JUNE, 1927 *PHYSICAL REVIEW* *VOLUME 29*

THE NUMBER OF RADIATING ATOMS IN A HYDROGEN DISCHARGE TUBE*

By W. H. Crew and E. O. Hulburt

Abstract

About 90% of the energy radiated from a long hydrogen tube filled with moist hydrogen at a pressure of 0.54 mm of mercury and absorbing 400 watts was found to be carried by the first three lines of the Balmer series. From the measured values of this energy and of the relative intensities of Hα, Hβ and Hγ, the number of quanta of these lines emitted per atom per second was calculated to be 2.84, 0.43 and 0.10, respectively.

A GLASS hydrogen discharge tube may be arranged to emit the Balmer lines of hydrogen in great purity, their total energy being much greater than that of the other spectral radiations, such as the infra-red atomic lines, the spectrum of the molecules and the continuous spectrum. If the entire energy radiated from the tube in all directions is measured, if the number of atoms in the discharge tube is known, and if the relative intensities of each of the Balmer lines is known, the average number of quanta of each Balmer radiation emitted by each atom per second may be calculated. Experiments based on these ideas are described in the following pages. It has been found, for example, that in the case of Hα under, let us say, normal discharge conditions this number is of unit order.

Apparatus. The discharge tube consisted of a straight tube of Pyrex glass 79 cm in length and of internal diameter 9 mm, with long side tubes leading to bulbs containing the electrodes, to a pressure gauge, to the pumps and to the hydrogen. The tube was excited by a 1 KW, 30 KV, 25 cycle transformer, the electrical energy in the tube being taken to be the product of the current and voltage.

Calibration of the thermopile. The radiation from the tube was measured by a thermopile and Paschen galvanometer, the thermopile being diaphragmed so that only about 2mm^2 were exposed to the radiation. An energy calibration was effected by observing the deflection caused by the radiation from a calibrated ribbon filament tungsten lamp. We are indebted to Dr. H. T. Wensel of the Bureau of Standards, who kindly loaned us the lamp and furnished its calibration, i.e. the temperature-current curve. With the filament at 2560° Kelvin and diaphragmed so that an area 0.12 cm^2 was exposed, the galvanometer deflection caused by the radiation, emitted normally from the surface, falling on the thermopile a meter away was 66 mm. A calculation of the spectral energy curve of the tungsten, by means of the black body formula and the emissive powers[1,2] of tungsten,

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* Published by permission of the Navy Department.

[1] Worthing, Phys. Rev. **10**, 377 (1917).

[2] Weniger and Pfund, Phys. Rev. **14**, 477 (1919).

showed that 65 watts/cm^2 were emitted normally, and that 99% of this was in the spectral region of transparency of the glass bulb, 0.32 to 3μ. The glass bulb thus caused a loss of 9%, 1% being due to absorption and 8% to reflection. At a meter's distance the flux of energy was

$$0.91\times 65\times 0.12\times 10^7\div 10^4=7.10\times 10^3 \quad \text{ergs/cm}^2.$$

This produced a deflection of 66 mm. Therefore 1 mm meant an energy flux of 108 ergs/cm^2.

Total energy from the hydrogen tube. With moist hydrogen in the tube at a pressure of 0.54 mm of mercury excited with 400 watts (66 milliamperes × 7 kilovolts) the Balmer lines were intense, fourteen of them appearing on plates taken in five minutes with the large quartz spectrograph. Other lines and the continuous hydrogen spectrum of course were also on the plates, but with relatively feeble intensity. In addition there are certain infra-red lines from atomic hydrogen of wave-length below 3μ which may come through the glass, i.e. the entire Paschen series and a portion of the Brackett and Pfund series. The entire intensity I_R of these infra-red lines was compared with the intensity I_B of all the Balmer lines by means of a Corning "Heat Transmitting" glass filter. Measurements showed that this filter transmitted 83% of the energy from 1.4 to 2.7μ and was opaque below 0.7μ. With the thermocouple at the side of the tube, the unscreened radiation produced a galvanometer deflection of 86 mm and when screened by the filter a deflection of 3 mm. Therefore

$$I_B/I_R=86\times 0.83/3-1=22.8.$$

This number was not very accurate, depending as it did on a 3 mm deflection, but sufficed to show that about 95% of the radiation from the tube was carried by the Balmer lines, the weak molecular lines, the continuous spectrum, etc.

A 43 mm deflection was observed with the thermopile 5 cm away from the side of the tube, (the excitation being always 400 watts and pressure 0.54 mm of mercury), and at other distances up to 15 cm the deflections were proportional inversely to the distance. The total energy E_s ergs/sec radiated from the side of the tube was, therefore,

$$E_s=2\times 5\times \pi\times 79\times 43\times 108=1.153\times 10^7 \quad \text{ergs/sec.}$$

Radiation from the end of the tube produced a deflection of 122 mm which remained constant when the thermopile was moved from 2 to 5 cm from the end of the tube. The total energy E_e radiated from the two ends of the tube was, then,

$$E_e=2\pi\times 0.45^2\times 122\times 108=0.00168\times 10^7 \quad \text{ergs/sec.}$$

The entire energy E radiated from the tube was, neglecting the end effects of E_s,

$$E=E_s+E_e=1.155\times 10^7 \text{ ergs/sec.}$$

The efficiency of the tube. The total length of the hydrogen tube was 300 cm. When the tube was absorbing 400 watts, a section 79 cm long absorbed 105 watts and radiated 1.155 watts. Therefore the efficiency of the tube as a radiator of Balmer energy was about 0.9%.

Relative energy from the side and end of the tube. The small amount of energy delivered from the ends of the tube compared with that from the side deserves a few remarks. The measurements showed that $E_s/E_e=685$. An exact theoretical derivation of this ratio would be tedious. It is evident, however, that the radiation from elements of the tube remote from the ends does not get out to the ends in full amount mainly because it escapes through the glass walls of the tube when the angle of incidence is not too close to grazing; it also suffers absorption on its way along the tube. For example, only 60% of the energy of rays striking the walls at a grazing angle of 10° is reflected (60% being the average of the reflecting powers 72 and 48%, for the electric vector parallel and normal, respectively, to the surface, as calculated from Fresnel's equations, taking the refractive index of the glass to be 1.5). Therefore after a few reflections practically all the energy of these rays has passed out to the side. It is only when the grazing angle becomes less than 3° that the average reflecting power is above 80% and that the light proceeds along the tube without much loss. For a grazing angle of 3° the calculated ratio E_s/E_e was greater than 400. If the absorption of energy along the tube were taken into account (there are no exact data yet for the absorption) E_e would be decreased and the number 400 increased, and we might expect satisfactory theoretical agreement with the observed number 685. Silvering the external walls of the tube would increase E_e; this effect was demonstrated qualitatively by Merton and Johnson.[3] In the present instance we surrounded the tube throughout its length by mercury, and obtained a galvanometer deflection of 180 with the thermopile at the end of the tube, whereas without the mercury the deflection was 122.

Relative intensities of Hα, Hβ, *and* Hγ. The relative intensities of the first three lines of the Balmer series were obtained by a spectrophotometric comparison with the spectrum of the calibrated tungsten lamp. When the discharge tube was filled with moist hydrogen at a pressure of 0.54 mm of mercury and was absorbing 400 watts, the relative intensities of the Balmer lines in the radiations from the side and the end of the tube were; side, $\mathrm{H}\alpha:\mathrm{H}\beta:\mathrm{H}\gamma=1.00:0.207:0.054$; end, $\mathrm{H}\alpha:\mathrm{H}\beta:\mathrm{H}\gamma=1.00:0.40:0.08$. These values and those of other observers show some variance. Although this is perhaps to be ascribed to widely differing experimental conditions, the question of the Balmer intensities can hardly be regarded as a settled one. For example Merton and Nicholson[4] found that in a small capillary tube $\mathrm{H}\alpha:\mathrm{H}\beta:\mathrm{H}\gamma$ as 1.00:0.264:0.183, and Nutting and Tugman[5] 1.00:0.315:0.0055. In the electrodeless discharge in hydrogen Schlesinger[6] observed that $\mathrm{H}\alpha:\mathrm{H}\gamma=1.00:0.06$.

The fact that the intensity of Hα compared to the other lines is relatively less from the end of the tube than from the side is of course to be ascribed to absorption in the luminous hydrogen. It would follow that in the radiation from the end of the tube only the layers near the end are effective con-

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[3] Merton and Johnson, Phil. Mag. **46**, 448 (1923).

[4] Merton and Nicholson, Phil. Trans. **217** (1917).

[5] Nutting and Tugman, Bull. Bur. Stand. **7**, 49 (1911).

[6] Schlesinger, Zeits. f. Phys. **39**, 215 (1926).

tributors of Hα, whereas for Hβ and Hγ the more remote layers are effective as well. A pretty demonstration of this is obtained by gazing into the tube through a red glass which transmits only Hα; in this case one sees hardly more than 50 cms into the tube. With a blue screen opaque to Hα and transparent to Hβ and Hγ the far end of the tube 80 cms away is quite distinct. The experiment is exactly in the manner of the spectroheliograph for seeing into the sun.

The number of quanta emitted per atom. In accordance with the foregoing measurements 90% of the energy delivered by the tube was carried by the first three Balmer lines, 5% by the infra-red lines, and the remaining 5% by the higher members of the Balmer series, the molecular lines, the continuous spectrum, etc. Then with Hα:Hβ:Hγ $=1.00:0.207:0.054$, and with $E=1.155\times10^{7}$, the total energy each second emitted from the tube in the form of Hα comes out to be 8.24×10^{6} ergs; this amounts to 2.75×10^{18} quanta of Hα. We have shown in another investigation[7] that the hydrogen under the conditions of the present experiment was almost entirely atomic. Therefore the Hα energy was emitted by 9.65×10^{17} atoms (the pressure in the discharge tube being 0.54 mm of mercury), and on the average each atom in the tube emitted 2.84 quanta of Hα per second. Similarly, the average numbers of Hβ and Hγ quanta per atom per second were 0.43 and 0.10 respectively.

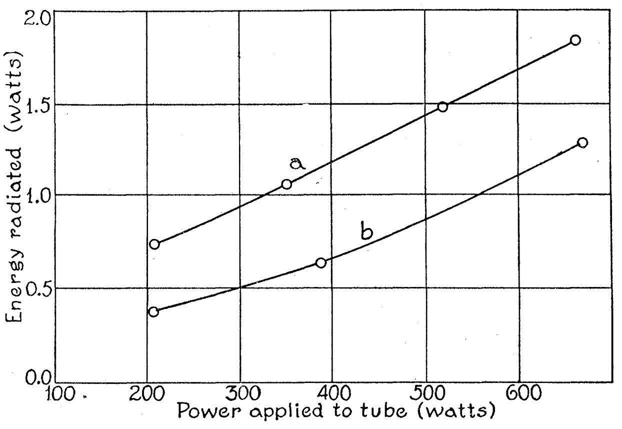

Fig. 1. Total radiation E as a function of the power for constant pressures 0.47 and 0.72 mm of mercury, curves a and b, respectively.

Pfund[8] has found that the total intensity of the Lyman series from much the same sort of hydrogen discharge as that of the present experiment was 8.8 times that of the Balmer, Paschen and Brackett series all added together. We may then conclude that the order of magnitude of the number of Lyman quanta emitted per atom per second was about 10.

Variation of the radiated energy with the power and pressure in the tube. The manner in which the total energy E varied with the power and pressure

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[7] "Pressures in Discharge Tubes," to be published soon.

[8] Pfund, Journ. Optical Soc. Amer. **12,** 467 (1926).

in the tube is shown in the curves of Figs. 1 and 2, the curves *a* and *b*, Fig. 1, which are for constant pressures of 0.47 and 0.72 mm of mercury, respectively, and the curve of Fig. 2 for a constant power of 400 watts. The full line portion of this curve was obtained by pumping the pressure down in steps and observing the galvanometer deflection with the tube lighted at each step. Towards the end of such a procedure at the lower pressures the tube became whitish and no longer glowed with the crimson radiance characteristic of a pure Balmer spectrum. This was due, it was supposed, to the burning off of the water vapor from the walls of the tube, thereby permitting them to catalize the atoms to the molecular state. If the curve was repeated each point being obtained by refilling the tube with fresh moist hydrogen and then pumping down to the desired pressure, the dotted branch of the curve of Fig. 2 was obtained, the curve for pressures above 0.45 being unchanged. In Fig. 1 for powers above 300 watts the hydrogen was practically all atomic, and the number of quanta emitted per atom was therefore proportional to E. From the highest point of curve *a*, Fig. 1, with 665 watts in the tube, each atom emits 5.2 quanta of Hα per second. If we suppose that the time during which the atom remains in the excited state is 10^{-8} seconds, it is seen that the atoms of hydrogen, even under rather violent discharge conditions, are on the average in an unexcited state a relatively large part of the time.

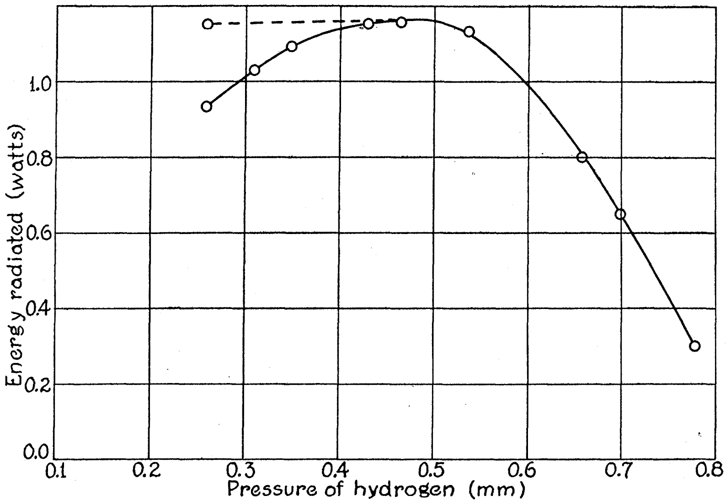

Fig. 2. Total radiation E as a function of the pressure for constant power of 400 watts.

In conclusion, we may remark that the present method is by no means restricted to the hydrogen lines, although, to be sure, these are comparatively easy to isolate spectroscopically, but is directly applicable to the determination of the number of quanta emitted per atom, or molecule, of any spectral line.

Naval Research Laboratory,
Washington, D. C.,
February 17, 1927.