

THE ABSORPTION OF SLOW HYDROGEN
POSITIVE RAYS IN HYDROGEN

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ABSTRACT

An experimental method for studying the absorption of slow hydrogen positive rays in hydrogen is described. The absorption coefficients of H^+ , H_2^+ and H_3^+ in hydrogen were measured in the region between 60 and 850 volts. The absorption coefficient of H_3^+ was found to be smaller than that of H_2^+ and very much nearer the absorption coefficient of H^+ in magnitude. The absorption coefficient of H_2^+ decreased from a value of $40 \text{ cm}^2/\text{cm}^3$ at 60 volts velocity to $20 \text{ cm}^2/\text{cm}^3$ at 850 volts and that of H_3^+ decreased from $17 \text{ cm}^2/\text{cm}^3$ at 60 volts to $12 \text{ cm}^2/\text{cm}^3$ at 500 volts. The absorption coefficient of H^+ remained nearly constant at $8 \text{ cm}^2/\text{cm}^3$, about one-half the kinetic theory value. No minimum of absorption was observed for any of the ions in the region investigated. Qualitative experiments upon the nature of the absorbing process indicate that the absorption of H_2^+ is probably due to neutralization while scattering is probably the most important factor in the absorption of H^+ and H_3^+ ions.

INTRODUCTION

THE first quantitative measurements on the absorption of very slow protons in hydrogen were made by Aich¹ in 1922. Using a Lenard type of apparatus he found that the collision radius of an H_2 molecule and a 25 volt proton was approximately the same as the kinetic theory value of the radius of the H_2 molecule. In 1925, Dempster,² using the type of apparatus which he had previously described, studied the absorption of 900 volt protons in hydrogen. Since the beam of protons was absorbed in a magnetic field, a proton which was neutral over part of its path would have the apparent radius of its path increased while one which lost velocity would have its apparent path radius decreased. Dempster observed no neutralization or loss of velocity equivalent to a change of 2 volts in the 900 volt accelerating potential as the pressure in the absorbing chamber was increased from 0.00017 to 0.008 mm of mercury. Dempster therefore concluded that at 900 volts the proton moved through several hydrogen molecules without apparent neutralization or loss of velocity, that between 900 and 25 volts there was a critical potential at which the proton lost its ability to penetrate the hydrogen molecule and that between 900 and 13.000 volts³ there was another critical potential at which the proton acquired the ability to ionize the hydrogen molecule. He notes that "Electrons acquire the velocity of protons used in this experiment by falling through 0.5 volt and it is significant

¹ W. Aich, *Zeits. f. Physik* **9**, 372 (1922).

² A. J. Dempster, *Proc. Nat. Acad. Sci.* **11**, 552 (1925).

³ E. Rütchardt, *Ann. der Physik* **73**, 228 (1924).

that electrons of this speed pass through many molecules without absorption."

While the work of G. P. Thomson⁴ on protons of between 5,000 and 25,000 volts velocity does not lead to a direct measurement of the effective size of the hydrogen molecule, his conclusions are worthy of note. Measuring the scattering of a beam of protons in hydrogen by observing blackening of a photographic plate beyond the edge of the image of the geometrical beam, he found: (1) appreciable small angle scattering in the velocity range studied, (2) a rapid decrease of scattering between 5,000 and 25,000 volts, (3) single scattering below 0.01 mm, (4) proportionality between scattering and pressure between 0.001 mm and 0.012 mm and (5) an inverse cube law of force at scattering centers.

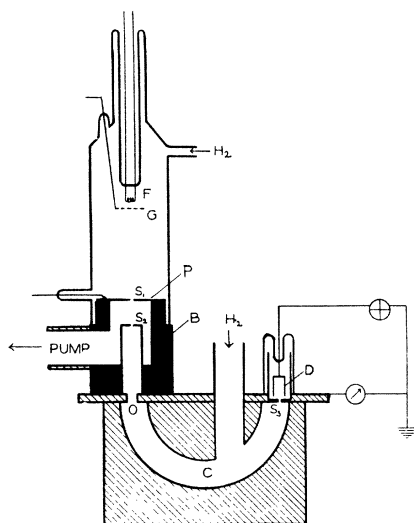


Fig. 1. Diagram of apparatus.

The present experiment was undertaken to measure quantitatively the absorption of protons in hydrogen in the region between the measurements of Aich and Dempster and to compare the absorption of protons with the previously unmeasured absorption of H_2^+ and H_3^+ in hydrogen.

APPARATUS

The apparatus employed in the experiment consisted essentially in an ionization tube of the type used by Smyth,⁵ Hogness and Lunn⁶ and others for producing the hydrogen ions under controlled conditions and a Dempster⁷ mass spectrograph for analyzing the rays. A simple diagram of the apparatus is shown in Fig. 1.

⁴ G. P. Thomson, *Phil. Mag.* **1**, 961 (1926).

⁵ H. D. Smyth, *Phys. Rev.* **25**, 452 (1925).

⁶ T. R. Hogness and E. G. Lunn, *Proc. Nat. Acad. Sci.* **10**, 398 (1924).

⁷ A. J. Dempster, *Phys. Rev.* **11**, 316 (1918).

Electrons from the incandescent filament, F , were accelerated toward the grid, G , by a potential difference of 60 volts. The primary ions were produced by electron impact in the space between G and the plate P . The spacing of F and G was 0.5 cm and of G and P , 10 cm. A drift field of 4 volts carried a small fraction of the ions formed between G and P through slit S_1 , into the highly evacuated space between S_1 and S_2 where the major part of the accelerating potential was applied. The plate P was insulated from the adjacent metal parts B by a mica disk and picene wax. All metal parts in the ionization tube at ground potential (B) were completely covered by mica and wax.

S_1 and S_2 , defining the beam of ions, were each 0.1 mm wide and 3 mm long. Their separation was 1 cm. The path of the beam between S_1 and O was shielded by a soft iron block, B , to which the ionization tube was waxed. The block, in turn, was soldered to the brass absorption and analyzing chamber placed between the pole faces of a large electromagnet so that the field was perpendicular to the plane of the diagram. When an ion passed S_2 it entered the absorption chamber and when it emerged from O it was deflected in a semicircular path the radius of which was determined by the mass and velocity of the ion and the strength of the magnetic field. If the magnetic field was so adjusted that the radius of the path was 4.75 cm the ion reached the slit S_3 , 1.5 mm wide and 3 mm long, at the entrance to the collecting chamber. The total path length between S_2 and S_3 was 20.0 cm. A Faraday cylinder 0.5 cm in diameter and 1 cm deep was used to collect the ions. It was connected to a Compton electrometer and was insulated from the apparatus by 3 cm of Pyrex glass.

The pressure control was effected by steady flow through capillary leaks from reservoirs to the ionization and absorption chambers, respectively. The gas flowed from the chambers through S_1 and S_2 into the space evacuated by a Gaede three stage mercury vapor pump. Liquid air traps were included in all the vacuum lines and gas feeds to the apparatus. The pressures in the ionization and absorption chambers were practically independent. With a pressure of 0.0120 mm in the ionization, the "back pressure" built up in the absorption chamber was 0.0003 mm. A change of 0.006 mm in the absorption chamber produced a change of less than 1.5 percent (minimum detectable on the McLeod gauge) in the ionization chamber. The pressure in the ionization chamber was approximately 0.01 mm and that in the absorption chamber, between 0.007 and 0.001 mm.

The gas was electrolytic (tank) hydrogen which was passed over hot copper turnings at 300°C, stored over P_2O_5 and finally passed through two liquid air traps after leaving the capillary while the pressure was less than 0.015 mm.

The magnetic field, calibrated by a test coil and Grassot fluxmeter, was found to be roughly proportional to the current flowing in the coil of the magnet when care was taken to reverse the magnet current before measurement.

The apparatus described produced a heterogeneous beam of hydrogen ions,

all of which had fallen through the same accelerating potential (i.e. within 4 volts). As the magnetic field was increased the rate of deflection of the electrometer reached several maxima corresponding to the various products of ionization. A typical graph of the results is shown in Fig. 2. All of these products of ionization have been observed previously.

MEASUREMENTS

The absorption of the various ions was measured in terms of the absorption coefficient which appears in the well known absorption formula $I = I_0 e^{-\alpha x p}$, in which I_0 is the initial intensity of a beam of particles, I , the intensity of the beam after traversing a gas layer x cm thick at a pressure of

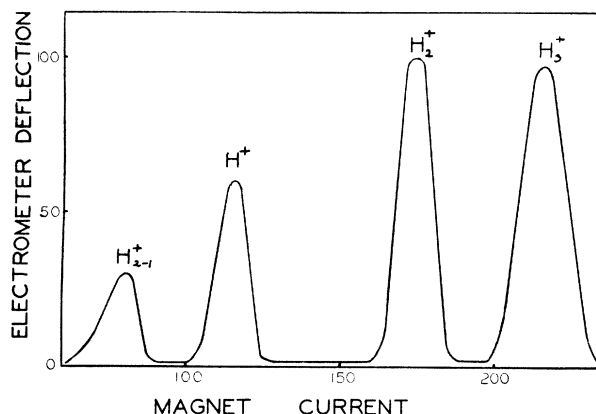


Fig. 2. Analysis of the products of ionization.

p mm, and α is the absorption coefficient, the effective absorbing cross-section of all of the molecules in 1 cubic centimeter of gas at 1 mm pressure. The equations

$$I_1 = I_0 e^{-\alpha x p_1} \tag{1}$$

$$I_2 = I_0 e^{-\alpha x p_2} \tag{2}$$

indicate the respective intensities of a beam originally of intensity I_0 after passing through a layer of gas, x cm thick, first at pressure p_1 and later at pressure p_2 . Dividing (1) by (2) and taking the natural logarithm of both sides of the resulting equation,

$$\ln I_1/I_2 = \alpha x(p_2 - p_1).$$

Solving for α ,

$$\alpha = \frac{1}{x(p_2 - p_1)} \ln \frac{I_1}{I_2}.$$

This equation is valid as long as I_0 remains unchanged and at once suggests a method of determining the absorption coefficient without measuring the absolute value of I_0 .

In the experiment, I_0 was the intensity of a beam of ions of given mass and velocity that would have reached the Faraday cylinder had the absorption chamber been kept at high vacuum. I_0 was directly proportional to the intensity of the beam which entered S_2 and was roughly proportional to the current which reached the plate containing S_2 . Since I_0 was a rather critical function of the filament current, the ionization tube pressure, and the applied potentials, keeping it constant was perhaps the greatest experimental difficulty encountered. A milliammeter measuring the differential current to P was used as an indicator of tube conditions while a galvanometer connected between the main metal portion of the apparatus and ground was used to determine the constancy of I_0 .

The procedure in determining a value of α for a given ion at a particular velocity was briefly as follows. The tube was allowed to reach a steady state. The magnetic field was so adjusted that the maximum of one of the "peaks" (see Fig. 2) was observed. The rate of deflection of the electrometer (I_1) was recorded while the gas in the absorbing chamber was maintained at a given value p_1 (measured by a McLeod gauge). In practice the value of I_1 was taken as the average of three or four trials. The pressure was quickly raised by compressing the gas in the reservoir behind the leak to the absorbing chamber. Within a minute and half equilibrium was reached at the new pressure, p_2 , which was 2 or 3×10^{-3} mm higher than p_1 , and I_2 was measured. The pressure was then lowered to p_3 , nearly the same as p_1 , and the process was repeated. The set of measurements usually required from 7 to 10 minutes. The data thus obtained were sufficient to determine two values of α which served as an additional check on the constancy of conditions. In those cases where the values of α differed by more than 25 percent and the galvanometer showed signs of fluctuation, the measurements were discarded. If, however, the galvanometer deflection steadily increased or decreased, an average of the values of α was taken as a fair approximation to the true absorption coefficient.

It was necessary to be certain that the accelerating potential did not vary, for a change sufficient to shift a peak one quarter of its width was in most cases sufficient to render the coefficient meaningless.

The formula $I = I_0 e^{-\alpha x p}$ holds when α is independent of the pressure or when $\log I \propto p$. Independent measurements were made to check this point. The relation was found to hold in the region studied, i.e., between 0.001 and 0.007 mm. This result is in accord with the results of G. P. Thomson for faster positive rays cited above. A further piece of evidence on this point is that α seemed to be essentially the same no matter what absolute values of p_1 and p_2 were used.

To obtain some idea of the processes involved in absorption of the ions a series of intensity measurements was made with a number of settings of the magnetic field for each of several pressures. The results of the measurements are shown graphically in Fig. 4. The meaning of the curves is briefly discussed in the following section.

DISCUSSION OF RESULTS

The absorption of the various hydrogen ions in hydrogen is of interest since H^+ resembles the electron more than any other positive ion, H_2^+ is similar to H_2 in structure and H_3^+ has a mass comparable to that of H_2 but is unlike it in structure.

The absorption coefficients of H^+ , H_2^+ , and H_3^+ in hydrogen were observed in a region between 60 and 850 volts. The actual velocity ranges studied were 1.1 to 4.1×10^7 cm/sec for H^+ , 0.76 to 2.9×10^7 cm/sec for H_2^+ , and 0.62 to 1.79×10^7 cm/sec (corresponding to the range from 60 to 500 volts) for H_3^+ . The results are shown graphically in Fig. 3.

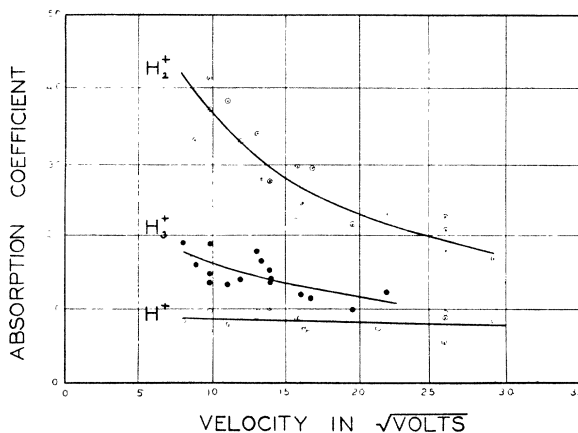


Fig. 3. Absorption coefficients.

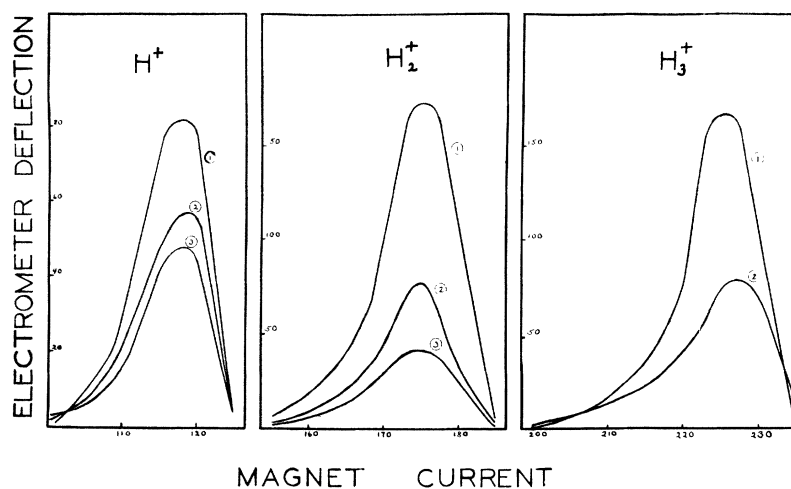
H_2^+ has markedly the largest coefficient varying from $40 \text{ cm}^2/\text{cm}^3$ at 60 volts to $20 \text{ cm}^2/\text{cm}^3$ at 850 volts. Assuming the radius of the ion given by Birge⁸ and the kinetic theory value of the radius of the molecule, α would be $64 \text{ cm}^2/\text{cm}^3$. This value of α is definitely of the same order of magnitude as the experimental value of α at 60 volts. The absorption coefficient for H_3^+ is smaller and varies less, decreasing from $17 \text{ cm}^2/\text{cm}^3$ at 60 volts to $12 \text{ cm}^2/\text{cm}^3$ at 500 volts. The absorption coefficient for H^+ is nearly constant at $8 \text{ cm}^2/\text{cm}^3$, roughly half the kinetic theory value assuming H^+ of negligible dimensions.

In surveying the results, it is at once apparent that the kinetic theory "size" is not as important a factor in determining the absorption coefficient as the possibility of an energy transfer from the ion to the molecule. One would scarcely anticipate a lower value of α for H_3^+ in H_2 than H_2^+ in H_2 yet the value is not only smaller but far nearer H^+ than H_2^+ at the lower velocities. This result may be due to the fact that energy of ionization of an H_2 molecule is equivalent to the energy of neutralization of an H_2^+ ion and that a capture of an electron by an H_2^+ ion in H_2 is very probable. Since the

⁸ R. T. Birge, Proc. Nat. Acad. Sci. **14**, 12 (1928).

same is probably not true of H_3^+ , it is less likely to be eliminated by neutralization.

An examination of Fig. 4, showing the intensity and width of the H_2^+ peak at various pressures indicates that there is no spreading due to small angle scattering and no shift of the peak with increasing pressure. The process of absorption of the H_2^+ ion eliminates it completely from the beam. Since the free path is relatively long at the pressures used neutralization of the



Curve	H^+ $p \times 10^3$	H_2^+ $p \times 10^3$	H_3^+ $p \times 10^3$
1	0.0	1.8	0.0
2	2.1	2.9	2.3
3	4.3	3.5	

Fig. 4. Relative absorption of the products of ionization.

ion would definitely eliminate it from the beam. Neutralization and some large angle scattering are evidently the most important factors in the absorption of H_2^+ in H_2 .

The H_3^+ peak broadens with increasing pressure and diminishes in area. Since neutralization is not very probable the chief factor in the absorption of H_3^+ is presumably scattering. Some dissociation may occur although this point cannot readily be checked with the present type of apparatus.

The principal process in the absorption of H^+ is apparently scattering since in Fig. 4 the width at half-maximum does not decrease as the pressure increases and the bases of the peaks show a tendency to spread. Neutralization is not very probable since the energy of ionization of H_2 does not correspond to the energy of neutralization of H^+ .

J. S. Thomson⁹ has shown that α is a function of the geometry of the

⁹ J. S. Thompson, Phys. Rev. **35**, 1196 (1930).

apparatus when small angle scattering is important. Since the results in Fig. 4 indicate very little small angle scattering, it is assumed that α is not markedly a function of the apparatus for any of the ions, less so for H_2^+ than either of the others.

The experimental value of α for H^+ at 60 volts is about one-half of Aich's value at 25 volts. These results are not discordant since one expects scattering to increase with decreasing velocities, very markedly in the region below which a minimum of absorption can be expected. However, the value of α does not show any sign of approaching zero at 900 volts as agreement with Dempster's results would require. Since Dempster gave no indication that the pressure in the ionization chamber was independent of the pressure in the absorption chamber, an increase in the intensity of the initial beam of hydrogen ions due to increased pressure in the ionization chamber may have masked the absorption effect.

The results of this experiment give no indication of a minimum of absorption of protons at 900 volts where the *Handbuch der Physik*¹⁰ has interpreted Dempster's results as showing a Ramsauer effect. G. P. Thomson's¹¹ investigations of the scattering of protons in argon and helium indicate that the shape of the absorption curve for protons is similar to the shape of the absorption curve for electrons in these gases in the same velocity ranges. If this conclusion may be carried over to the case of the absorption of protons in hydrogen, a minimum of absorption is to be expected at 1800 volts instead of 900 volts, since Normand¹² has found a minimum of absorption for electrons in hydrogen at 1 volt. It is hoped that measurements of the absorption of 1800-volt protons in hydrogen can be made with the present apparatus in the very near future.

It is a pleasure to acknowledge my indebtedness to Professor R. B. Brode for suggesting this problem and for offering valuable advice and assistance throughout the course of the experiment.

¹⁰ *Handbuch der Physik*, Bd. 24, S. 100.

¹¹ G. P. Thomson, *Phil. Mag.* 2, 1076 (1926).

¹² C. E. Normand, *Phys. Rev.* 35, 1217 (1930).

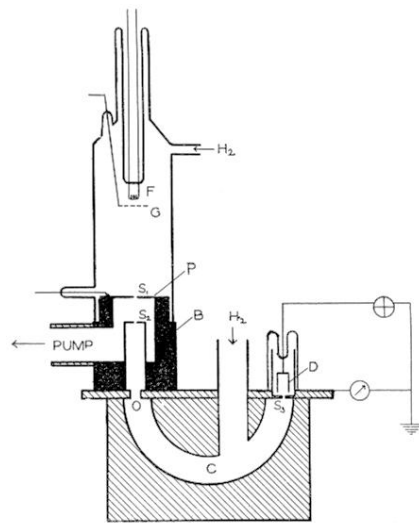


Fig. 1. Diagram of apparatus.