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EXCITATION OF THE L_α LINE DURING STRIPPING OF FAST NEGATIVE HYDROGEN IONS IN INERT GASES

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The intensity of the L_α line emitted during collisions between fast negative hydrogen ions (5–40 keV) and He, Ne, Ar, Kr, and Xe atoms has been measured and the cross section for the formation of the hydrogen atom in the 2s and 2p states, and the total excitation cross sections for the n = 2 level, have been determined. The cross sections $\sigma(2p)$, $\sigma(2s)$, and $\sigma(n = 2)$ are of the order of 10^{-16} cm^2 in the energy range under investigation, and $\sigma(2p) > \sigma(2s)$. The cross sections $\sigma(2s)$, $\sigma(2p)$, and $\sigma(n = 2)$ for all the gases are slow functions of the energy of the H^- ions with the exception of He. For Xe the cross sections $\sigma(2s)$, $\sigma(2p)$, and $\sigma(n = 2)$ exhibit a minimum in the energy range 12–30 keV. A possible mechanism for the formation of excited hydrogen atoms during stripping of negative hydrogen ions as a result of the removal of the "inner" electron from He^- is discussed.

THE first Lyman line of the hydrogen atom, L_α (1216 Å), is observed when a beam of fast negative hydrogen ions passes through a low-pressure gas target. This line is excited in the course of the process

$$H^- + A \rightarrow H^0(2s, 2p) + e + A, \qquad (1)$$

where A is an atom of the target gas. Measurements of the intensity of the L_α line have enabled us to determine the cross sections for the excitation of the 2s and 2p states of the hydrogen atoms formed in the process defined by Eq. (1).

EXPERIMENTAL METHOD

The measurements were carried out with the mass-spectrometric apparatus described in[1,2], using negative hydrogen ions of 5–40 keV and He, Ne, Ar, Kr, and Xe as the target atoms. Negative hydrogen ions were extracted directly from the plasma in the arc-type ion source. They were then deflected by the magnetic field of the mass-spectrometer through 180°, and were focused by a quadrupole lens in the collision chamber. A plane-parallel capacitor was mounted in front of the collision chamber and was used to separate charged and neutral beam components. The H^- ion current in the collision chamber was varied in the range 1–10 μA, depending on the ion energy.

In the case of the negative hydrogen ions, it was particularly important to verify that the L_α emission was, in fact, due to the process defined by Eq. (1) and was not the result of a secondary excitation phenomenon involving hydrogen atoms formed from the negative ions as a result of the removal of electrons ($H^- \rightarrow H^0 \rightarrow H^{0*}$). It is well known[3] that the electron loss cross section of the H^- ion is very high. This has forced us to investigate with great care the dependence of the L_α intensity on the gas pressure in the collision chamber. For all the cases we have investigated this relation was linear up to a pressure of 6×10^{-4} Torr. All the measurements of the excitation cross sections were carried out with the target-gas pressure in the collision chamber between 10^{-4} Torr (Xe) and 5×10^{-4} Torr (He). It may therefore be concluded that the L_α line emission was largely due to single collisions between H^- ions and the gas atoms.

To determine the cross-section ratio $\sigma(2s)/\sigma(2p)$ we used the well-known method described in[1,2] and based on the increase in the L_α intensity due to the decay of the metastable 2s state of the hydrogen atom in the external field. In the present experiment the 2s state was de-excited in the collision chamber by a constant electric field of 600–800 V/cm. The absolute values of the excitation cross section $\sigma(2p)$ were determined by comparing the L_α intensity due to the process defined by Eq. (1) with the intensity of the same line excited as a result of the capture of an electron by the proton. The absolute values of the excitation cross section $\sigma(2p)$ for the latter process were reported in an earlier paper.

RESULTS AND DISCUSSION

Figure 1 shows the measurement results. The mean experimental uncertainties in the measured L_α intensity, the uncertainties in the position of the curves relative to each other, and uncertainties in the absolute values of the excitation cross sections did not exceed ±15%, ±20%, and ±40%, respectively. Figure 1 also shows the ionization cross section of the hydrogen atom taken from[4]. It follows from the analysis of the curves in Fig. 1 that:

1. the cross sections $\sigma(2s)$ and $\sigma(2p)$ in Ne, Ar, and Kr are not very dependent on the incident H^- ion energy (Fig. 1b, c, d). In the case of helium, the excitation cross section for the 2s state is practically constant in the energy range which we have investigated, whereas $\sigma(2p)$ decreases by a factor of about two as the H^- energy increases from 5 to 40 keV (Fig. 1a). For Xe the cross sections $\sigma(2s)$ and $\sigma(2p)$ exhibit a minimum between 12 and 30 keV (Fig. 1e).

2. The excitation cross sections $\sigma(2s)$ are lower by 20–30% than $\sigma(2p)$ for all gases, with the exception of Ne. In the case of Ne, they are practically equal to each other throughout the energy range.

3 The absolute values of the cross sections $\sigma(2s)$

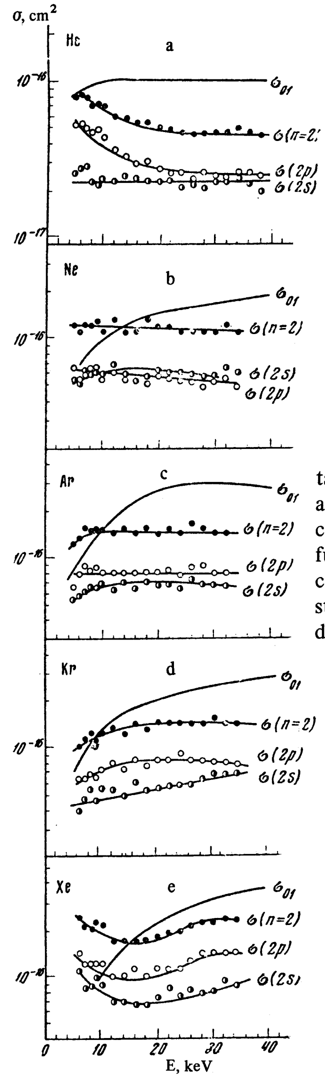

FIG. 1. Cross sections for the excitation of the hydrogen atom in the 2s and 2p states and the total excitation cross sections for the n = 2 state as functions of the H⁻ ion energy during collisions with inert-gas atoms. σ_{01} – stripping cross section of neutral hydrogen atoms. [4].

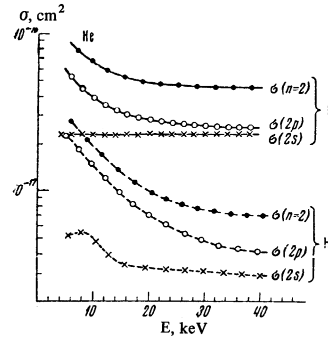

FIG. 2

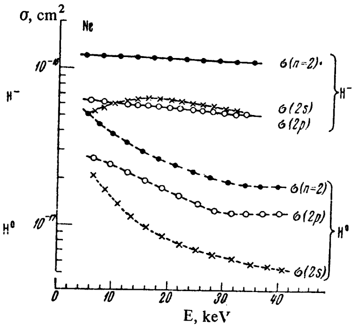

FIG. 3

FIG. 2 Comparison of the excitation cross sections for the 2s and 2p states and the n = 2 level of the hydrogen atom for the following processes: 1) $H^- + He \rightarrow H^{0*} + e + He$; 2) $H^0 + He \rightarrow H^{0*} + He$.

FIG. 3. Same as Fig. 2 but for Ne.

E, keV	He		Ne		Ar		Kr		Xe	
	$\frac{\sigma(2s)}{\sigma_{01}}$	$\frac{\sigma(n=2)}{\sigma_{01}}$	$\frac{\sigma(2s)}{\sigma_{01}}$	$\frac{\sigma(n=2)}{\sigma_{01}}$	$\frac{\sigma(2s)}{\sigma_{01}}$	$\frac{\sigma(n=2)}{\sigma_{01}}$	$\frac{\sigma(2s)}{\sigma_{01}}$	$\frac{\sigma(n=2)}{\sigma_{01}}$	$\frac{\sigma(2s)}{\sigma_{01}}$	$\frac{\sigma(n=2)}{\sigma_{01}}$
5	0.34	1.00	0.94	2.06	0.61	1.34	—	—	—	—
10	0.25	0.66	0.51	1.00	0.43	0.94	0.42	0.97	0.68	1.92
15	0.24	0.53	0.42	0.84	0.32	0.69	0.30	0.72	0.40	1.04
20	0.23	0.51	0.43	0.85	0.24	0.53	0.25	0.63	0.33	0.81
25	0.21	0.46	0.37	0.70	0.22	0.49	0.24	0.61	0.28	0.72
30	0.23	0.47	0.35	0.67	0.24	0.53	0.26	0.57	0.25	0.69
35	0.24	0.50	0.35	0.62	0.22	0.49	0.24	0.52	0.25	0.68
40	0.21	0.47	—	—	—	—	—	—	—	—

and σ(2p) increase with increasing atomic number of the target atom. The only exception is Kr. A similar anomaly is observed in experiments on the removal of two electrons from the H⁻ ions.[5] 1)

We can now proceed to a discussion of our results, but let us first note that the change in the internal energy during the process involving the removal of one electron from the H⁻ ion with the formation of the hydrogen atom in the excited state is higher by only 0.75 eV than the energy loss for the process of direct excitation of a fast hydrogen atom during collisions with gas atoms, which was reported earlier.[2] However, the cross sections for these processes are quite different.

Thus, in the case of the excitation process involving the participation of negative hydrogen ions, the cross sections σ(2s) and σ(2p) for the heavy gases Ar, Kr, and Xe exceed the corresponding cross sections for the direct excitation of the hydrogen atom by factors of 1.5–2. Still greater differences occur for the light gases He and Ne (Figs. 2 and 3). The cross sections σ(2s) and σ(2p) for the process defined by Eq. (1) is greater by factors of 3–9 than the corresponding cross sections for the direct excitation of the hydrogen atom. The differences between these two processes tend to increase with increasing incident particle energy. These discrepancies can be naturally related to different mechanisms for the formation of excited hydrogen atoms in the processes under consideration.

Stripping of the negative hydrogen ion with the formation of an excited hydrogen atom at sufficiently high H⁻ ion energy can be looked upon as a process in which, as a result of the collision with the target atom, the "strongly bound" electron is ejected from the H⁻ ion and this is followed by the attachment of a "weakly bound" electron to the modified field.2) It is then possible that the position of the remaining electron will correspond to the n = 2 excited state of the hydrogen atom. The mechanism in which the field is suddenly switched-on is discussed in[6]. The excitation of the hydrogen atom during collisions of fast negative hydrogen ions with neutral atoms is discussed in[3] in terms of the Born approximation. It is shown that at sufficiently high H⁻ energies the cross sections for the excitation of the hydrogen atoms in the s state during the sudden removal of the "strongly bound" electron has the same energy dependence as the ionization cross section σ_{01} of the hydrogen atom during collisions with neutral atoms. During this process $\sigma(2s)/\sigma_{01} = 0.5$.

Figure 1 shows that above 10–15 keV the energy dependence of σ(2s) and σ_{01} is similar. However, the cross section ratio $\sigma(2s)/\sigma_{01}$ obtained experimentally, and shown in the table, is considerably lower than the theoretical value. This difference appears to be related

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1) It should be noted that the total cross section for the excitation of the hydrogen atom to the n = 2 level during collisions between H⁻ atoms and inert gas atoms are considerably smaller than the loss cross sections σ_{-11} for two electrons. [3,5]

2) On the idea of "strongly bound" and "weakly bound" electrons in the negative hydrogen ion see [6].

to the fact that, in the approximation for the wave function of the negative hydrogen ion used in[6], the only nonzero cross sections were those for the excitation of the s states of the hydrogen atom, whereas experiment shows that $\sigma(2p)$ is somewhat greater than $\sigma(2s)$.

Cascade transitions from the 3s or higher s states cannot explain the experimental values of the cross sections for the excitation of the 2p states.

It may be supposed that the observed excitation of the 2p state of the hydrogen atom during the process defined by Eq. (1) is due to the "mixing" of the 2s and 2p states. It is then useful to compare the ionization cross section σ_{01} of the hydrogen atom with the total cross section σ (n = 2) for the excitation of the n = 2 level during removal of an electron from the H^- ion. This comparison is shown in the table and indicates that the ratio $\sigma(n = 2)/\sigma_{01}$ for energies in excess of 25 keV is a slow function of the ion energy and is close in its magnitude to the theoretical value of 0.5.

To obtain a more definite explanation of the contribution of the process involving ejection of the "strongly bound" electron from the H^- ion to the excitation cross sections of the hydrogen atoms during collisions between the H^- ions and inert gas atoms, it will be necessary to carry out measurements of these cross sections in the Born energy region of the H^- ions, and to take states with $l \neq 0$ into account in the theory.

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