EXCITATION OF BALMER HYDROGEN LINES UPON PASSAGE OF H^+, H_2^+, *AND* H_3^+ *THROUGH HELIUM AND NEON*

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Excitation cross sections are measured for the first five Balmer lines of atomic hydrogen produced by proton charge exchange and H_2^+ and H_3^+ dissociation in single collisions of the ions while passing through helium and neon. The ion energy range is 5–30 keV. It is shown that the relative excitation probabilities of H_α, H_β, H_γ, H_δ, and H_ϵ depend slightly on the kind of gas and incident ion. An attempt is made to estimate the excitation cross sections for levels with the principal quantum numbers n = 8, 9, 10.

1. INTRODUCTION

RENEWED interest has recently been manifested in the excitation of radiation when fast atoms or ions, especially those of hydrogen, collide with gas molecules. Two problems have been mainly responsible for this revival of interest. One is the quantitative interpretation of auroral spectra.[1,2] The other problem deals with the filling of thermonuclear devices of the magnetic trap type by using highly-excited atomic deuterium or hydrogen beams ionized in magnetic and electric fields.[3] The practical realization of the latter purpose depends on the production of intense atomic deuterium or hydrogen beams in highly excited states having principal quantum numbers $n \geq 10$, a condition required for ionization by the magnetic fields actually existing in thermonuclear magnetic traps.

Beams of highly excited hydrogen atoms can be produced by proton charge exchange or by the dissociation of molecular hydrogen ions colliding with various gas molecules or atoms in reactions such as

$$H^+ (H_2^+, H_3^+) + A \rightarrow H^{0*} + \dots . \quad (1)$$

The number of atoms produced in an excited state can theoretically be measured "electrically" by determining the proton flux resulting from the ionization of excited atoms in an electric or magnetic field.[3]

The number of excited atoms produced in processes (1) can also be determined by measuring absolute line intensities in the spectrum of atomic hydrogen. The wavelength of a line determines the level of excitation unambiguously. It is convenient to use lines of the Balmer series, which lie in the visible region close to the ultraviolet.

In the present work we have attempted to measure "optically" the number of excited atoms produced through charge exchange of protons (H^+) and dissociation of the ions H_2^+ and H_3^+, in order to determine the conditions for producing the largest amount of highly excited atoms.

Beams of protons or molecular hydrogen ions traversed a chamber filled with helium or neon at pressures permitting mainly single collisions which yielded excited hydrogen atoms. We measured the excitation cross sections for the first five Balmer lines (H_α, H_β, H_γ, H_δ, H_ϵ) to obtain their dependences on the velocity and kind of ion and also on the kind of gas target, for primary ion energies 5–30 keV.

2. APPARATUS AND EXPERIMENTAL PROCEDURE

1. Our apparatus is represented in Fig. 1. The ion source 1 and collision chamber 2 were located in a large vacuum chamber 3 evacuated to $\sim 7 \times 10^{-7}$ mm Hg by a VA-5-4 vacuum system with a nitrogen trap. The entire volume of the chamber was within a homogeneous magnetic field which rotated the ion beam 180° and extracted the required component.

The ion source was an arc discharge within a longitudinal magnetic field. The construction and power circuit of the source were similar to those described in [4]. Ions were extracted across the magnetic lines of force by an electrode to which potentials up to 40 kV were applied from a power rectifier (40 kV, 0.7 A).

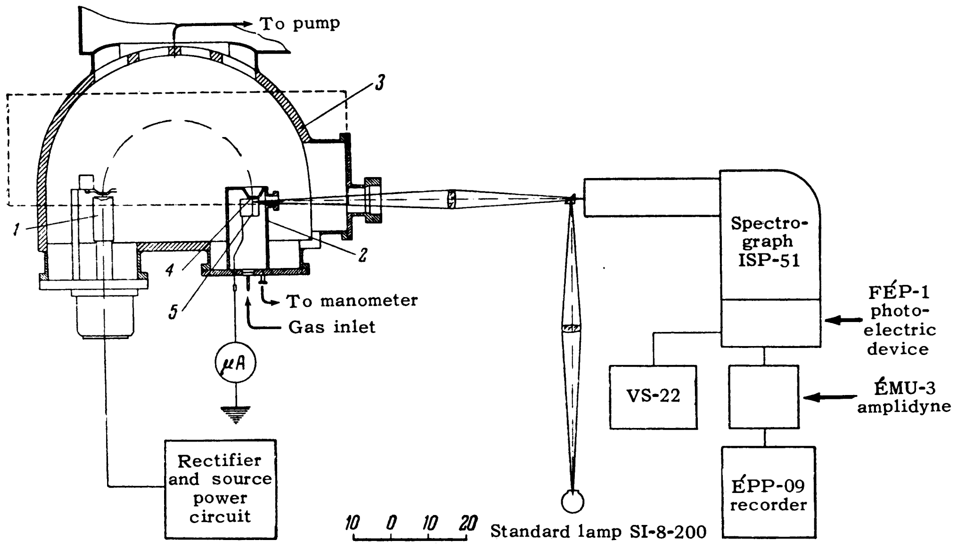

FIG. 1

The very simple stabilization circuits of the arc current in the source and of the extraction potential enabled the maintenance of a constant ion current during the time required for the measurement of a single experimental point. The ion beam entered the collision chamber 2 through a 3 × 7-mm slit 4; the beam current was measured with a Faraday cylinder 5. Secondary electrons from the walls and bottom of the cylinder were restrained by the magnetic field in the collision chamber. The ion current density, which had the maximum value 2 mA/cm^2, depended on the kind and energy of the ions.

Pure helium or neon entered the chamber 2 through a needle valve. The collision-chamber pressure was measured with a McLeod manometer and was monitored with an ionization gauge measuring pressures to 0.1 mm Hg. The residual pressure in the chamber during the operation of the ion source did not exceed 5×10^{-5} mm. A liquid nitrogen trap was located inside the collision chamber. The evacuation system produced approximately a 200 : 1 pressure differential at the gap 4 when the collision chamber pressure was 10^{-2} mm.

2. Light excited in the space traversed by the ion beam was focused by a lens on the entrance slit of an ISP-51 three-prism spectrograph. The geometry of light collection is sketched in Fig. 2. Light entered the spectrograph from the volume V of length Δl = 0.2 mm and height 7 mm located at the distance l = 12 mm from the entrance slit 4 of the collision chamber. The intensities of individual lines at the spectrograph exit were measured by means of a photoelectric device (FÉP-1).

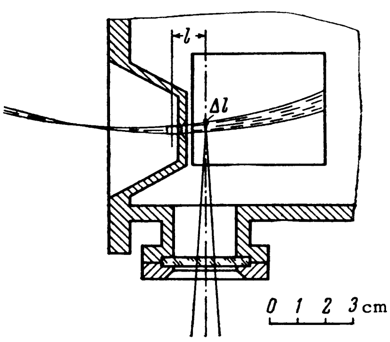

FIG. 2

Signals from the FEU-18A photomultiplier used as the detector were registered with a dc amplifier; the linear range of the registration system was 1000.

The optical system was calibrated with a SI-8-200 tungsten ribbon-filament lamp based on a Mendeleev Metrological Institute standard. During the calibration process the lamp and spectrograph were arranged as shown in Fig. 1 (the scale being given in centimeters).

We used a standard procedure for determining absolute line intensities, as described in detail in [5].

3. The line excitation cross sections σ_{ji} were determined from

$$J_{ji} = N\sigma_{ji}\frac{I}{e}\Delta l h\nu_{ji}, \qquad (2)$$

where J_{ji} is the intensity of a frequency ν_{ji} corresponding to a j → i transition from the space V, Δl is the length of the beam from which light entered the spectrograph, I is the beam current strength, e is the electron charge, h is Planck's constant, and N is the number of atoms per cm^3 in the collision chamber.

In the derivation of (2) it was assumed that atomic excitation results from the collision of a fast hydrogen ion with a gas atom. An excited atomic level is reached either by direct excitation or through a cascade from higher-lying levels. It is also assumed that a secondary process such as the formation of a neutral hydrogen atom that is subsequently excited by a second collision with a gas atom or with electrons freed by ionization etc. plays no important part. If these conditions are satisfied the emitted line intensity should depend linearly on the gas pressure in the collision chamber and on the ion current density.

The experimental result was strictly linear up to the highest utilized pressure of 10^{-2} mm and the largest beam currents for all ions in the entire working range of ion energies. One of the experimental curves is shown in Fig. 3.

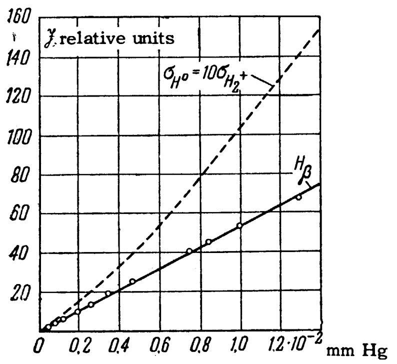

FIG. 3. Intensity of line H_β as a function of pressure for 20-keV H_2^+ ions.

When an ion beam traversing the collision chamber contains a large number of hydrogen atoms H^0 and when the cross section for atomic hydrogen excitation through collision with a helium atom is sufficiently large, the observed linear pressure dependence of light intensity can be determined by the secondary process. Upon entering the collision chamber the ion beam was free of any appreciable number of hydrogen atoms since the ions were moving in a circular trajectory, but fast neutral hydrogen atoms could appear in the collision chamber as a result of charge exchange and dissociation.

The potential method was used to determine the number of neutral atoms in the ion beam within the collision chamber. The measurements show that in the case of proton charge exchange the number of neutral atoms did not exceed 3–4% at all energies, while for the dissociation of H_2^+ the neutral atoms comprised 7%.[1)]

Knowing the fraction of neutral atoms in the ion beam at the point from which light reaches the spectrograph, we plotted the pressure dependence of the H_β line assuming that the excitation cross section $\sigma(H^0)$ of this line as a result of collisions between hydrogen and helium atoms was ten times larger than the analogous cross section $\sigma(H_2^+)$ in the case of H_2^+ dissociation. In Fig. 3 we see that the linear portion of this (dashed) curve, unlike the experimental curve, does not pass through the zero point of the pressure scale. Only the improbable assumption that $\sigma(H^0)$ is many orders larger than $\sigma(H_2^+)$ can account for the linear pressure dependence of line intensity if it is assumed that the here considered secondary process makes a dominant contribution to the intensity.

3. RESULTS AND DISCUSSION

1. We started by photographing the spectra accompanying the passage of 10-keV H_2^+ ions through helium or neon. The spectrograms recorded with the ISP-66 and SP-49a spectrographs revealed, in addition to helium and neon lines, the following lines of the Balmer series: H_α (6563 Å), H_β (4861 Å), H_γ (4340 Å), H_δ (4102 Å), H_ϵ (3970 Å), H_ξ (3889 Å), H_η (3835 Å), H_θ (3798 Å), and H_i (3771 Å); these represent transitions from levels having the principal quantum numbers n = 3–11. The line intensity diminished monotonically with increasing value of n.

2. We measured photoelectrically, under conditions for single collisions, the intensities of the lines H_α, H_β, H_γ, H_δ, and H_ϵ (n = 3–7) excited by dissociation and charge exchange of H^+, H_2^+, and H_3^+ in helium and neon in the energy range 5–30 keV.[2)]

The cross section measurements for Balmer line excitation were complicated by the fact that

[1)]The measurements of the number of neutral atoms in the beam were accompanied by measurements of the cross section for proton charge exchange and H_2^+ dissociation at 20 keV. The results agreed with [7-10], thus showing that our potential method yielded correct results.

[2)]The presence of the very strong line He $2^3S - 3^3P$ (3888.7Å), prevented measurement of the strong line H (3889.1Å), although the expected intensity of the latter was sufficient for reliable registration. Measurements in neon were hindered by the presence of the band of the first negative N_2^+ system (3914 Å). This band is very easily excited by hydrogen particles; the residual air in the collision chamber produced a band of appreciable intensity.

light was being emitted by a rapidly moving particle. A fraction of the atoms formed in the observed volume V left this space before being able to emit light, because in our experiments the time of flight of these atoms through the collision chamber was comparable to the mean atomic lifetime in the excited state. In addition, the spectrograph was able to receive light from atoms excited before they reached V. Both effects must be taken into account for a correct determination of the cross sections. It is easily shown that, with our registration geometry (Fig. 2), in order to determine the line-excitation cross section σ_{ji} the measured intensity J_{ji} must be multiplied by

$$K_j = [1 - \exp(-l/L_j)]^{-1}. \qquad (3)$$

Here $L_j = \tau_j v$, where τ_j is the mean lifetime of hydrogen atoms in the excited j state, and v is the atom velocity. Equation (3) is valid when $\Delta l \ll L_j$.

Wien[11] determined the mean lifetimes of excited hydrogen atoms experimentally by observing the decay of canal-ray light emission. Wien's work was subsequently criticized and his data cannot be regarded as correct.

It has been shown theoretically[12] that when 5—30 keV protons are involved in charge exchange with hydrogen atoms the excitation of a p state ($l = 1$) is favored. If it is assumed that in our experiments mainly the p state was excited, we can use the theoretical p-state lifetimes[13] to determine the excitation cross sections.

3. Our measurements of relative Balmer line intensities were compared for the different ions and target gases. In both helium and neon the relative intensities are independent (within 10%) of ion energy in the range 10—30 keV. At lower energies (5—7 keV) the fraction of more highly excited particles (n = 6, 7) becomes somewhat smaller (20%).

Table I gives the average relative intensities in the range 10—30 keV for the lines H_α, H_β, H_γ, H_δ, and H_ϵ. For each pair of neighboring lines we give the measured ratios (first column) without corrections for the lifetime, and the ratios calculated from the experimental values assuming that the mean lifetime of excited atoms equals the lifetime of the p state (second column). Although the correction factor (3) depends on the energy, the values in the second column are almost independent of energy in the entire investigated range.

The data in Table I also show that the Balmer line intensities did not drop off much more rapidly due to any particular one of the investigated processes as compared with the other processes.

4. It is interesting to compare the yield of highly excited atoms in proton charge exchange and H_2^+ and H_3^+ dissociation for identical velocities of the resulting excited hydrogen atoms. For this purpose the absolute intensities of the spectral lines must be known. Measurements of H_β were used to determine the excitation cross section σ_{ji} for this line in all the investigated processes at 20 keV, assuming isotropic emission of all lines from the space V. The remaining cross sections were determined from the relative measurements. Errors in the cross sections up to 40% were possible; these were associated mainly with the calibration of the optical system by means of a standard lamp (20%) and with pressure measurements in the collision chamber (10%).

Table II gives the excitation cross sections for H_α, H_β, H_γ, H_δ, and H_ϵ calculated from the experimental intensities with a correction for the p-state lifetime. The excitation cross sections for H_2^+ dissociation are seen to depend very little on the target gas.

The excitation cross sections for the first five Balmer lines are, as a rule, larger in the case of molecular ion dissociation than in the case of proton charge exchange (Table II).

5. As mentioned in the introduction, the injec-

Table I. Intensity ratios of Balmer lines excited by proton (H^+) charge exchange and H_2^+ and H_3^+ dissociation at 10—30 keV

Gas	Neon						Helium					
Ions	H^+		H_2^+		H_3^+		H^+		H_2^+		H_3^+	
H_α/H_β	9,0	5,5	10,6	7,1	—	—	10,7	6,5	10,6	7,1	—	—
H_β/H_γ	4,7	2,8	4,7	2,9	4,7	3,0	3,9	2,3	4,7	2,9	3,9	2,5
H_γ/H_δ	3,9	2,4	4,5	2,9	3,8	2,5	3,7	2,3	4,5	2,9	3,9	2,5
H_δ/H_ϵ	2,5	1,7	3,3	2,2	3,3	2,2	2,9	1,9	3,3	2,2	3,5	2,3

Table II. Cross sections (10^{-19} cm^2) for Balmer line excitation at a single ion velocity

Gas	Helium			Neon		
Ions	H^+	H_2^+	H_3^+	H^+	H_2^+	H_3^+
E, keV	10	20	30	10	20	30
H_α	9.6	78.6	—	18.6	82.4	—
H_β	1.1	8.2	7.3	2.5	8.6	6.4
H_γ	0.43	2.5	2.6	0.79	2.7	1.9
H_δ	0.18	0.84	1.0	0.31	0.89	0.72
H_ε	0.09	0.37	0.4	0.18	0.43	0.32

tion of hydrogen atoms excited to levels having principal quantum numbers $n \geq 10$ could be of practical value for the accumulation of protons in magnetic traps. To evaluate this possibility we must know the production cross sections of excited atoms with $n \geq 10$.

Utilizing the assumed preferential excitation of the p state, we used our line-excitation data to calculate the excitation cross sections for levels with $n = 3-7$, taking the probabilities of hydrogen transitions from [13]. Since the line intensity, as shown in Table I, decreases rapidly as n increases, cascade transitions can be neglected.[14] The excitation cross section of a level is then

$$\sigma_j = (A_j/A_{ji})\sigma_{ji}, \qquad (4)$$

where A_{ji} is the probability of a transition from level j to level i; $A_j = \sum_{i<j} A_{ji}$; the subscript i indicates a lower energy level than the subscript j.

Having determined the excitation cross sections for $n = 3-7$ from Eq. (4), we can estimate the cross sections for $n = 8-10$. An attempt of this kind is shown in Fig. 4, where the logarithms of the cross sections for $n = 3-7$ are plotted as a function of the excitation potential V_j; the excitation cross section for $n = 4$ ($\sigma_{n=4}$) and the corresponding excitation potential $V_{n=4} = 12.7$ eV are both taken as unity. The extrapolated (dashed) curve provides an estimate of the excitation cross sections for $n = 8-10$ when H_2^+ ions are dissociated in helium and neon: $\sigma_{n=8} = 2.4 \times 10^{-19}$ cm^2; $\sigma_{n=9} = 1.8 \times 10^{-19}$ cm^2; $\sigma_{n=10} = 1.3 \times 10^{-19}$ cm^2. The excitation cross sections for $n \geq 8$ in the cases of the other processes studied here can be estimated similarly.

Extrapolation is permissible here because there is no reason to expect anomalies for levels with larger quantum numbers as compared with levels having $n = 5-7$. In addition, it is seen from the aforementioned spectrograms that the Balmer line intensities diminish monotonically up to the last observed line H_i ($n = 11$).

Jackson and Schiff[15] have shown theoretically that when protons pass through molecular hydrogen the probability that hydrogen atoms will be excited to $n \geq 3$ through charge exchange is proportional to n^{-3}. The foregoing cross sections for $n = 8-10$ are in good agreement with this law.

6. Figure 5 shows the excitation functions of

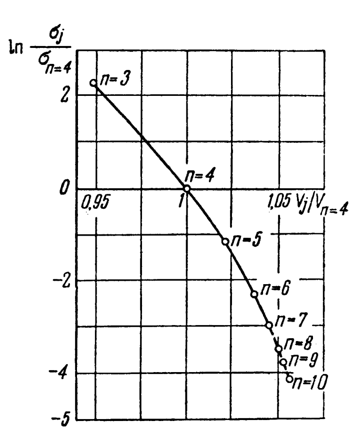

FIG. 4

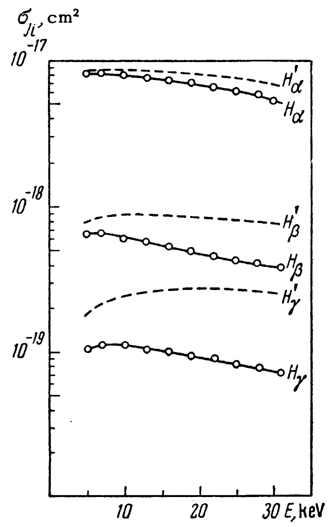

FIG. 5

various Balmer lines for H_2^+ dissociation in neon. The continuous curves represent the results of direct measurements, while the dashed curves were calculated from the experimental curves taking the p-state lifetime into account. In our energy range there is no strong dependence of line intensity on the velocity of fast H_2^+ ions.

The excitation cross sections of H_α, H_β, and H_γ for H_2^+ charge exchange in helium diminish with increasing energy even following a correction for the effect associated with the excited state lifetime using Eq. (3). The cross section is reduced by a factor of 1.5 in the range 10—30 keV.

4. CONCLUSION

It is easily seen from the foregoing that for a complete interpretation of our present data we must know the mean lifetime of excited hydrogen atoms produced in a collision chamber. We plan an early experiment to determine the mean lifetime of excited hydrogen atoms formed through proton charge exchange and through H_2^+ and H_3^+ dissociation in helium and neon.

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