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Collisions between electrons and H_2^+ ions VI. Measurements of cross sections for the simultaneous production of H^+ and H^-

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Abstract. Inclined beams of electrons and H_2^+ ions have been used in an experiment to measure cross sections for the reaction $e+H_2^+ \rightarrow H^+ + H^-$. The cross section was found to fall from $4{\cdot}9\times10^{-18}\,cm^2$ at 0·4 eV to $1{\cdot}16\times10^{-18}\,cm^2$ at 4·96 eV and systematic errors of the measurement were assessed to be less than $\pm 8\,\%$. An ion source was used which produced H_2^+ with the vibrational population measured by von Busch and Dunn (1972). The results are discussed and compared with theoretical predictions by Dubrovskii and Ob'edkov (1967).

1. Introduction

Earlier papers in this series (Peart and Dolder 1971a, 1972a, b, 1973, 1974) described measurements of cross sections for the dissociative excitation (σ_e), dissociative ionization (σ_i), dissociative recombination (σ_r) and the production of protons (σ'_p) by collisions between electrons and H_2^+ ions, but we have not previously considered the process

$$e+H_2^+ \rightarrow H^+ + H^- \tag{1}$$

although it is of both fundamental and practical interest.

The process is closely related to dissociative recombination,

$$e+H_2^+ \rightarrow H + H \tag{2}$$

and a detailed theoretical treatment of recombination would probably include reaction (1). Assuming that there is no excited state of H^- one could regard reaction (1) as a single channel in the dissociative recombination process so the present measurements ought to provide an additional test for *ab initio* theories of the dissociative recombination of H_2^+ which are being developed.

Practical aspects of reaction (1) have been discussed by Prelac and Sluyters (1973) who reviewed the various process which lead to the formation and destruction of H^- and considered their relevance to ion sources which are being designed to produce intense beams of negative ions for nuclear accelerators and thermonuclear experiments. There have been no previous measurements of cross sections (σ_n) for reaction (1) but Dubrovskii and Ob'edkov (1966, 1967) calculated that, for vibrationally unexcited H_2^+, the reaction has a threshold at 1·89 eV and an almost constant cross section of about $10^{-17}\,cm^2$ for energies up to 4 eV. This is an interesting result because it represents cross sections two or three orders of magnitude larger than those of dissociative attachment processes,

$$\begin{array}{l} \nearrow H^+ + H^- + e \\ e + H_2 \rightarrow H + H^- \\ \searrow H^* + H^- \end{array} \tag{3}$$

which are often assumed to be the most important sources of H^-. It follows that, if the predictions of Dubrovskii and Ob'edkov are verified, it may be necessary to take account of the production of H^- by reaction (1) in ion sources and other laboratory devices and, perhaps, in certain astrophysical plasmas. Prelac and Sluyters cite the example of a magnetron ion source which Bel'chenko *et al* (1972) developed to produce intense beams of H^-. The high density of H^- obtained from this source was partly attributed to the formation of H^- ions near the cathode by reaction (1).

Our results, which will be presented in § 3 of this paper, support Dubrovskii and Ob'edkov's prediction of large cross sections (compared with dissociative attachment) although they are roughly three times smaller than those of theory. The two results are not, however, strictly comparable because the theory refers to vibrationally unexcited H_2^+ ions whilst it is impossible to produce adequate beams of unexcited H_2^+ for laboratory measurements. We therefore performed our experiment with H_2^+ ions which had a known distribution of vibrational states. These were produced by the source described in the following section.

In earlier papers (Peart and Dolder 1971, 1972b) we defined a proton production cross section σ'_p as the sum of σ_e and σ_i. We ought, however, to have included the production of protons by reaction (1) and written,

$$\sigma'_p = \sigma_e + \sigma_i + \sigma_n. \tag{4}$$

However, since $\sigma_n \ll \sigma_e$ and $\sigma_n \ll \sigma_i$ no significant error ensues from our earlier definition.

2. Apparatus and method

In this experiment well collimated beams of electrons and H_2^+ ions were made to intersect an angle (θ) of 10° so that pairs of H^+ and H^- ions were produced according to reaction (1). Since reaction (1) is the only way in which H^- ions can be formed by the interaction of an electron with H_2^+, it was sufficient to measure the rate at which H^- ions were produced for the various currents, energies and geometries of the H_2^+ and electron beams.

With the exception of the ion source and the arrangements used to separate the H_2^+, H^+ and H^- ions, the apparatus and method were the same as previously used to obtain cross sections for dissociative recombination (Peart and Dolder 1974 hereafter referred to as I). A magnetic field separated the H_2^+, H^+ and H^- ions downstream from the electron gun and the H^- ions were then deflected upwards through 90° by an electric field between two concentric cylindrical electrodes before they were detected by a particle multiplier. This deflection and detection system has already been illustrated and described (Peart and Dolder 1971b).

When the rate of production of H^- ions had been determined, the procedures described in I were used to deduce the cross sections and 90% confidence limits of random error.

Because the measured cross sections are orders of magnitude smaller than those previously reported for the dissociative excitation and recombination of H_2^+ the experiment presented some difficulties. It was, for example, necessary to develop a new ion source to ensure a conveniently rapid production of H^- by electron impacts. In our previous experiments with H_2^+ ions a source was used (see Peart and Dolder 1971a) in which energetic electrons ionized a cold, tenuous, molecular beam of hydrogen. The ions formed were then extracted before they could change their vibrational state. These principles were retained in the new source but the electrons, after they had attained their maximum energy, were made to traverse the molecular beam several times to enhance the rate of production of ions and the geometry of the source was altered to improve the extraction efficiency.

Typical values for this experiment were $R_s \simeq 1\ s^{-1}$, $R_b \simeq 100\ s^{-1}$. $I \simeq 2 \times 10^{-8}$ A, $J \simeq 1{\cdot}5 \times 10^{-5}$ A where I and J are the beam currents of ions and electrons, R_s is the rate at which H^- ions were formed and R_b is the background count rate. The ion and electron laboratory energies are presented in table 1. It was estimated that the pressure in the region where the beams intersected was of order 3×10^{-10} Torr.

Table 1.

Interaction energy (eV)	Cross section (10^{-18} cm^2)	90% confidence limits of random error (%)	Ion lab energy (keV)	Electron lab energy (eV)
0·40	4·94	15	40	12·4
0·50	4·10	10	40	13·4
0·60	4·01	8	40	14·2
0·70	3·90	9	50	17·4
0·80	3·37	7	40	15·5
0·99	3·46	9	40	16·5
1·09	3·31	8	40	17·0
1·31	3·22	8	40	18·0
1·56	3·22	6	40	19·0
1·77	2·79	4	40	19·8
1·96	2·78	9	40	20·5
1·99	2·80	6	40	20·6
2·19	2·27	5	50	24·7
2·40	2·61	12	40	22·0
2·59	1·89	4	40	22·6
2·73	1·68	7	50	26·6
2·88	1·52	8	40	23·5
3·18	1·36	6	40	24·4
3·39	1·37	8	40	25·0
3·60	1·15	9	40	25·6
3·96	1·16	11	40	26·6

3. Results and discussion

Table 1 presents the measured cross sections and their 90% confidence limits of random error for the various interaction (ie centre of mass) energies. The energies of the ion and electron beams, in laboratory coordinates, are also recorded. Systematic errors of the experiment were assessed to be less than $\pm 8\%$.

These results and random errors are presented in figure 1 which also illustrates the predictions of Dubrovskii and Ob'edkov by the broken curve. This theory refers to vibrationally unexcited H_2^+ ions whilst the experiment employed ions with the vibrational population measured by von Busch and Dunn (1972). The presence of vibrationally excited ions in our beam explains the finite cross sections observed at energies less than 1·89 eV and it can also be seen that the measurements are smaller than the theoretical predictions. This is not surprising because our measured cross sections for dissociative recombination were also smaller than those calculated and Dubrovskii and Ob'edkov by a similar factor. However, the cross sections for dissociative attachment (reaction 3) collected by Prelac and Sluyters are two or three orders of magnitude smaller than the present results. It follows that, in environments with appreciable numbers of H_2^+ ions, reaction (1) may make an appreciable contribution to concentration of H^-.

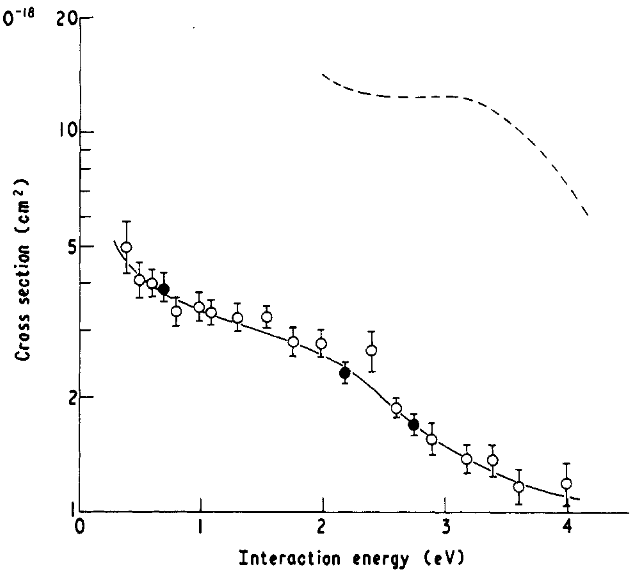

Figure 1. The symbols represent cross sections for the production of H^- by collisions between electrons and H_2^+ ions plotted against interaction energy. The open and full circles respectively refer to measurements with ion laboratory energies of 40 and 50 keV and the brackets show 90% confidence limits of random error. Theoretical results of Dubrovskii and Ob'edkov are illustrated by the broken line.

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