CHARGE EXCHANGE OF PROTONS AND THE DISSOCIATION OF H_2^+ AND H_3^+ IONS IN HELIUM AND NEON ACCOMPANIED BY THE FORMATION OF FAST HYDROGEN ATOMS IN EXCITED STATES

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Submitted to JETP editor October 17, 1964

J. Exptl. Theoret. Phys. (U.S.S.R.) **48**, 833-836 (March, 1965)

The cross sections are given for the excitation of hydrogen atoms, formed by the charge exchange of protons and the dissociation of H_2^+ and H_3^+ ions (10—30 keV), to the levels with n = 3—7. The cross sections are calculated from the results given in the earlier paper of the present authors[1] and also using new experimental data on the average lifetimes of excited hydrogen atoms.[3] The excitation cross section of the levels decreases with increase of n in accordance with the law $n^{-2.5}$ when the population of the fine-structure sublevels of the hydrogen atom corresponds to their statistical weights.

1. We published earlier[1] the results of a study of the Balmer spectrum of hydrogen, which is formed when protons and H_2^+ and H_3^+ ions of 5—30 keV energy pass through helium and neon. Under the conditions of our experiments, the Balmer lines were emitted by fast hydrogen atoms produced in excited states by the charge exchange of protons and the dissociation of H_2^+ and H_3^+ ions.

In the determination of the excitation cross sections of spectral lines emitted by fast atoms, it is necessary to introduce a correction for the delay of the emission of light by excited atoms.[1-3] The expression for this correction includes the average lifetime of atoms in the initial state relating to the emission of a given spectral line.

The lifetimes τ of the hydrogen atom in the states with quantum numbers n, l have been calculated by the exact methods of quantum mechanics.[4] For a given n but different l, the values of τ differ considerably from one another. Under the experimental conditions of the excitation of light in atomic collisions, the fine structure is not resolved even for the H_α line. The lifetime, and consequently the correction in the calculation of the absolute intensity of an observed spectral line, depends on the distribution of atoms over the fine-structure levels. Following the hint in the theoretical paper of Bates and Dalgarno,[5] we assumed in our earlier work[1] that the average lifetime of hydrogen atoms, excited by the charge exchange of protons and the dissociation of H_2^+ and H_3^+ ions, is governed, for a given n, by the lifetime of the shortest-lived state p (l = 1). Using the data, given in [4], on the lifetimes of the states n, p of the hydrogen atom, we calculated the correction for the delay in the emission of light and determined from our measurements the relative intensities and excitation cross sections of the lines H_α, H_β, H_γ, H_δ, and H_ϵ.

2. However, the results obtained did not seem to us sufficiently reliable because the correctness of the assumption about the predominant excitation of the p-states was in doubt since under our experimental conditions the formation and de-excitation of the excited hydrogen atoms took place in quite a strong magnetic field (1000—2000 Oe). In view of this, we carried out direct measurements of the average lifetimes of the excited states of the fast hydrogen atoms formed in the process of the dissociation of H_2^+ and H_3^+ ions under the experimental conditions used in [1]. The average lifetimes of the levels with n = 3, 4, 5, obtained by us,[3] were found to be in good agreement with the quantum-mechanical calculations carried out for the case of a "random population" of the fine-structure sublevels.[4] Thus, the assumption of the predominant excitation of the p-states was not justified when the excitation of fast hydrogen atoms took place in a sufficiently strong magnetic field. Therefore, the numerical data obtained in [1] with an allowance for the lifetime of the p-states (second columns of Table I; Table II; Fig. 4; Fig. 5—dashed curves; all in [1]) must be reviewed and corrected.

3. Using the measured lifetimes of the excited states of the hydrogen atom with n = 3, 4, 5 and

Table I. Cross sections for the excitation of hydrogen atoms (10^{-18} cm^2) to the levels with n = 3—7

n	Ion energy, keV			Ion energy, keV			Ion energy, keV		
	10	20	30	10	20	30	10	20	30
	H^+, He			H_2^+, He			H_3^+, He		
3	1.6	2.2	3,2	21	18	14	19	18	16
4	0.69	1.1	1.6	8.0	7.3	5.8	8.0	7.6	6.5
5	0.55	0.87	1.1	4.7	4.6	3.6	5.5	5,3	5.0
6	0,39	0,78	0.94	2.9	2,8	2.5	3.8	3.7	3.5
7	0.29	0.58	0,70	1.8	1,8	1.6	3.2	3.1	2.9
	H^+, Ne			H_2^+, Ne			H_3^+, Ne		
3	4.6	9.0	3.8	19	19	19	12	14	14
4	2.2	4.7	2,9	4.7	7.6	8.7	5.1	5.8	5.8
5	1.3	3,5	1.4	2.8	4.9	5.4	2,7	3.4	3.8
6	1.0	2.3	0,94	1.7	3.2	3.2	1,9	2.4	2.7
7	0.82	2,0	0,82	1.2	2.2	2.2	1,2	1.5	1.7

the theoretical values[4] for n > 5, averaged over l, we calculated anew the correction for the delay in the emission of light by rapidly moving excited atoms of hydrogen. After the inclusion of this correction, we obtained the following relative intensities of the spectral lines in the Balmer series, emitted upon the charge exchange of protons and the dissociation of H_2^+ and H_3^+ ions in helium and neon: 1)

	H_α/H_β	H_β/H_γ	H_γ/H_δ	H_δ/H_ϵ
Experiment:	2.8	1.75	1.73	1.42
Theory [4]:	2.2	1.87	1.91	1.42.

It is evident that these values agree with the theoretical ratios of the intensities of the same lines calculated for the excitation conditions under which the electrons are distributed in accordance with the statistical weights of the levels, i.e., when the same number of electrons is found, on the average (with respect to time), in each excited state n, l, m.[4]

Comparison of the experimental and theoretical data on the lifetimes and relative intensities of the Balmer lines of the excited hydrogen atom confirms that if the charge exchange of protons and the dissociation of molecular hydrogen ions in gases takes place in a magnetic field, the distribution of excited hydrogen atoms over the fine-structure sublevels is close to a random distribution. This is because the effective electric field $\mathbf{E} = \mathbf{v} \times \mathbf{H}/c$ of 1—4 kV/cm intensity, appearing due to the motion of atoms at velocities of $(1\text{—}2) \times 10^8$ cm/sec, is sufficient to make the Stark splitting of the levels in this field considerably greater than their total fine splitting, which leads to the "mixing" of the fine structure sublevels, as a result of which the average lifetimes and relative intensities become closer to the "random" case.

4. Table I lists the values of the cross sections for the excitation of hydrogen atoms to the levels with n = 3—7, in the processes of proton charge exchange and dissociation of H_2^+ and H_3^+ ions in helium and neon, for three values of the ion energy. The cross sections were calculated from the data of the earlier work[1] but include the new correction for the lifetime of the excited states of the hydrogen atom; the role of the cascade transitions in the excitation of the levels was not allowed for, since the intensity of the lines decreased rapidly as the principal quantum number increased. The error in the absolute values of the cross sections amounted to 40—50%; the precision of the relative values was ± 10%.

It follows from Table I that the excitation of hydrogen atoms is more likely on dissociation of molecular ions than during proton charge exchange. The cross sections decrease with increase of n. The law which gives the dependence of the excitation cross sections of the levels on the principal quantum number is obviously governed by the population of the fine-structure sublevels. It is known[6] that the cross sections for charge exchange of fast protons (E > 20 keV) in the s-state are proportional to n^{-3}. It can be shown that if the population of the fine-structure sublevels in the excitation processes is of the random type, then the excitation cross sections of the levels vary as $n^{-2.5}$. In fact, the intensity of the line corresponding to the transition $nl \rightarrow n'l'$ is in this case[4]

$$J_{nl,\,n'l'} \sim (2l+1) A_{nl,\,n'l'} h\nu_{nl,\,n'l'}$$

1)Since we discovered[1] that the relative intensities of the Balmer lines depended weakly on the type of gas and on the energy and type of the incident ion, only the average values of these intensities are given here.

Table II. Extrapolated values of the cross sections (10^{-18} cm^2) for the excitation of the hydrogen atom levels with n = 8, 9, 10

n	Ion energy, keV			Ion energy, keV			Ion energy, keV		
	10	20	30	10	20	30	10	20	30
	H^+, He			H_2^+, He			H_3^+, He		
8	0.21	0.42	0.50	1.3	1.3	1.1	2.3	2.2	2.1
9	0.16	0.31	0.38	0.97	0.97	0.86	1.7	1.7	1.6
10	0.12	0.24	0.29	0.75	0.75	0.67	1.3	1.3	1.2
	H^+, Ne			H_2^+, Ne			H_3^+, Ne		
8	0.59	1.4	0.59	0.86	1.6	1.6	0.86	1.1	1.2
9	0.44	1.1	0.44	0.64	1.2	1.2	0.64	0.81	0.91
10	0.34	0.83	0.34	0.50	0.92	0.92	0.50	0.63	0.71

(here $A_{nl,n'l'}$ is the probability and $\nu_{nl,n'l'}$ the frequency of the transition $nl \rightarrow n'l'$; h is Planck's constant). The intensity of the experimentally measured unresolved line corresponding to the transition $n \rightarrow n'$ is equal to

$$J_{n,n'} = \sum_{ll'} J_{nl,n'l'} \sim n^2 A_{n,n'} h\nu_{n,n'}.$$

Since the excitation cross section is found from the relationship

$$J_{n,n'} = \sigma_{n,n'} N \frac{I}{e} h\nu_{n,n'} \Delta l,$$

where I is the current in the ion beam, N is the density of the gas target, e is the electron charge, and Δl is the length of the beam, the light from which is recorded by the spectrograph; we therefore have

$$\sigma_{n,n'} \sim n^2 A_{n,n'}.$$

The excitation cross section of the level n is found without allowance for the cascade transitions from the expression $\sigma_n = \sigma_{n,n'} A_n / A_{n,n'}$, where A_n is the probability of a transition from the level n to all the levels below. For a random population of the fine-structure sublevels, $A_n = 1/\tau_n \sim n^{-4.5}$; hence, $\sigma_n \sim n^{-2.5}$.

Our measured values of the cross sections for the excitation to the levels with n = 5, 6, 7, in the processes of dissociation of H_2^+ ions in helium and neon and of H_3^+ ions in neon, agree with this law, within the experimental error. For H^+ in helium and neon and H_3^+ in helium the agreement is somewhat poorer, but on the average the dependence of the experimental cross sections on the principal quantum number n (n > 5) is closer to $n^{-2.5}$ than to n^{-3}. For the levels with n = 3, 4, no agreement with the law $n^{-2.5}$ was found. In our opinion, this is because the conditions of the excitation to these levels in our experiments were further from random than for the higher levels. Moreover, it is possible that the population of the levels with n = 3, 4 is affected more strongly by the cascade transitions from the higher levels.

For the levels with n > 8, we may assume that the excitation is completely random and therefore we may extrapolate the measured cross sections in accordance with the law $n^{-2.5}$. Table II lists the cross sections for the levels with n = 8, 9, 10 calculated in this way. These cross sections are of interest in connection with the problem of injection of highly excited hydrogen atoms into magnetic traps. We note that for the levels with $n \geq 9$ the magnetic field of the earth is sufficient to establish, when there is Stark splitting of these levels, nearly random values of the lifetime and of the probability of population of the fine-structure sublevels in a rapidly moving hydrogen atom ($v = 10^8 - 10^9$ cm/sec).

The authors are grateful to Professor V. M. Dukel'skiĭ for his interest in this study.

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Translated by A. Tybulewicz
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