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THE DURATION OF RADIATION EXCITED IN HYDROGEN BY 10.2 VOLT ELECTRON IMPACTS

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Abstract

By the use of a four electrode tube, in which high frequency voltages are applied in phase to the grids of the excitation and photo-electric systems, the life of the $2P$ state in hydrogen, excited by 10.2 volt electron impacts, was measured. Because of the small amount of hydrogen dissociated by the hot cathode it is improbable that absorption and re-radiation played any part. A discussion of other possible errors leads to the conclusion that the observed effects are due to the persistence of the radiation. The experimental results, which were obtained with tubes of different dimensions and for pressures from .075 to .25 mm, check well with those calculated on the assumption that starting at the instant of impact the radiation falls off exponentially. The exponential constant found was $.83\times10^8$ sec^{-1}. Unless the form of the curve is the result of a lag in the photo-electric effect, as seems improbable, the average duration of the radiation resulting from the 10.2 volt electron impact in hydrogen is $\tau=1.2\times10^{-8}$ sec. If the photo-electric lag is effective this is the maximum value of τ. Preliminary measurements made for the 11.9 volt radiation, attributed to the hydrogen molecule, indicate an approximate value of $\tau=3.5\times10^{-8}$ sec.

Direct measurements of the time associated with the decay of radiation[1] have been made by Wien[2] and by Dempster.[3] These measurements were made by means of a canal ray tube. Atoms were excited by high voltage in one chamber of the tube and passed through a narrow opening into a second chamber where the radiation was observed to decay exponentially and the time constant was computed from the observed data. Interpretation of the results was made difficult because the atoms were completely ionized in the excitation chamber and it was impossible to determine just when the atom arrived at any one state or by what processes the normal state was finally reached.

In this investigation an attempt has been made to avoid such complications and to obtain a direct measurement of the rate of decay

[1] Foote and Mohler, "The Origin of Spectra," Chap. IV.
[2] W. Wien, Ann. d. Physik **73**, 483 (1924).
[3] A. J. Dempster, Astrophys. J. **57**, 193 (1923).

of radiation in hydrogen when excited to the $2P$ state by simple electron impact. The measurement was made for the simplest possible transformation and on the simplest type of atom, only the excitation of the first line of the Lyman Series ($\lambda = 1216$) being possible under the conditions of the experiment.

Method

The method used is that devised and described by Webb.[4] In a four electrode tube, the hot cathode F and accelerating grid G made up the exciting system while the photo-electric grid H and photo-electric plate P served as the receiving system (see Fig. 1). The voltages on these systems were so arranged that the formation of positive ions was prevented and no electrons were allowed to pass from one system to the other. Therefore the photo-electric system responded only to radiation. A d. c. potential of 10.2 volts impressed between F and G gave the electrons, emitted from the hot cathode F, a velocity just below that necessary to excite the hydrogen atom to the $2P$ state. An a.c. voltage, of about 2.0 volts peak value, superimposed on this d.c. bias excited the atom only during the positive half of the voltage cycle, no excitation being possible in the negative half-cycle. A voltage of the same frequency, magnitude, and phase applied to the photo-electric system between H and P reversed the photo-electric current in alternate half-cycles. These electrical connections are shown in Fig. 2. The accompanying curves, (*a*), (*b*), (*c*) and (*d*) of Fig. 2 show the processes involved. The solid curves of (*a*) and (*c*) represent the sinusoidal voltages as applied to the excitation system at 60 cycles and at 10^7 cycles respectively. The dotted curves represent the resulting radiation present throughout the cycle, assuming an exponential law of decay. At 60 cycles, because of the long period, the persistence is negligible, while at sufficiently high frequencies (10^7 cycles in this case) a measurable part of the radiation persists into the negative half-cycle. Curves (*b*) and (*d*) show the effect of this on the photo-electric system. The solid lines represent the applied voltages between H and P at 60 cycles and 10^7 cycles; the dotted lines represent the photo-electric current due to the incident radiation. At 60 cycles, as no appreciable radiation persists into the negative half-cycle, no negative current affects the electrometer. At highei frequencies the distribution of the same energy over more than the initial half-cycle reduces the positive current and at the same time contributes a negative current during the negative half-cycle, resulting in a decrease of current

[4] H. W. Webb, Phys. Rev. **24,** 113 (1924); Phys. Rev. **21,** 479 (1923).

to the electrometer. By measuring the current for various frequencies the current-frequency relation is obtained. These data are sufficient to check the assumed exponential law of decay and to determine the exponential constant.

Apparatus

Two tubes, designated as tube 1 and tube 2, were used. These gave identical results. A schematic diagram of tube 2 is shown in Fig. 1.

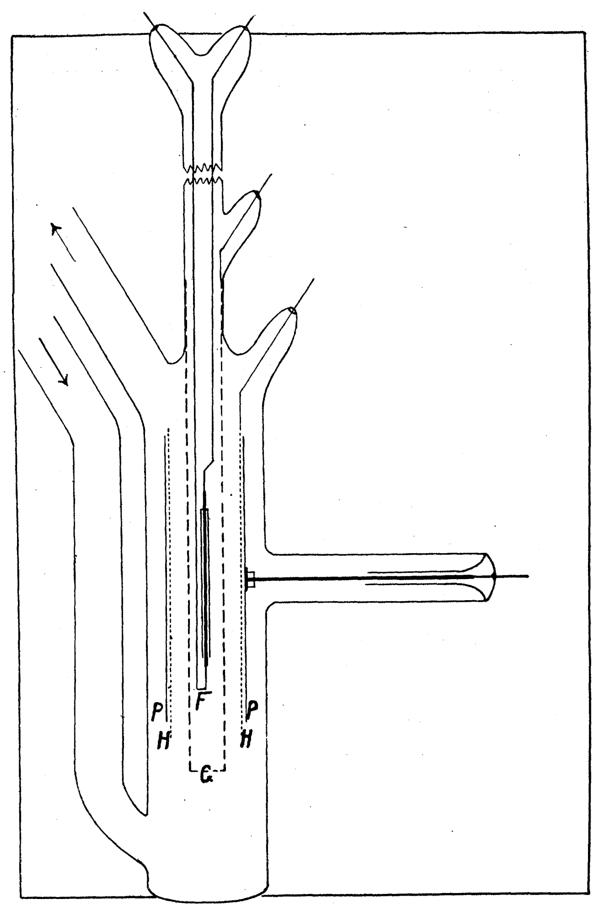

Fig. 1. Schematic diagram of experimental tube 2. Drawn to scale.

The two tubes differed in the spacing of the grids and in the nature of the photo-electric grids H. In both tubes the cathode F consisted of an equipotential sheath of barium-and-strontium-oxide-coated platinum insulated from the platinum heater by mica. The dimensions of the surfaces were approximately 2×25 mm. A current of about 5 amperes was used through the heating unit which kept the surface at a bright red. This caused sufficient dissociation of the hydrogen to make possible the needed amount of excitation. The cylindrical accelerating grids G were made of nickel gauze of 1.6 mm spacing and were supported in the neck of the tube. The photo-electric system was co-axial with the excitation grid. The plate P was a cylinder of nickel sheet supported by the nickel electrometer lead which was held rigidly by the glass seal. The photo-electric grids H in both tubes were supported by the photo-electric plate and insulated from it by

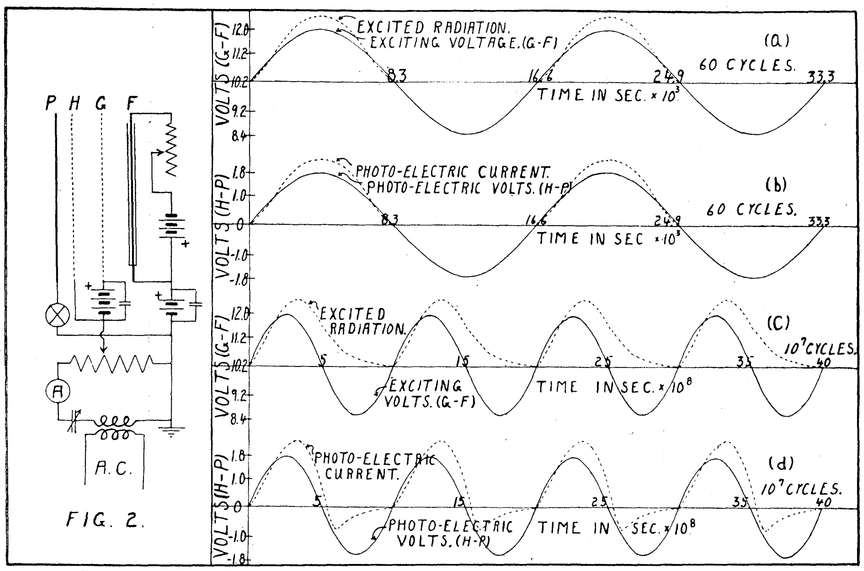

Fig. 2. Electrical connections for persistence measurements. Curves (*a*), (*b*), (*c*), and (*d*) show the processes involved in measurements.

quartz separators. In tube 1 this grid H was made of the same nickel gauze as was used for the accelerating grids G. The quartz separators were 3.2 mm thick. In tube 2 a special grid was made by drilling a nickel plate with a drill of .32 mm diameter, the holes being spaced 1 mm apart and the grid separated from the plate by 1 mm quartz separators. This was done to prevent possible overlapping of the electric fields and to simplify the paths of the electrons. The dimensions of the tubes were as follows :

	Exciting grid G		P.E. grid H		P.E. plate P	
	Inside diam.	Length	Inside diam.	Length	Inside diam.	Length
Tube 1	1.12 cm	13.5cm	2.40cm	8.0cm	3.20cm	7.5cm
Tube 2	.95cm	14.0cm	1.90cm	8.4cm	2.12cm	7.6cm

The tubes were so constructed that a steady stream of gas could be passed through and in all cases measurements were taken with a flow of hydrogen through the tube. The hydrogen was generated electrolytically at a pressure of about 2 cm kept constant by an automatic relay. After being thoroughly dried by passing through calcium chloride and phosphorus pentoxide drying tubes, the gas passed through a capillary tube sealed into a stopcock with De Khotinsky cement, and then through a liquid air trap into the experimental tube. Upon leaving the tube it passed through a second liquid air trap and capillary to a mercury diffusion pump which was kept in continual operation. A McLeod gauge connected by a T between this second trap and capillary was used to measure the pressure. The two capillaries one on either side of the experimental tube were used to reduce the pressure gradient in the tube. For the purpose of pumping out the system, by-passes, normally closed by stop-cocks, were provided around these capillaries.

Great care was necessary to keep mercury and other contaminations such as vapor from grease joints out of the tube and the tube itself was not connected into the system until liquid air had been put on both the inlet and outlet freeze-out traps. The tube was then baked at about 300°C for several hours and liquid air kept on the freeze-out traps continually until the tube was removed.

Voltages were applied to the grids by dry cells and the filament was heated by a six-volt storage battery. Alternating voltages were supplied by the 60 cycle lighting circuit or by a 5 watt vacuum tube oscillator. The voltages applied to the grids, normally from 1.5 to 2.0 volts peak value were tapped off a potentiometer. This consisted of a fine platinum wire stretched along the axis of a brass tube, and was part of a tuned circuit coupled with a Hartley oscillating circuit by a variable coupler. These voltages were measured by means of a vacuum tube voltmeter which had been calibrated by known d.c. and 60 cycle voltages. The grid of this tube was tied directly to the grids of the experimental tube and the voltage indication was given by the current from grid to filament read on a micro-ammeter. A Radiotron UV-201 was used with a plate voltage of 23 volts. The frequencies were measured by a General Radio Co. precision wave-meter with special coils calibrated for the higher frequencies. The electrometer used for measuring the photo-electric current was of the Dolezalek type and had a sensitivity of about 8000 mm per volt.

EXPERIMENTAL

It was necessary for interpreting the results to determine the d.c. characteristics of the tube during each run. The connections used in taking these curves are shown in Fig. 3a. Fig. 3b shows the characteristics of the excitation system and is taken with a constant voltage between H and P. Below 10.2 volts the curve shows "stray" energy due probably to light from the filament. At 10.2 volts we find the characteristic "break" due to resonance radiation from the hydrogen atom.[5] In taking this curve which is typical of all those taken the following voltages were used: $P=0$, $H=2.8$, $F=4.2$, and G variable.

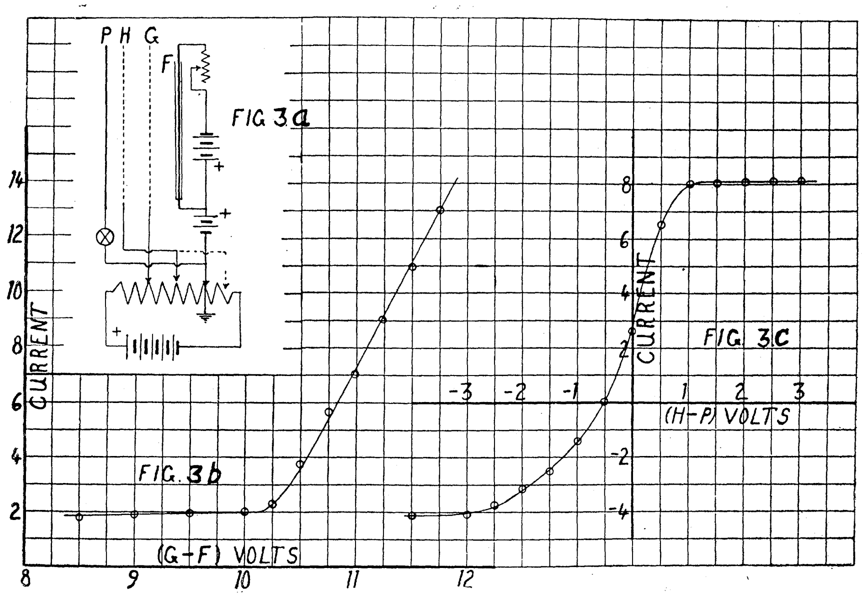

Fig. 3a. Electrical connections for d.c. characteristics.
Fig. 3b. D.C. characteristics of excitation system.
Fig. 3c. D.C. characteristics of photo-electric system.

Fig. 3c is typical of the photo-electric characteristic curves taken with the d.c. voltages $P=0$, H variable, $F=4.2$, and $G=14.7$. This curve shows saturation for the photo-electrons passing from plate to grid with H positive and for the reverse photo-electric current when H is negative with respect to P. The latter accounts for the reverse current due to radiation persisting into the negative half-cycle when a.c. voltages are applied to both systems as explained above.

[5] Horton and Davies, Phil. Mag. **46,** 872 (1923);
K. T. Compton, Phys. Rev. **20,** 283 (1922);
P. S. Olmstead and K. T. Compton, Phys. Rev. **22,** 559 (1923).

In taking the measurements to determine the persistence of the radiation P and F were kept at the above voltages. A d.c. voltage of 10.2 furnished by small flashlight cells, paralleled with a condenser, of 0.1 m.f. capacity, was put on G (Fig. 2). An a.c. voltage superimposed on this bias gave sufficient velocity to the electrons to excite resonance radiation in the positive half-cycle only. The photo-electric grid H was connected to G by as short a connection as possible, that is, just outside the biasing battery. Thus the same a.c. voltage was impressed on H and G in phase. The grid of the vacuum tube voltmeter was also connected to this common connection of H and G.

In making these measurements the rate of charging of the electrometer was measured, and the ratio of the current at each frequency to the corresponding current at 60 cycles, taken as 100 percent, was then found. It was in general necessary to take several measurements alternating between the higher frequency and 60 cycles to establish this current ratio. In addition for each frequency two tests were made as a check on the operation of the apparatus. High frequency surges, harmonics, double peaked waves, or other difficulties, met with in attempting to impress pure sine waves on the grids at the high frequencies used, made these tests necessary. The first of these tests consisted in impressing the a.c. voltage on the excitation grid G only, with a d.c. voltage of about 3.0 volts on H. In this case the electrometer current at 60 cycles and at higher frequencies should remain the same because the same total amount of radiation should be produced by the voltages on G regardless of frequency and all would be recorded as positive photo-electric current. In the second test a d.c. voltage sufficient to excite the resonance radiation was impressed on G with a.c. only on the photo-electric system. In this case also the current should not vary with the frequency. In case either of these tests gave differences between the 60 cycle and the higher frequency measurement of more than one percent the data were discarded and in practically every such case some direct cause for such action was discovered and remedied.

Data were taken with the two tubes described under varied conditions of filament current and electrometer shunt, and with tube 2 at pressures varying from .075 mm to .25 mm.

RESULTS

The indicated points on the curve in Fig. 4 represent the experimental data. The points indicated by solid circles were taken with tube 1;

those indicated by the crossed circles with tube 2 at a pressure of .25 mm, and those by the plain circles with tube 2 at .075 mm. Since only three or four points could be measured in any one run and since the d.c. characteristic curves of the excitation and photo-electric systems varied slightly from day to day the following approximate correction was applied to the data before plotting so as to make the results comparable; the shape of the d.c. photo-electric characteristic was assumed constant and all data were corrected to correspond to the same ratio of positive and negative saturation currents.

The result shown in this curve can best be explained by assuming the law of decay of the radiation to be exponential, starting at the instant of impact. The relation between the rate of excitation and time, which is obtained by combining the d.c. excitation characteristic with the a.c. sine voltage wave used to produce radiation, is represented by a curve practically sinusoidal in the positive half-cycle; if we neglect the radiation due to "stray" energy it vanishes for the negative half-cycle. Then, using only positive values of the sine, the expression

$$I_0(\sin 2\pi f t_1)e^{-k(t-t_1)}dt_1$$

represents the intensity of radiation falling on the photo-electric system at any time t resulting from the excitation $I_0(\sin 2\pi f\, t_1)dt_1$ produced in the interval dt_1 at the time t_1, where k is a constant depending on the mean life of the radiation. Denoting by I the total intensity of the radiation falling on the photo-electric system at the time t, we have

$$I=\int_0^t I_0(\sin 2\pi f t_1)e^{-k(t-t_1)}dt_1$$

which gives for values of $t<1/2f$

$$I=\frac{I_0}{4\pi^2f^2+k^2}\left[k\sin 2\pi ft-2\pi f\cos 2\pi ft+2\pi fe^{-kt}\right]$$

and for $t>1/2f$

$$I=\frac{2\pi fI_0}{4\pi^2f^2+k^2}\left[e^{-k(t-1/2f)}+e^{-kt}\right]$$

With the aid of these expressions curves may be plotted for any values of k showing the relation between the intensity of radiation arriving at the photo-electric system and the time for various frequencies. (See the dotted curves of (a) and (c) in Fig. 2.) By summing up the energy in the various periods and multiplying by the frequency (f) the total energy arriving at the photo-electric system per second in the positive half-cycles and in the negative half-cycles may be determined.

The photo-electric characteristics to which all experimental results were reduced before plotting was such that the result of applying an a.c. voltage to the photo-electric system could be approximated very closely by multiplying the total radiation arriving at the photo-electric system in the positive half-cycles by four and subtracting from it that arriving in the negative half-cycles multiplied by one. Thus we may obtain a value of the resultant current for each frequency and the ratios of these currents to that computed similarly for 60 cycles gives ratios determining the current-frequency relation resulting from the assumed exponential law of decay. By trial the value of k giving a current-frequency curve best agreeing with the experimental data

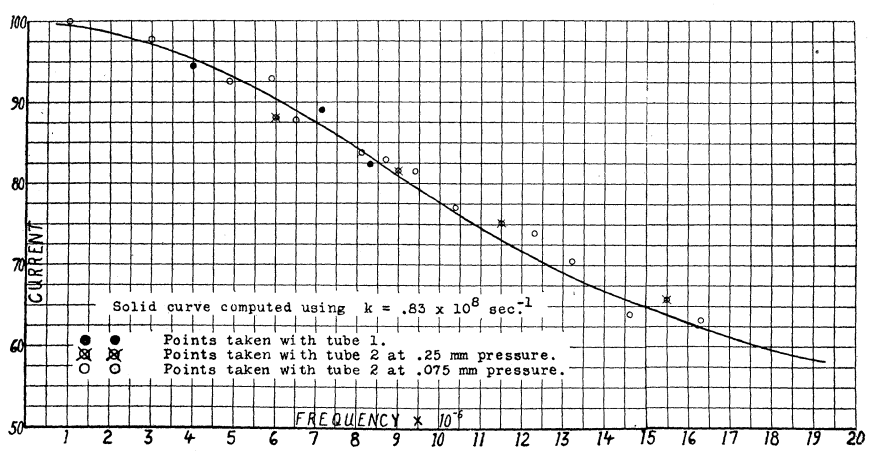

Fig. 4. Graph of experimental results.

was found. The solid curve of Fig. 4 is computed using this value, $k = .83 \times 10^8$ sec.$^{-1}$. The agreement is such as to justify the assumption of an exponential decay.

To verify this, complete calculations free from approximations have been carried out and the results are shown in Table I. In order to determine accurately the effect of the radiation falling on the photo-electric system it is necessary to combine the d.c. photo-electric voltage-current characteristic curve shown in Fig. 3c with the curve of sine voltage impressed on the grid H to form a new curve which is used as an operator on the curves described above, showing the relation between the radiation arriving at the photo-electric system and time. From this combination of curves, which can only be obtained by a graphical method, the value of the current for each frequency, stated in percent of the corresponding current at 60 cycles is obtained and the results thus computed are tabulated in column four of Table I. Column three of this table represents the corresponding experimental data. A slight correction has been made for "stray" energy as indicated by the form of the d.c. characteristic curve below 10.2 volts. The correction is made by subtracting from the electrometer readings a quantity proportional to the initial level and assumes that this energy contributes to the total radiation uniformly during the entire cycle. The agreement between the experimental and computed results may readily be seen. The differences between these values are shown in the last column and indicate on the average an agreement better than two percent. The constant $k=.83\times10^8$ sec.$^{-1}$ used above in computing the solid curve of Fig. 4 was also used in computing the values given in column four and it was found that a variation from this value of k as great as one percent gives an agreement not nearly so good. In the table under "Remarks" are recorded the date on which the data were taken, the tube used, the pressure p at which the hydrogen was passed through

TABLE I

Remarks	Frequency $\times10^{-6}$	Experimental current corrected for initial energy Percent	Computed current $k=.83\times10^8$ Percent	Diff. Percent
Sept. 11, 1925				
Tube 2	5.90	91.3	91.2	.1
$p=.075$ mm	8.70	78.7	80.5	−1.8
July 3, 1925	8.33	84.0	88.2	−4.2
Tube 1	7.15	90.0	90.5	− .5
$p=.09$ mm	3.94	95.0	96.0	−1.0
Oct. 25, 1925	3.00	96.3	93.5	2.8
Tube 2	8.10	71.0	72.0	−1.0
Bias on grid *H*	10.4	60.0	61.0	−1.0
$p=.11$ mm				
Oct. 30 and 31	4.90	91.6	91.4	.2
Tube 2	6.50	87.2	89.5	−2.3
$p=.10$ mm	9.40	81.5	79.5	2.0
	14.6	62.2	66.0	−3.8
	12.3	71.7	70.3	1.4
Nov. 8, 1925	13.2	73.5	72.0	1.5
Tube 2	16.3	67.0	66.6	.4
$p=.10$ mm				
Nov. 20, 1925	9.0	80.0	79.5	.5
Tube 2	11.5	73.2	72.0	1.2
$p=.25$ mm	6.0	87.0	90.5	−3.5
	15.5	63.5	64.5	−1.0

the tube, and any variation in the circuits used. Column two gives the frequencies at which the measurements were taken and for which the computations were made.

The results given in the table and indicated by the curve show a close agreement between the computed data and that found experimentally even with tubes of very different dimensions and for pressures varying from .075 mm to .25 mm. Apparently the assumptions that the radiation begins immediately upon impact and decays exponentially with the exponential constant $k = .83 \times 10^8$ sec.$^{-1}$ describe the processes involved. This gives the reciprocal of k, $\tau = 1.2 \times 10^{-8}$ sec., for the average duration of radiation in hydrogen excited to the $2P$ state by 10.2 volt electron impacts. It should be noted that this experiment gives no indication of the behavior of the electron during this period of time, a part of which may be spent by the electron in an idle state.

Errors. There is possibility of several errors in the method involved in these measurements but a careful study and the results of tests show that it is improbable that any of these play even a small part. (a) *Phase shift between voltages impressed on the grids*: To give the results found a shift of from 30 to 60 degrees in the phase would be required. Phase shifts of this amount seem impossible in view of the precautions taken. Furthermore, no effects could be observed when the length of leads, the position of the batteries, etc., were altered for the purpose of investigating the possibility of trouble of this nature. Finally calculation shows that the observed results would not be consistent with the values of inductance or capacity required for these shifts. (b) *Effect of electron velocities:* At the pressure used the mean velocity of the electron under the voltages used was sufficient for it to traverse the distance between the photo-electric plate and grid in less than one-thirtieth of a half-cycle even at the highest frequencies used. Thus the effect of electrons caught in the reversing field was negligible. This is also borne out by the fact that the same results were obtained with tubes of different dimensions and at different pressures. (c) *Absorption and re-radiation:* It is improbable that this process played any part due to the limited amount of dissociated hydrogen present.

If the time required for an electron to be released from a surface by photo-electric action were of the order of 10^{-8} sec. or more, which seems improbable from other considerations, the duration of this photo-electric lag would affect the time constant measured and it would be possible to state only that $\tau = 1.2 \times 10^{-8}$ sec. represents a maximum value of the duration of the excited radiation. Further experiments in this laboratory are contemplated in which different materials will be used in the photo-electric systems in order to determine if this gives any measurable change in the results.

W. Wien[2] found by his canal ray method times of the order of 2×10^{-8} sec. for the average life of Hα and Hβ and for several radiations of shorter wave-length. His result for the life of $H\alpha$ is in good agreement with that computed by the classical theory assuming a linear oscillator, but according to this theory shorter times should be found for the shorter wave-lengths. The theory gives for the mean duration of the 10.2 volt radiation about 7×10^{-10} sec. which is much shorter than the life, 1.2×10^{-8} sec., found in the present investigation.

Preliminary measurements have been made on the first resonance radiation attributed to the hydrogen molecule by Horton and Davies.[5] A much cooler cathode was used which did not dissociate sufficient hydrogen to give appreciable radiation at 10.2 volts. It was thus possible to work only with the molecular radiation which starts at 11.9 volts. The results indicate a life for this radiation not less than 3.5×10^{-8} sec.

In conclusion I wish to express my indebtedness to Professor Harold W. Webb, at whose suggestion and under whose guidance this work was done. Thanks are also due to Mr. J. Horace Coulliette for assistance in adjusting the apparatus.

Phoenix Physical Laboratories,
Columbia University,
April 15, 1926.