Doppler Displacements in the Spectrum of Hydrogen Canal Rays

ANNA I. MCPHERSON, *University of Chicago*
(Received November 13, 1933)

Hydrogen canal rays of uniform energy have been obtained by accelerating the hydrogen ions formed in a low voltage arc through a short electric field. The spectrum has been observed at $H\beta$ and $H\gamma$, in the direction of motion, and the Doppler displacements of the lines H_{31}, H_{21}, H_1, from atoms accelerated as H_3^+, H_2^+, H_1^+, agree acceptably with the values of the displacements calculated from the applied potentials between 7000 and 17,000 volts. H_{31} diminishes in intensity and H_{21} and H_1 increase with decrease of pressure. H_{31} and H_{21} are equal in intensity at 0.019 mm which is of the order of pressure expected if the numbers of H_3^+, H_2^+ are determined in the arc space. An apparent minimum velocity for excitation of radiation in the neutral hydrogen atom moving in hydrogen was observed at about 40 volts. In a helium-hydrogen mixture the hydrogen Doppler lines H_{21} and H_1 alone were perceptible, H_{31} not appearing.

IN general, the spectrum of hydrogen canal rays viewed in the direction of motion, shows each of the Balmer lines accompanied by three rather diffuse displaced Doppler lines, whose relative positions indicate their sources to be atoms which have passed the accelerating field as H^+, H_2^+, H_3^+ ions. The displacements are less than one would expect from the applied field, and this defect increases with the field.[1, 2, 3, 4]

With hydrogen canal rays of uniform energy, produced in the one case by magnetic deflection, in the other by acceleration of ions through a narrow condenser, Riezler,[5] and Batho and Dempster[6] have observed Doppler lines which were sharp, and whose displacements agreed well with the expected values. Batho and Dempster also found a variation in the relative intensities of the lines with the gas pressure.

In the present experiments, by using the method of Batho and Dempster, the variation of intensity of the lines with pressure has been studied, and displaced lines observed under various conditions.

[1] J. Stark, Phys. Zeits. **6**, 892 (1905).

[2] F. Paschen, Ann. d. Physik **23**, 247 (1907).

[3] J. Stark and W. Steubing, Ann. d. Physik **28**, 974 (1909).

[4] H. Krefft, Ann. d. Physik **75**, 75 (1924).

[5] W. Riezler, Ann. d. Physik **2**, 429 (1929).

[6] H. F. Batho and A. J. Dempster, Astrophys. J. **75**, 34 (1932).

APPARATUS

The apparatus was similar to that previously described.[7] Perforated aluminum electrodes were mounted with their adjoining parallel surfaces 1.5 mm apart. The hydrogen was purified by admission through a palladium thimble, and its pressure was measured with a McLeod gauge. The gas could be made to flow through the system continuously, or as was usually sufficient, could be renewed for each photograph. The Steinheil spectrograph with dispersion 58.3A per mm at $H\beta$, 32.4 Angstroms per mm at $H\gamma$ was used, with Eastman 40 plates.

The brightness of the beam increased with increasing voltage, and with increasing pressure. The upper limit of pressure, about 0.15 mm of mercury was reached when the displaced lines became very diffuse, the lower limit, about 0.003 mm necessitated very long exposures. The upper limit of voltage was set by the nature of the discharge tube, as occasional sparking took place between the electrodes at 17,000 volts; at 7000 volts the least displaced lines at $H\beta$ were not easily resolved. The voltage across the low voltage arc was kept at about 90 volts.

EXPERIMENTAL RESULTS

The plates showed $H\beta$, $H\gamma$, very brightly, with their shifted companion lines H_1, H_{21}, H_{31}

[7] A. I. McPherson, Phys. Rev. **44**, 711 (1933).

radiated from atoms formed from H_1^+, H_2^+, H_3^+ ions respectively, and the secondary spectrum of hydrogen fairly intense besides.

To compare the separations of the displaced lines with those calculated from the measured voltage, a series of pictures was taken, with pressures from 0.003 to 0.145 mm, voltages 7500 to 17,000 volts, and all plates were used on which at least three separations could be measured. The values $d\lambda/\lambda$, $d\lambda/\lambda\sqrt{2}$, $d\lambda/\lambda\sqrt{3}$ were computed from each voltage, and compared with $d\lambda/\lambda$ from the measured separations of H_1, H_{21}, H_{31}. The agreement is very good, thus for Plate No. 30 the values from the voltage are 0.00448, 0.00317, 0.00259, while measurements at $H\beta$ give 0.00448, 0.0030, 0.00275, and at $H\gamma$, —, 0.00303, 0.00259. Fig. 1 shows these results graphically, the observed $d\lambda/\lambda$ plotted against the calculated v/c. Points marked dot, plus, circle, are from measurements of H_{31}, H_{21}, H_1. The average percentage excess of the calculated over the measured value for the 124 measured separations is 3.5, which is well within the experimental error. All three ions show similar agreement over the entire range of speeds used.

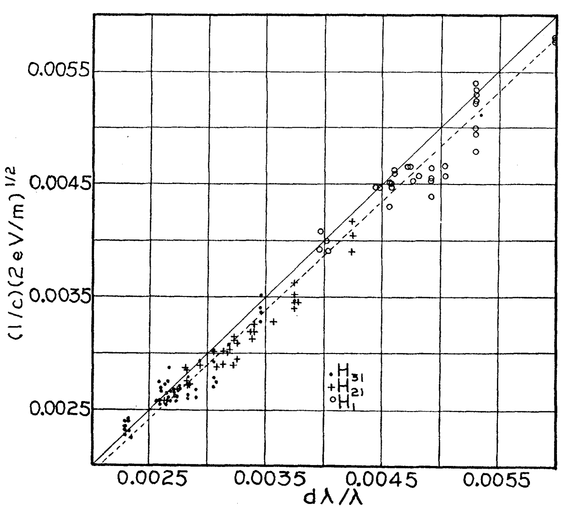

FIG. 1. Vertical. Displacements expected from voltage measurement $(1/c)(2eV/m)^{\frac{1}{2}}$. Horizontal. Observed displacements $d\lambda/\lambda$. The heavy line represents the theoretical equality, the broken line the average of the measured values, 3.5 percent low.

Krefft[4] observed displacements only 85 percent of those expected up to 3000 volts, still less for higher voltages, while Batho and Dempster for 20 displacements at 5300, 12,000 and 15,000 volts found agreement to better than 90 percent.

With the present experimental arrangement, the displacement of the Doppler lines in hydrogen is calculable from the applied potential, over the range of velocities from 7500 to 17,000 volts.

Dependence of intensity of displaced lines on pressure

Three sets of plates were taken at 11,800, 13,450 and 16,900 volts, at pressures 0.003, 0.007, 0.026, 0.04, 0.06, 0.105, 0.14 mm. At 0.14 mm the displaced lines were very diffuse, the line from the diatomic ion was missing, the lines H_{31} and H_1 were visible. As the pressure was reduced to 0.05 mm the shifted lines were less diffuse and consequently more intense, and the line H_{21} could be seen as a faint shadow. With further decrease of pressure the lines became definitely sharp, and as observed by Batho and Dempster, the intensity of H_{21} increased steadily, while that of the other lines decreased. The monatomic line H_1 is always faint, the lines H_{31}, H_{21}, at a pressure between 0.013 and 0.026 mm have equal intensities less than that of the rest line, but comparable to it. The number of radiating atoms in the beam which passed the field as H_3^+ is equal to the number which passed as H_2^+ at this approximate pressure of 0.019 mm, which is of the order of magnitude of that calculable from the results of very different positive ray experiments of Smyth[8] and Hogness and Lunn,[9] and Harnwell,[10] assuming that the distribution of the ions is principally determined by the pressure in the arc space.

From the known paths for neutralization of hydrogen ions[11] it may be shown that little change of charge takes place within the accelerating field at the lower pressures used; the displaced lines are sharp and as all the ions undergo the full acceleration the Doppler lines have the full displacement calculable from the field. At the higher pressures used, a considerable

[8] H. D. Smyth, Phys. Rev. **25**, 452 (1925).

[9] T. R. Hogness and E. G. Lunn, Phys. Rev. **26**, 44 (1925).

[10] G. P. Harnwell, Phys. Rev. **29**, 830 (1927).

[11] H. Bartels, Ann. d. Physik **6**, 957 (1930).

part of the ions change charge in the field, giving rise to the observed diffuse lines.

Minimum velocity for light excitation by neutral hydrogen atoms

At the higher pressures the H_{31} lines were decidedly less sharp on the side nearer the rest line, shading off to a faint fog which extended uniformly towards the rest line but broke off before reaching it. This fog decreased in both intensity and extent with decreasing pressure, becoming imperceptible at 0.01 mm. At the highest pressure used a similar fainter fog extended from H_1 to H_{31}. These effects may be due to radiation from atoms which traversed only a small part of the electric field as ions. An estimate of the width of the clear strip shows it to correspond to 40 volts, which may be compared with the minimum velocity of 50 volts for radiation by neutral hydrogen atoms, reported by Dempster.[12]

Doppler effect in helium-hydrogen mixtures

In observations of the Doppler effect in helium, as previously described,[7] at a total pressure of 0.02 mm, sufficient traces of hydrogen were present to show $H\beta$ and $H\gamma$ in considerable intensity, in each case accompanied by a relatively strong displaced line whose position identified it as H_{21}, and in two instances by a very faint line, H_1. H_{31} did not appear. These observations accord with those of Harnwell,[10] that the ratio H_3^+ to H_2^+ formed in hydrogen at partial pressure below 0.02 mm in presence of helium is negligible; indeed H_3 is necessarily a secondary product unlikely to be formed under these conditions.

No indication was seen of the helium hydride ions HeH^+ and HeH_2^+ reported by Hogness and Lunn.[9] If they were formed they did not decompose to produce hydrogen atoms in a perceptible number.

No radiation was observed from the unstable fourth hydrogen ion H_4^+, suggested by Döpel[13] and apparently confirmed by Ney-Valerius[14] at velocities of the order of 1000 volts, nor were there any variations in the relative positions of H_{21} and H_1 with change of pressure, as observed under certain conditions in the latter experiments. In the present experiments, the shifted lines lost their sharpness with the higher pressures, but as the measured separations for pressures to 0.1 mm show, the positions of the maxima were not observably affected. Also, change of velocity caused no perceptible change in the relative intensities of the lines.

[12] A. J. Dempster, Phys. Rev. **8**, 651 (1916).

[13] R. Döpel, Ann. d. Physik **76**, 1 (1925).

[14] F. Ney-Valerius, Ann. d. Physik [5] **6**, 721 (1930).

Discussion

The secondary hydrogen spectrum was developed in considerable intensity. Comparison of the plates indicated no change in its intensity relative to the Balmer lines, with pressure or voltage, and none of its lines in the region between $H\beta$ and $H\gamma$ showed any Doppler displacement. Evidently the secondary spectrum is excited by the positive rays, in the gas at rest, no appreciable part of its intensity coming from molecules which have formed from the neutralization or decomposition of the molecular ions.

For particles in the positive ray beam the free path traversed before neutralization increases with the speed,[11] and the number of paths terminated in the observation space decreases. If the radiation were emitted mainly as a result of neutralizing collisions, the intensity should decrease with increasing speeds, but the observed intensity increases considerably with the speed, in similar degree for the rest lines and the displaced lines. It is probable that many collisions occur between the moving particles and the stationary, which result in excitation and radiation of either or both particles, without ionization. The increase of intensity with speed may then imply merely a greater probability of excitation of the colliding particles at high speeds.

These experiments were suggested and directed by Professor A. J. Dempster, to whom the writer expresses sincere thanks. The friendly advice and aid of fellow students is also gratefully acknowledged.