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Lifetimes of Resonance Lines of Cadmium*

HAROLD W. WEBB AND HELEN A. MESSENGER**
Pupin Physics Laboratories, Columbia University, New York, New York

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The mean lifetime of the triplet resonance line $5^1S_0-5^3P_1$, 3261A, of cadmium was measured by the alternating voltage method. The value found was 2.14×10^{-6} second, with an estimated precision of three percent. Similar measurements made to determine the mean lifetime of the singlet resonance line, $5^1S_0-5^1P_1$, 2288A, showed that the excitation which resulted in the emission of this line was mainly due to cascading from a higher level (or levels) by infra-red transitions, the excitation to the 5^1P_1 level by electron impact being relatively much less probable than that to the higher level. The lifetime of the infra-red transition was found to be 9.0×10^{-9} second. From the form of the curve showing the dependence of the persistence of the radiation emitted by the excitation tube upon the vapor concentration, the mean lifetime of the 2288A transition was estimated as approximately 2.1×10^{-9} second. The lifetime of the subordinate series lines 5086–4800–4678A was found to be 10^{-7} second, but since the measurements were affected by absorption and re-emission of the radiation, this value can be taken only as the maximum possible value of this lifetime. For the diffuse subordinate series lines, 5^3P-5^3D, similar measurements showed that their lifetime was not greater than 10^{-7} second.

THE lifetimes of each of the two resonance states of cadmium, 5^1P_1 and 5^3P_1, has been measured by several methods. Koenig and Ellett,[1] by measuring directly the decay of the resonance radiation in a stream of cadmium vapor, found for the lifetime of 3261A ($5^1S_0-5^3P_1$), 2.5×10^{-6} sec. Kuhn[2] obtained the value 2.3×10^{-6} sec. by the magneto-rotation method, and Ellett[3] and Soleillet,[4] from studies of the depolarization in a magnetic field, obtained the values 2.3×10^{-6} and 2×10^{-6} sec., respectively. The lifetime of 2288A ($5^1S_0-5^1P_1$) as measured by Kuhn,[5] again using the magneto-rotation method, was 1.98×10^{-9} sec. Zemansky[6] found the value 1.99×10^{-9} sec., using the line absorption method of Ladenburg and Reiche. Soleillet[4] computed the value of this lifetime as 10^{-9} sec. from the magnetic depolarization data; however, to account fully for his results, he resorted to the assumption that there existed a second hyperfine energy level of the 5^1P_1 state with the lifetime of 10^{-6} sec., which is not in accord with the generally accepted theory.

Measurements of the lifetimes of these two resonance lines of cadmium made by use of the alternating voltage method, previously employed to measure the lifetimes of lines of hydrogen, mercury, and potassium,[7] are described in this paper, together with some results obtained in studying the lifetimes of several subordinate series lines in the cadmium spectrum for which no earlier measurements are on record.

METHOD

The method used in determining the mean lifetimes of lines has been described in the several earlier papers[7] and will be but briefly discussed here. The radiation studied was produced in an excitation tube which contained cadmium vapor at low pressure and which was provided with a grid for controlling the excitation. This radiation, isolated by suitable filters, passed to a photoelectric tube so designed that saturation occurred at very low values of its control-grid voltage. An alternating sinusoidal voltage was applied to the control-grids of the respective tubes in phase. The bias voltage on the excitation tube grid insured that excitation occurred only during a known fraction of the positive half-cycle, and a

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** Hunter College, New York, New York.

[1] H. D. Koenig and A. Ellett, Phys. Rev. **39**, 576 (1932).

[2] W. Kuhn, Naturwiss. **13**, 725 (1925).

[3] A. Ellett, Phys. Rev. **33**, 124 (1929).

[4] P. Soleillet, Comptes rendus **187**, 212 (1928).

[5] W. Kuhn, Naturwiss. **14**, 48 (1926).

[6] M. Zemansky, Zeits. f. Physik **72**, 587 (1931).

[7] F. G. Slack, Phys. Rev. **28**, 1 (1926); H. W. Webb and H. A. Messenger, Phys. Rev. **33**, 319 (1929); R. H. Randall, Phys. Rev. **35**, 1161 (1930); P. H. Garrett, Phys. Rev. **40**, 779 (1932); D. Sinclair and H. W. Webb, Phys. Rev. **50**, 440 (1936).

suitable bias voltage on the photoelectric tube caused the current to the collecting electrode to reverse with the voltage on the control-grid. At low frequencies radiation reached the photoelectric tube only in the positive half-cycle, and hence there was no reverse photoelectric current. At higher frequencies, the radiation, because of its persistence, reached the tube in both half-cycles; the positive current was reduced, and reverse current appeared. The net photoelectric current to the collecting electrode therefore diminished with increasing frequency and approached asymptotically a "final level" when the persistence resulted in a uniform emission from the excitation tube.

The first step in the measurement of τ, the lifetime of a line, by this method, was the determination for this radiation of the "static characteristics" of the excitation tube (radiation as a function of grid voltage) and of the photoelectric tube (photoelectric current as a function of grid voltage, for constant radiation). The alternating voltages were then applied to the control-grids of the two tubes in phase and the photoelectric current measured for a suitable range of values of the frequency f. The voltages applied to the grids were made the same for all frequencies to maintain constant the total radiation excited. The results are expressed as the ratio R of the photoelectric current at the frequency f to the photoelectric current at a frequency so low that the persistence of the radiation was practically negligible. This will be called the "reference frequency" hereafter. Data from the curve obtained when R was plotted as a function of f were used to compute τ, the mean lifetime of the line.

In measuring the lifetimes of resonance lines the absorption of the radiation presents a serious complication. Each photon absorbed produces an excited atom which persists in its excited state with the same mean lifetime as an atom originally excited by electron impact. The observed radiation consists, then, of photons which come directly from atoms excited by impact and photons which leave the excitation tube after one or more absorption-re-emission processes. This increases the persistence in the mass of vapor in the excitation tube, and hence the "apparent" lifetime T is greater than τ, the difference increasing with the vapor pressure. To determine τ it is therefore necessary to correct for the effect of absorption and re-emission, which it is difficult to compute precisely, or else to make measurements at pressures so low that absorption is negligible. This occurs at such low pressures that the radiation is usually insufficient for precise measurements. For example, in measuring the lifetime of 2288A, it was necessary to work at a vapor pressure below 1.5×10^{-6} mm. At this pressure the kinetic mean free path of the electrons in the vapor was of the order of 10^4 cm, so that the efficiency of the excitation tube was exceedingly low. This difficulty, usually encountered only in measurements with resonance lines, proved troublesome also in measurements on subordinate series lines when intense excitation was used.

APPARATUS

Figure 1 shows schematically the essential elements of the apparatus used, for the measurements with 3261A and 2288A. In the main it was similar to that used in earlier experiments and fully described by Garrett.* The excitation tube is shown in cross section. The envelope was of fused quartz; S was an indirectly heated, oxide coated cathode; G, the control-grid, was of nickel mesh and covered only the front half of the cathode; W, the wall grid, was of nickel mesh on the front, or window, side and of solid sheet in the rear. Since it was essential that absorption of radiation be reduced to a minimum, the tube was

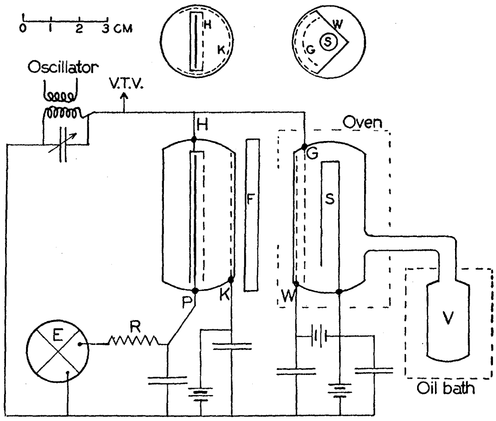

FIG. 1. Diagram of apparatus.

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* P. H. Garrett, reference 7, p. 781.

so designed that by the application of suitable voltages to the grids excitation would occur mainly between G and W and radiation reach the window by traversing only a thin layer of vapor. The tubes were sealed off after evacuation in the usual manner, with especial care to eliminate traces of mercury.

Adjoining the excitation tube was a reservoir V, on the walls of which a thin layer of carefully purified cadmium metal had been evaporated before the tube was sealed off from the pumps. This reservoir was immersed in an oil bath, electrically heated, and maintained by a thermostat within 0.5°C of the temperature corresponding to the vapor pressure desired in the tube. The body of the tube was in an oven consisting of a copper cylinder with very heavy walls heated by gas jets. A fused quartz window opposite the cathode transmitted the radiation. The temperature of the oven was held only slightly higher than that of the oil bath to permit the concentration of cadmium atoms N in the tube to be taken as that corresponding to the temperature of the bath without correction. This concentration was computed from the vapor pressure given by the formula in the *International Critical Tables* for the appropriate range.

The photoelectric tube used in studying the resonance radiations is shown in cross section in the figure. The envelope was of quartz. The sensitive surface was magnesium, selected for the measurements with 3261A and 2288A because its long wave-length limit is in the neighborhood of 4000A and its maximum sensitivity is near 2500A.[8] This was deposited on the plate P, a nickel sheet 1 cm×4 cm. The control grid H was rectangular in cross section and was of nickel mesh in the front and of sheet nickel on the sides and back with a clearance of 2 mm between it and P. The shape and clearance were designed to give current-voltage ($H-P$) characteristics which would reverse sharply with the voltage and to cut down the time lag of the tube produced by the time of passage of the photoelectrons between P and H. The auxiliary electrode K was also of nickel mesh and served to prevent the return to P of electrons which had passed through the grid H into the region between H and K. The plate P was coated with magnesium by the method described by Rentschler.[9] An auxiliary electrode (not shown in the figure) was used, consisting of a magnesium wire, 1 mm in diameter, placed between H and K, parallel to the axis of the tube. After baking the tube and outgassing the electrodes, the tube was filled with argon at a suitable pressure and with the magnesium wire as cathode and the electrodes P and H as anode, a coating of magnesium was deposited on P by sputtering. The argon was then removed by absorption by cocoanut charcoal contained in a side tube immersed in liquid air. After the argon had been absorbed, this tube was sealed off.

Provision was made for interposing between the excitation and photoelectric tubes various filters including a quartz cell containing pure cadmium vapor. A water cell, with windows of quartz or of glass with high ultraviolet transmission, was interposed between the tubes when it was necessary to protect the photoelectric tube from the heat of the oven.

Photoelectric current was measured by a sensitive quadrant electrometer. To avoid disturbances on opening the electrometer key and to simplify the high frequency circuit, the lead from P was connected to ground through a condenser C of approximately double the capacity between P and H. The electrometer was connected in parallel with this condenser through a resistance R of 13×10^9 ohms, which isolated it from the high frequency circuit.

A vacuum-tube oscillator with loosely coupled tuned secondary circuit was the source of the alternating voltage. A calibrated peak voltmeter was employed to measure and monitor the voltage. By the use of switches, not shown in the figure, either grid could be connected independently to sources of direct potential or to the source of alternating voltage. When alternating voltage was used on both grids, their terminals were connected as directly as was possible to minimize any differences between the magnitudes and phases of the voltages on these two electrodes.

The cadmium absorption cell employed as a filter in some of the measurements was especially useful in determining the purity of the resonance

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[8] A. L. Hughes and L. A. DuBridge, *Photoelectric Phenomena* (McGraw-Hill Book Company, Inc., New York and London, 1932), p. 162.

[9] H. C. Rentschler and D. E. Henry, J. Frank. Inst. **223**, 135 (1937).

radiations. It was a cylindrical cell of fused quartz, 2 cm in diameter with plane faces 1 cm apart. Solid cadmium in a side tube, the temperature of which was controlled by an electric heater, furnished cadmium vapor at the desired concentration. The body of this cell was enclosed in an oven to keep the vapor at a temperature slightly higher than that of the side tube. Quartz windows permitted the transmission of the radiation to and from the cell.

EXPERIMENTAL PROCEDURE AND RESULTS

3261A

The measurements of the mean lifetime of the resonance triplet resonance line 3261A were made with vapor concentrations in the excitation tube ranging from 8.7×10^{12} atoms cm^{-3} (204°C) to 3.3×10^{14} atoms cm^{-3} (280°C). The radiation 2288A, which was very intense at these concentrations, was filtered out with a Corex D filter (Corning Glass Company), which absorbed all wave-lengths shorter than 2500A. When testing for the presence of wave-lengths other than 3261A in this filtered radiation, the cadmium absorption cell was interposed between the excitation tube and the Corex D filter. With $G-S$ equal to 11.0 volts, and the excitation tube at 214°C, approximately the temperature at which precise measurements were desired, no measurable amount of radiation was transmitted by the absorption cell when the vapor pressure therein was 0.05 mm (300°C), showing that of wavelengths above 2500A the excitation tube was emitting substantially only 3261A. The absorption coefficient for this line computed from the absorption measurements taken at lower pressures in the absorption cell, was $1.3\times10^{-14}N$.

Measurements to determine the lifetime were made with the bias voltage $W-S=4.5$ volts, and bias voltage $K-P=4.5$ volts. In each determination of the lifetime it was first necessary to determine the "static characteristics" of the excitation and photoelectric tubes for the radiation in question at the selected vapor pressure. When the intensity of 3261A radiation in the excitation tube was studied as a function of the $G-S$ voltage, taken with $H-P$ constant at three volts, the curve first showed the excitation of 3261A at $G-S=4.5$ volts, with no correction for contact potential or drop in the leads. The accepted excitation potential for this line is 3.8 volts. At higher voltages there were several breaks in the curve, which departed sufficiently from a linear relation between radiation and voltage to necessitate a graphical calculation when determining an accurate value of the lifetime. The static characteristics of the photoelectric tube were of exceptionally simple form. Saturation was reached when $H-P$ was little more than 0.4 volt. The reversal point was at $H-P=-0.1$ volt, making it unnecessary to use a bias voltage on $H-P$ during the alternating voltage measurements. The reverse current was approximately 30 percent of the positive saturation current and varied only 5 percent as $H-P$ was varied from -2 to $+9$ volts. In such measurements special care is necessary to eliminate the effects of charges which accumulate on the walls of the tube and give erroneous results.

When the alternating voltages were applied to the control-grids, the peak value used was 6.6 volts, with a fixed bias of 4.5 volts applied to $G-S$, so that radiation was excited only in the positive half-cycle. The crest voltage attained by $G-S$, 11.1 volts, was sufficiently low to insure that the radiation excited and transmitted through the filter was substantially 3261A and that the ionization was negligible. A test made with alternating voltage applied to $G-S$ only, $H-P$ being held at constant voltage, showed the electrometer current to be independent of the frequency, indicating that the voltage applied at the external terminals of G and S was the same as that between the electrodes G and S and that the behavior of the excitation tube could be predicted from the static characteristics. With the alternating voltage applied directly to $G-S$ and $H-P$, a series of measurements was made to determine the $R-f$ curve for each of several concentrations of cadmium vapor in the range specified above. In this case R was the ratio of the photoelectric current at the frequency f to that at the reference frequency, 1300 cycles. It was found that the final level R_∞, the value of R approached asymptotically by the curve at high frequencies, agreed well with that calculated from the static characteristics. This is an important check, signifying that the behavior of the photoelectric tube could be correctly predicted from these characteristics.

The lowest concentration at which the energy was sufficient to make precise measurements possible was that corresponding to 218.5°C. At this concentration the secondary radiation resulting from absorption and re-emission which reached the photoelectric tube was less than 10 percent of that resulting from direct excitation. At this concentration the $R-f$ curve was taken with special care, and a precise value of R for $f=80{,}500$ cycles, 0.647, was determined by repeated observations. Then from the $R-f$ curves taken at oil bath temperatures of 244°, 232°, 215°, and 203°C, respectively, the values of the frequency f_0, for which R had this same value, 0.647, were also determined. Graphical calculations made from the respective static characteristics of the excitation and photoelectric tubes show that if the radiation had been emitted from the excitation tube according to a simple exponential relation (i.e., all radiation direct and no absorption and re-emission), τ, the lifetime of the line, would have been given by $\tau=(1.826\pi f_0)^{-1}$ sec. In Fig. 2 the values of $1.826\pi f_0$, determined from the five curves, are plotted as a function of the vapor concentration. Extrapolation of this curve to zero concentration gives the correct value of $1/\tau$ since the effect of absorption is thus eliminated. This extrapolation would ordinarily be difficult to carry out with precision because the form of the curve for low concentrations is not easily calculated from the tube geometry. However, for the tube used, the form of the curve is approximately known from the very careful measurements of the lifetime of the 2537A line of mercury made by Garrett,* who used an excitation tube approaching closely in size, shape, and positions of electrodes the tube used in these measurements. The curve drawn in Fig. 2 is the curve of Fig. 3b of his paper, with the scales so adjusted that the curve passes through the precisely determined point for 218.5°C and best approximates the experimental curve for higher values of the concentration. The departure of the experimental points from this curve is in every case within the experimental error of the measurements. The ratio of the scales of abscissas is approximately the reciprocal of the ratio of the atomic absorption coefficients of the two lines. For zero concentration the curve gives $1.826\pi f_0=1/\tau=0.467\times 10^5$ sec.$^{-1}$. The mean lifetime of the line 3261A is therefore determined as 2.14×10^{-6} sec., the precision of the measurements being estimated as better than three percent.

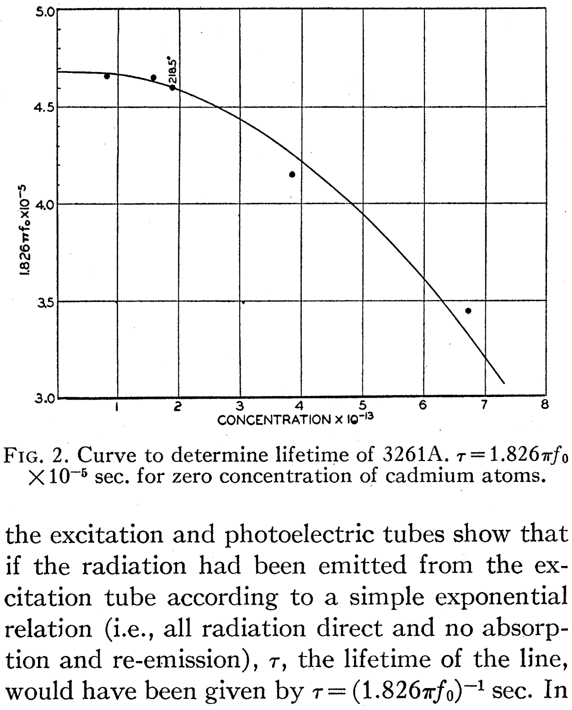

FIG. 2. Curve to determine lifetime of 3261A. $\tau=1.826\pi f_0 \times 10^{-5}$ sec. for zero concentration of cadmium atoms.

This result is about seven percent lower than values given by the magneto-rotation and magnetic depolarization methods.[2–4] The value 2.5×10^{-6} sec., found in the measurements of Koenig and Ellett,[1] was probably subject to larger error than the other methods because of the difficulties inherent in the method.

In the measurements here reported, the excitation of the 5^3P_1 level by cascading from higher levels was considered as a possible source of error. However, a series of studies made with varied peak voltages indicated this excitation to be negligible.

Some additional measurements made with 3261A are of interest because of the light they throw upon the effect of the absorption-re-emission process. These were made with a second excitation tube which was practically identical in construction with the tube used in the measurements just described except that the envelope was of glass of high ultraviolet transmission, instead of quartz. The average value of τ calculated from measurements with this tube was double that determined with the first tube for the same vapor density and electrode voltages. The measurements were inconsistent and not reproducible. With a peak alternating voltage of 4.5 volts on $G-S$ and $H-P$, and temperatures between 200°

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* P. H. Garrett, reference 7, p. 784.

and 214°C, the calculated lifetime varied between 6.4 and 3.8×10^{-6} sec. On the other hand, when the peak voltage was decreased to 1.5 volts, the calculated lifetime was 2.3×10^{-6} sec. Absorption measurements showed that the radiation measured was still substantially 3261A. These spurious results were later found to be due to a defective coating on the hot cathode. The greater part of the electron emission was from the lower tip of the cathode, which was not opposite the window of the oven. The bulk of the radiation which reached the photoelectric tube was excited in this region and could reach the photoelectric tube only by being absorbed by the vapor in the region opposite the window and reradiated. As a result the calculated lifetime was approximately twice the true lifetime. The variability in the results and their dependence upon voltage was due to the variation of the distribution of the emission over the surface of the cathode with time and applied voltage. When the window was lowered to expose the active part of the cathode, the measurements gave results in close agreement with those found with the quartz tube.

2288A

A series of measurements was made to study the behavior of the principal series resonance line 2288A, with the same quartz excitation and photoelectric tubes as were used with 3261A.

The concentration of cadmium vapor in the excitation tube was varied between 1.6×10^{10} (113°C) and 2.7×10^{12} (184°C), atoms cm^{-3}. The more precise and significant measurements were made at temperatures of the reservoir V below 140°C and with crest values of the voltage $G-S$ less than 10.5 volts. Under these conditions the only radiation emitted by the excitation tube, to which the photoelectric tube responded, was 2288A. To test the radiation for the presence of 3261A, a Corex D filter which absorbs all wavelengths shorter than 2500A was interposed between the tubes. When the temperature of the reservoir was below 170°C and the crest value of $G-S$ was less than 12 volts, no radiation was transmitted which could be detected by the photoelectric tube; i.e., no radiation between 2500A and 4000A was present in a measureable amount. To test for radiation shorter than 2500A, other than 2288A, absorption measurements were made with the cadmium vapor absorption cell between the excitation and photoelectric tubes. The radiation tested was from the excitation tube when the reservoir was at 145°C. The tubes were separated so that the distance between excitation tube and absorption cell was 72 mm and that between absorption cell and photoelectric tube was 90 mm. With high pressures in the absorption cell, absorption was practically complete, indicating that the radiation affecting the photoelectric tube was essentially 2288A.

With lower pressures in the absorption cell, the absorption coefficient of cadmium vapor for this radiation was computed to be $1.75\times10^{-11}N$, which agrees, within the precision of the observations, with the value, $1.64\times10^{-11}N$, given by Zemansky.[6] In these calculations allowance was made for that part of the radiation scattered from the absorption cell which reached the photoelectric tube.

Throughout this series of measurements the voltages $W-S$ and $K-P$ were held at 4.5 volts. The static characteristics were determined in the manner described above. That of the excitation tube (radiation as a function of $G-S$) was very nearly a straight line with an intercept on the voltage axis at 6.0 volts. The accepted excitation potential for 2288A is 5.4 volts. The characteristic of the photoelectric tube was of the usual form with saturation for $H-P$ less than 1 volt. The current reversal occurred at -0.7 volt.

The $R-f$ curves were made with fixed bias voltages; $G-S$ equal to 4.5 and $H-P$ to -0.7 volt. The alternating voltage impressed upon the directly connected external terminals of G and H was maintained for all frequencies at 5.0 volts, peak value. The reference frequency was 14,000 cycles. It was found, however, that the radiation from the excitation tube decreased with increase in frequency as determined by applying alternating voltages to $G-S$ only, $H-P$ being held constant. To correct for this, the ratio of the radiation for each frequency to that for the reference frequency was determined. The observed value of R was then corrected to correspond to equal radiation excited at all frequencies, by dividing by this ratio. The cause of this variation was presumed to be voltage drop in the leads within the excitation tube at high frequencies, resulting in a voltage difference between the electrodes less than that between their external terminals. A decrease in the electrode voltage $G-S$ of 3 percent would have accounted for the maximum observed variation of the radiation emitted, which was about 10 percent. A corresponding decrease in the voltage on the electrodes of the photoelectric tube would have had negligible effect on the measurements.

The results of the measurements are shown in Fig. 3, which gives, as a function of the concentration of cadmium atoms, the values of the "apparent lifetime" of the radiation emitted by the excitation tube. In an earlier paper the authors have shown[7] that in the case of radiation excited by electron impact, provided (a) that absorption is negligible, (b) that the excitation of radiation in the excitation tube is proportional to the instantaneous value of the alternating voltage during the positive half-cycle, and zero during the negative half-cycle, and (c) that the current in the photoelectric tube passes abruptly from a positive saturation value to a negative saturation value upon reversal of the alternating voltage, the relation between R and f is given by

$$R=1-\tfrac{1}{2}(1+s)(4\pi^2f^2\tau^2)(1+4\pi^2f^2\tau^2)^{-1}. \tag{1}$$

Here s is the ratio of the negative to the positive photoelectric saturation current, and τ is the mean lifetime of the radiation from the excited atom. Except for the effect of absorption and reradiation at the higher concentrations, these conditions were well satisfied in the measurements with 2288A as seen from the static characteristics and the bias voltages selected for the electrodes. When no complications due to absorption are involved, τ can easily be found from the curves. From (1) we find:

$$\text{for}\quad f=\infty,\quad R=R_\infty=1-\tfrac{1}{2}(1+s); \tag{2}$$

for $f=f_{\frac{1}{2}}=1/(2\pi\tau)$,

$$R=R_{\frac{1}{2}}=1-\tfrac{1}{4}(1+s)=\tfrac{1}{2}(1+R_\infty). \tag{3}$$

$$\text{Hence}\qquad \tau=(2\pi f_{\frac{1}{2}})^{-1}, \tag{4}$$

where $f_{\frac{1}{2}}$ is the frequency for which R is the mean of unity and the final asymptotic level R_∞, approached by the curve at high frequencies. In Fig. 3, the values of $(2\pi f_{\frac{1}{2}})^{-1}$ were found from the experimental curves, and from the value of s calculated from the photoelectric characteristic. The use of this value instead of the experimentally determined value was necessary because of the difficulty of making measurements at sufficiently high frequencies and because the curves departed markedly from the curve as given by the equation. The experimental curves dropped more sharply than the theoretical curve, and R fell to a value considerably lower than R_∞ as calculated from the static characteristic. Although it was not possible to verify this by measurements at sufficiently high frequency, there were indications that this low value of R was a minimum and that the curves would have approached the theoretical value of R_∞ had higher frequencies been used.

The extrapolation of the curve in Fig. 3 to zero concentration, to eliminate the effect of absorption and reradiation, gave 11.0×10^{-9} sec. for the limiting value of $(2\pi f_{\frac{1}{2}})^{-1}$. This would give a lifetime of 2288A about five and one-half times as great as the value 1.99×10^{-9} sec. found by earlier investigators.[5, 6] Because of this large difference in the results and because of the unusual form of the experimental curves, it seemed probable that the process under investigation was more complex than the simple excitation of 2288A postulated in the computations. This was confirmed by a study of the form of the curve in Fig. 3. For brevity, let $(2\pi f_{\frac{1}{2}})^{-1}$ be represented by T. The increase in T with the vapor concentration N is a complex function involving the geometry of the tube and cannot be readily computed. The earlier work of the authors and that of Garrett[7] with the

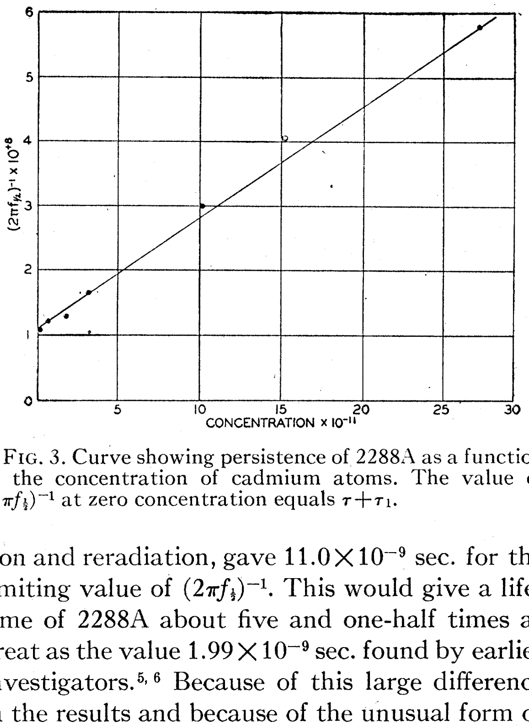

FIG. 3. Curve showing persistence of 2288A as a function of the concentration of cadmium atoms. The value of $(2\pi f_{\frac{1}{2}})^{-1}$ at zero concentration equals $\tau+\tau_1$.

2537A line of mercury showed that the relation between T and N is given approximately by the equation

$$T = T_0 + ANb\tau, \tag{5}$$

where A is the atomic absorption coefficient and b the "effective thickness" of the vapor traversed by the radiation. In the case of the mercury radiation, the constant T_0 is identical with τ, the lifetime of the resonance radiation. From (5) we have

$$\tau = (1/Ab)(dT/dN). \tag{6}$$

The value of b can in general be only roughly estimated from the geometry of the tube. However, the tube used in this work was nearly identical in design and dimensions with that used by Garrett, whose results are well described by (5) if b is taken as equal to 0.5 cm. Using this value of b and Zemansky's value of A, 1.64×10^{-11}, and dT/dN, 1.73×10^{-20}, determined from the curve, we find from (6) the value $\tau = 2.1 \times 10^{-9}$ sec., which, considering the approximations used, agrees well with the value 1.99×10^{-9} sec. determined by other methods.[6]

The possibility that the peculiar shape of the curve was due to a phase shift, causing the voltage on the excitation tube grid to lag behind the voltage applied to the photoelectric tube grid, was investigated. Such a phase shift would have resulted in a curve having a final level below the R_∞ calculated from the static characteristics. A comparison of the curves at high and low concentrations of cadmium vapor showed equal differences between the minimum values of R and R_∞ although the frequencies used in the two cases differed by a factor of ten. Since the phase shift should have decreased with the frequency, it was concluded that it was not sufficient to cause significant error.

The most consistent explanation of these results is that under the conditions of the experiment, the excitation of the atoms by electron impact was mainly to a level (possibly several levels) a few tenths of a volt above the 5^1P_1 level, and that excitation of the 5^1P_1 level was by an infra-red transition to it from the higher level. The persistence of 2288A observed by the method used in these measurements would depend, therefore, upon both the lifetime of the 5^1P_1 state and on τ_1 the lifetime of the infra-red transition. Since the photoelectric surface was sensitive only to the 2288A radiation, under the conditions used in these measurements the $R-f$ curves for such a cascade process are described by the equation

$$R = 1 - \frac{1+s}{2}\,\frac{\tau_1/\tau}{\tau_1/\tau^{-1}} \times \left[\frac{4\pi^2 f^2 \tau_1^2}{1+4\pi^2 f^2 \tau_1^2} - \frac{\tau}{\tau_1}\,\frac{4\pi^2 f^2 \tau^2}{1+4\pi^2 f^2 \tau^2}\right]. \tag{7}$$

From this equation it can be shown that with an error of less than two percent, T_0, the value of T at zero concentration, determined as described above is equal to $\tau + \tau_1$. Using the earlier determined value of τ, 1.99×10^{-9} sec., we find for the lifetime of the infra-red transition, or average lifetime of the several transitions if there were more than one, 9.0×10^{-9} sec. The curve representing Eq. (7) has the peculiarities observed in the experimental curves. It drops more sharply than the curve described by (1), falls to a minimum well below R_∞ and at high frequencies approaches it as a limiting value. Substituting in it the values of τ and τ_1, found above, we find, for zero concentration a minimum value of R at $f = 5f_{\frac{1}{2}}$, 0.06 below R, which agrees approximately with the observed values. This result is similar to that found for the corresponding line in the mercury spectrum 1849A by the authors.* It was shown that when excitation was produced by electron impact, practically all of the 1849A radiation emitted by the tube was due to cascading from a level about 0.4 volt above the 6^1P_1 level, this infra-red transition having a lifetime of 2.1×10^{-6} sec. This result agreed with that of Eldridge[10] who had found by other methods that for excitation by electron impact, the bulk of 1849A was excited indirectly through transitions from higher levels.

Subordinate Series Lines

Studies made to determine the mean lifetimes of several of the subordinate series lines of cadmium gave results which were not conclusive, but are briefly described because of certain interesting facts brought out by the measurements. These measurements were made with the potas-

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* H. W. Webb and H. A. Messenger, reference 7, p. 326.

[10] J. A. Eldridge, Phys. Rev. **23**, 685 (1924).

sium photoelectric tube previously used and described by Randall.[7] Filters were employed to isolate the lines being studied. To obtain sufficient energy in these lines it was found necessary to use voltages on the grid of the excitation tube which resulted in considerable ionization. There is consequently some uncertainty as to how closely the excitation followed in time the voltage impressed upon the grid. Numerous checks indicated, however, that this was not a serious source of error in the frequency range employed. A more serious one was the very considerable absorption of the radiation by atoms in the 5^3P states which in most of the measurements tended to obscure the effect of the persistence in the higher energy states. Figure 4 shows a typical $R-f$ curve taken under these conditions. Initially the curve falls off sharply to a value of R well above the final level, R_∞. The frequencies at which this drop occurs corresponded to a persistence one to two times as great as that which would be due to the lifetime of 3261A. Since the filters between the tubes did not transmit 3261A but only the subordinate series lines under measurement, it was concluded that this initial drop was due to absorption of the subordinate series lines by atoms in the 5^3P states and their subsequent re-emission. The decrease of R at very much higher frequencies will be discussed below.

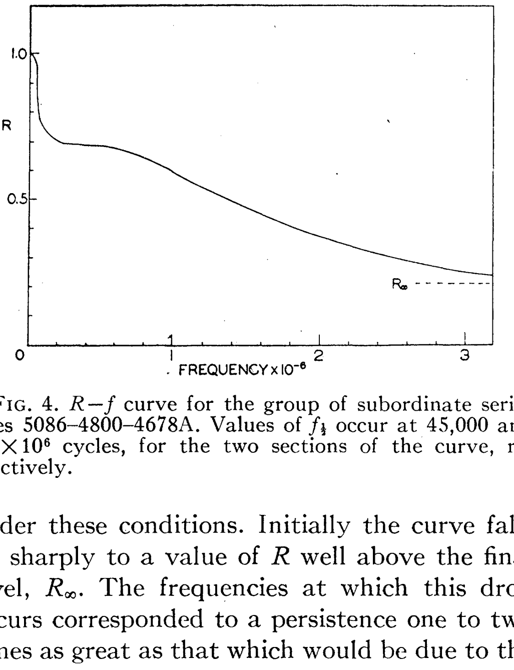

FIG. 4. $R-f$ curve for the group of subordinate series lines 5086–4800–4678A. Values of $f_{\frac{1}{2}}$ occur at 45,000 and 1.6×10^6 cycles, for the two sections of the curve, respectively.

Measurements of the mean lifetime of the 6^3S_1 level, from which emission of the lines 5086, 4800, and 4678A takes place, were made with a special excitation tube. This had an envelope of Pyrex glass and a cathode similar to that used in the other tubes. It was constructed with two coaxial electrodes of nickel mesh, G_1 and G_2, with radii 4.5 mm and 8.0 mm, respectively, and a coaxial wall electrode of sheet nickel W with radius 18 mm. The radiation was observed parallel to the axis through a window at the end of the tube, and baffles in the tube were so placed that only radiation from the region between G_2 and W reached the photoelectric tube. Corning filters 368 and 429 cut off all radiation of wave-length less than 4100A and isolated the subordinate series lines 5086, 4800, and 4678A as a group. The bias voltages used on the electrodes were: $W-S=45$ volts; $G_2-S=15$ volts. The alternating voltage, of 15 volts peak value, was applied between G_1 and S. The $R-f$ curve shown in Fig. 4 is typical of a group taken with a vapor pressure of 8.4×10^{-4} mm (216°C).

The initial drop of R was from 1.00 to 0.69, and the frequency for which R had the half-value (0.85) for this drop was 45,000 cycles, corresponding to a lifetime of 3.5×10^{-6}, which is approximately double the lifetime of 3261A. The value of R remained nearly constant until the frequency 500,000 cycles was reached, after which it dropped gradually to the final level 0.21. The $f_{\frac{1}{2}}$ for this portion of the curve was taken as the frequency, 1.6×10^6 cycles, for which R was the mean of the values 0.69 and 0.21. Assuming that this second drop in the curve was determined by the lifetime of the 6^3S_1 state and that no absorption and re-emission of these subordinate series lines was present, we find the lifetime of this state is approximately 10^{-7} sec. $(2\pi f_{\frac{1}{2}})^{-1}$. If absorption-re-emission processes were involved, this would be simply an upper limit which these experiments set for this lifetime. Some measurements made on these same lines with the tube of glass of high transmission in the ultraviolet, described earlier, gave values of $f_{\frac{1}{2}}$ in the neighborhood of 8×10^6 cycles, which can be interpreted as the result of sufficient absorption and re-emission of the radiation to increase the average persistence of the 6^3S_1 state to double that of the true mean life.

With a set of filters isolating the group of diffuse subordinate series lines 5^3P-5^3D, similar measurements were carried out. The curves are in most respects similar to those just described, and show that the value for the lifetime is not greater than 10^{-7} sec.

A detailed explanation of these curves is difficult. The initial drop seems best explained as dependent on the subordinate series radiation which was excited more or less continuously in the region screened from the photoelectric tube by the baffles and which was absorbed and reradiated by the excited atoms in the 5^3P states found in the unscreened part of the tube. The corresponding persistence would then be the same as the persistence of the 5^3P states in that part of the tube. The second drop in the curve, which occurred at high frequencies, would be explained in the case of the sharp series as due to the direct excitation to the 6^3S level (or 5^3D level for the diffuse series) of atoms in the unscreened region during the positive half-cycle of the alternating voltage and their radiation to the photoelectric tube either directly or with not more than one or two absorption-re-emission steps. For this radiation the persistence would be of the order of the mean lifetime of the level in question. Because of the uncertainties as to the exact processes involved in the measurements, the above results can probably be relied upon only as to the order of magnitude of the lifetimes.

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Production of Single Mesotrons by Non-Ionizing Radiation at Altitudes of 10,600 ft. and 14,200 ft.

JULIUS TABIN
University of Chicago, Chicago, Illinois

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The production of single mesotrons in various materials was studied by means of an apparatus consisting of 46 Geiger-Mueller counters arranged in 10 different three-, four-, and fivefold coincidence sets. The producing layers consisted of different thicknesses of paraffin, iron, and lead. The results indicate that photons are the most probable agent for the production of the single mesotrons. The cross section for the mesotron production has been calculated for the various producing materials.

INTRODUCTION

In 1938 Schein and Wilson[1] published a paper concerning the production of penetrating cosmic-ray secondaries in the atmosphere above 20,000 feet. They found considerable production at 25,000 feet and indicated that the secondary particles observed were produced by photons. Since then, many attempts have been made to identify the nature of the producing radiation. Shonka[2] found the production to be as high as 6.1 percent in a producing layer of 20 cm of lead at an altitude of 14,200 feet. Only 1.5 percent was attributed to penetrating radiation arising from photons. The other 4.6 percent was ascribed to neutral particles of greater penetration (neutrons). Schein, Jesse, and Wollan[3] undertook the investigation of the production of penetrating particles by non-ionizing radiation as a function of altitude. Their results indicated that an appreciable production takes place above 23,000 feet with increasing altitude. Because the intensity of the produced mesotrons followed the intensity of the soft component, photons were considered as the most probable producing agent. Rossi and Regener[4] studied the production of mesotrons at 14,200 feet. They found a definite production which was attributed to either neutrettos or high energy neutrons. They arrived at this conclusion because it appeared that the producing radiation had a large probability of

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[1] M. Schein and Wilson, Phys. Rev. **54**, 304 (1938).

[2] F. Shonka, Phys. Rev. **55**, 24 (1939).

[3] Schein, Jesse, and Wollan, Phys. Rev. **56**, 613 (1939).

[4] B. Rossi and V. Regener, Phys. Rev. **58**, 837 (1940).