effect of the absorption and imprisonment of frequencies larger and smaller than the heart of the 2536.7 line. There is no doubt that such absorption occurs, for it is known that the breadth of the absorption line at the temperatures studied is much larger than can be explained on the basis of the Doppler effect. The process of the diffusion of these frequencies comprising a broad absorption line must be very complicated, for we cannot consider that the imprisonment processes (repeated absorptions and re-emissions) of all the frequencies are independent of one another. Instead, we must take into account the fact that an atom that picks up a frequency corresponding to one part of the absorption line can re-emit a frequency corresponding to another part. Because of our ignorance of these changes of frequency we are not in a position to treat the effect of the broad absorption line rigorously, but since we are led to believe that the radiation composing the whole absorption line diffuses as a whole through the vapor, we may make the plausible assumption that the total radiation included in the broad absorption line obeys the same law of diffusion as that given by Eq. (2), except that, instead of α standing for an atomic constant (the atomic absorption coefficient), it represents a "mean or equivalent absorption coefficient" which is a function of the line breadth. Denoting by β the equivalent absorption coefficient and taking account of gaseous diffusion of excited atoms and impacts of the second kind between excited and normal atoms, we obtain the differential equation

$$\partial n_2/\partial t + kn_2 = (1/4\beta^2 N^2 \tau + g)\partial^2 n_2/\partial x^2$$

The solution of this equation gives the result that the radiation emerging from the far face of the slab of vapor after the exciting light incident on the front face is cut off, falls off exponentially with an exponential constant, $1/T$, given by

$$\frac{1}{T} = \frac{\pi^2}{4\tau l^2 \beta^2 N^2} + \frac{\pi c}{3(2)^{1/2} l^2 s^2 N} + (2)^{1/2}\pi b s^2 c N \tag{5}$$

The three terms of the right-hand member represent, in order, the effect of the imprisonment of the whole absorption line, the effect of gaseous diffusion, and the effect of impacts of the second kind.

The second term may be neglected completely, for numerical substitution shows it to be very small for the whole range of values of N. In the parts of the curves in Fig. 6 for which N is small, the third term may also be neglected. Comparison between experiment and the first term of Eq. (5) then, would serve only to determine the value of β as a function of N. Since the meaning of β in terms of physical constants of the vapor is not clear, the actual values of β are of no interest. It may be interesting, however to point out that if $1/\beta$ is taken as a linear function of N, good agreement is obtained between the form of the curves in Fig. 6 and the theoretical curves.

For large values of N the third term is of importance. This term, expressing the effect of impacts of the second kind, represents a linear relation between the exponential constant and N. Since the right-hand parts of the experimental curves in Fig. 6 show a distinct linear rise, we may regard this as strong indication that such impacts exist at these high vapor densities. There is abundant evidence for the existence of such collisions in *mixtures* of mercury vapor and inert gases, and the experiments of Wood and Kimura,[13] and Goos and Meyer[14] indicate that they are present also in pure mercury vapor. The experiments of Franck[15] and his students indicate that the probability of such impacts between normal and excited mercury atoms is small, but do not yield a numerical estimate of this probability.

The results of this experiment can be used to calculate this probability, if we make the assumption that the rise of the exponential constant for large values of N is due solely to impacts of the second kind. For Eq. (5) gives as the slope of the straight line representing this rise $(2)^{1/2}\pi b s^2 c$ and Fig. 6 gives for this slope the value 3×10^{-13} from which b, the probability of an impact of the second kind between a normal and an excited mercury atom, can be calculated in terms of s the distance between centers at impact and c the root mean square velocity of the atoms. With s equal to 6.0×10^{-8} cm, and c equal to 2.2×10^4 cm/sec, b is found to be approximately 9×10^{-4}. That is, about one out of every thousand collisions between an excited mercury atom and a normal one is of the second kind. This does not contradict the result of Cario that *every* collision between an excited mercury atom and an air molecule is of the second kind, for, if an excited mercury atom pass on its excitation to a molecule of a foreign gas, the excited state of the mercury atom is destroyed; whereas if an excited mercury atom pass on its excitation to a normal mercury atom, there is merely a change in rôle and there still remains an excited mercury atom. Consequently, one would not expect every collision between an excited and a normal mercury atom to be dissipative. Cario's result shows clearly what effect we should expect a small amount of air to have in this experiment. Since the probability of

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[13] R. W. Wood and Kimura, Phil. Mag. **32,** 329 (1916).

[14] Goos and Meyer, Zeits. f. Phys. **35,** 803 (1926).

[15] J. Franck, "Anregung von Quantensprüngen durch Stösse," p. 225.

a dissipative impact between an air molecule and an excited mercury atom is one thousand times the probability of such an impact in pure mercury vapor, air, at a pressure of .001 mm should have the same effect as mercury at a pressure of 1 mm. Consequently if there were air, at a pressure of .001 mm present in the cell at 100°C, instead of an exponential constant of 7000 we should expect a value of about 20000. This is approximately the value obtained by Miss Hayner for this temperature, and consequently it is suggested that the presence of a small quantity of air as an impurity liberated from the walls of the quartz absorption cell is a possible explanation of Miss Hayner's results. The failure of Miss Hayner to obtain persistent resonance radiation in a sealed-off absorption cell can be explained on the supposition that the cell was improperly evacuated and sealed off, so that, upon heating, the air pressure rose quickly to a value sufficient to increase the exponential constant to an unmeasureable value.

Further evidence that collisions of the second kind play an important rôle in the phenomenon of the diffusion of imprisoned resonance radiation is furnished by measurements of the opacity of the slab of mercury vapor. According to the simple theory of imprisonment neglecting impacts, the ratio of the incident to the transmitted light is

$$I_0/F_0=1+l\alpha N$$

whereas, rough measurements show that the opacity of the slab for radiation from a cold resonance lamp increases much more rapidly with vapor density. Taking into account impacts of the second kind, the opacity is found to be

$$I_0/F_0=\tfrac{1}{2}(\tau k)^{-1/2}\sinh 2l\alpha N(\tau k)^{1/2}+\cosh 2l\alpha N(\tau k)^{1/2}$$

which gives results in fair agreement with experiment.

In conclusion, I wish to express my indebtedness to Professor H. W. Webb, at whose suggestion and under whose guidance this work was done; and to Mr. L. J. Buttolph of the Cooper Hewitt Electric Company, I extend my sincere thanks for his kindness in placing at my disposal the mercury arc necessary for this work.

Phoenix Physical Laboratories,
Columbia University,
December, 1926.

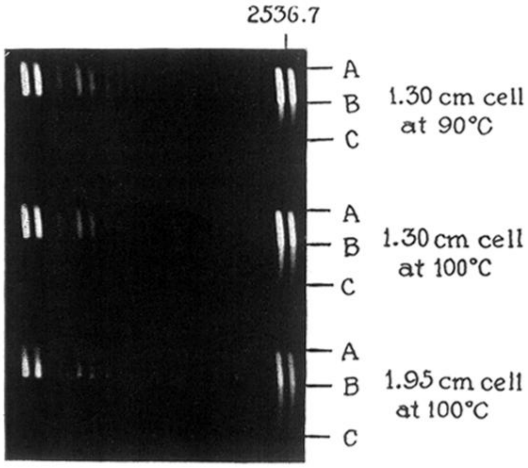
2536.7
A
B
C
1.30 cm cell
at 90°C
A
B
C
1.30 cm cell
at 100°C
A
B
C
1.95 cm cell
at 100°C

Fig. 5