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The formation of H^+ from H^- ions by electron impact

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Abstract. Cross sections of the reaction $H^- + e \rightarrow H^+ + 3e$ have been measured for interaction energies between 17.8 and 1000 eV. Comparison with the only other measurement shows present results to be much smaller. The discrepancy ranges from a factor four at low energies to a factor 12 at high energies. The influence of positive ion trapping in the electron beam has been carefully investigated in the course of this study as it could explain the large discrepancy.

1. Introduction

The formation of H^+ by electron impact on H^- ions is a simple case of electron impact multiple ionisation. Calculations of multiple ionisation phenomena are, as was demonstrated by Byron and Joachain (1966), very sensitive to the choice of target wavefunction and in particular to the terms involving electron correlation. Comparison of calculated and measured cross sections provides a sensitive check for correlation terms in atomic wavefunctions. Reliable experimental results are thus of basic importance.

The total cross section of reaction $H^- + e \rightarrow H^+ + 3e$ has been measured only by Peart *et al* (1971) by means of a 90° crossed beam method for interaction energies from 14.4 to 850 eV.

This paper presents the measurements of the cross section of the same reaction in the energy range 17.8–1000 eV. The new 90° crossed beam method, presented in an earlier work (Defrance *et al* 1981a, b), has been used.

A very large discrepancy is observed between present results and those of Peart *et al* (1971). Some work has therefore been done to look for possible reasons. The most plausible one is seen in terms of charge exchange of the primary negative ion beam with slow positive ions trapped in the potential well of the electron beam. A small section is devoted to present some results showing the influence of positive ion trapping.

2. Apparatus and method

The apparatus and method used for this experiment are the same as those used to measure cross sections for ionisation of $He^+(1s)$ (Defrance *et al* 1981a). Figure 1 shows a schematic plan of the apparatus. A H^- beam is directly extracted from a Colutron ion source (1) and given an energy of 3300 eV. After magnetic analysis (2) the beam passes a set of collimating diaphragms before entering the collision chamber

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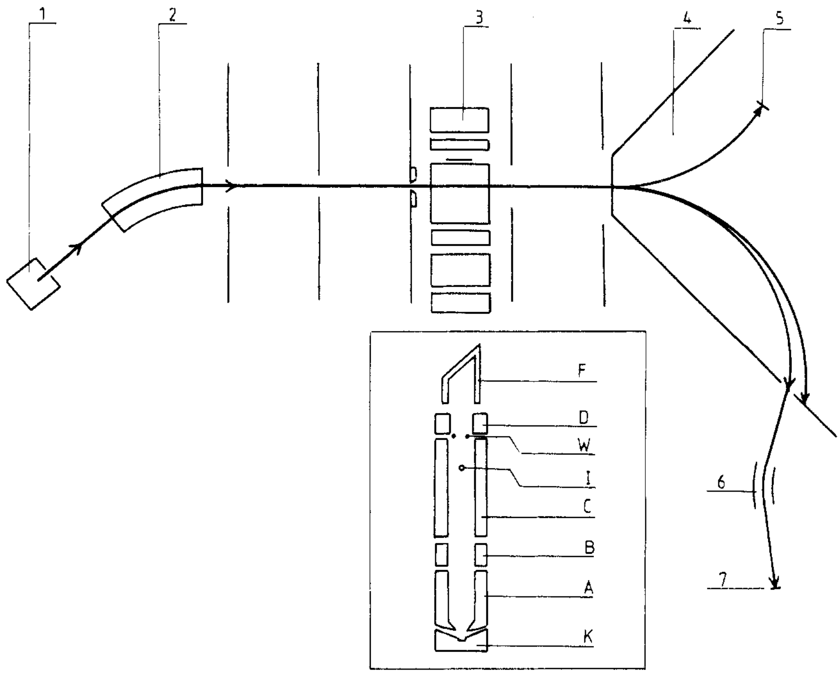

Figure 1. Schematic diagram of the apparatus: 1, colutron ion source; 2, magnetic selector; 3, interaction region; 4, magnetic analyser; 5, Faraday cup; 6, electrostatic deflector; 7, ion detector. The insert shows a schematic plan of the electron gun: K cathode; A, anode; B, focusing and deflecting electrodes; C, set of plates defining the potential of interaction region; I, ion beam; W, two wires parallel to the ion beam; D, suppressors; F, Faraday cup.

(3). The region where the ion beam crosses the electron beam is kept at a negative voltage of 150 V so that H^+ ions formed from H^- in this region decrease their energy by 300 eV before entering the magnetic analyser (4). Protons formed from H^- outside this region do not undergo this kinetic displacement and are rejected by the magnetic analyser (4). This confines the contribution of collisions with residual gas to reactions occurring only in the interaction region where the pressure is kept below 10^{-9} Torr. The H^- beam is collected in a Faraday cup (5). The H^+ ions are directed through an electrostatic deflector (6) to a Daly-type detector (7).

The electron gun (3) is schematically shown on the insert of figure 1. A ribbon electron beam is extracted in a Pierce cathode (K)–anode (A) configuration. The pair of plates (B) acts simultaneously as a lens and as a beam deflector. The bias voltage (−150 V) on the interaction region is applied to plates (C). The ion beam crosses the electron beam at location (I). The electron intensity is measured by collecting the electrons in a Faraday cup (F). The plates (D) in front of the Faraday cup act as suppressors.

In the method, the electron beam is swept across the H^- beam in a linear 'see-saw' motion at constant velocity u (Defrance *et al* 1981a). The cross section is related to the measured quantities in the following way

$$\sigma = \frac{e^2}{I_e I_i} \frac{v_e v_i}{(v_e^2 + v_i^2)^{1/2}} K u \tag{1}$$

where K is the total number of events produced during one passage across the ion beam, (v_e, v_i) and (I_e, I_i) are respectively the velocities and intensities of the electron and ion beams, e is the electron charge. The sweep velocity u is measured by means of two wires (W) located between the ion beam (I) and the Faraday cup (F) (figure 1). Besides circumventing the problem of determining geometrical factors, the method also circumvents the use of beam intensity modulation to determine the background contribution. Indeed, the sweep motion periodically brings the electron beam to positions where it no longer interacts with the ion beam and where proton formation is thus only due to charge exchange of H^- with residual gas in the interaction region.

During the measurements, the ion energy is 3300 eV and a typical H^- current is 10^{-8} A. The highest electron current is less than 2 mA at 1000 eV. The sweep frequency is 390 Hz. Typical values for u and K are:

$$u = 4\ \mathrm{m\,s^{-1}}$$

$$K = 0.05/\mathrm{sweep}.$$

The efficiency of the detector was derived from an analysis of the pulse height spectrum. It was found to be 87%.

The transmission was taken as 100% after it was established that a further increase of the geometrical acceptance did not change the observed cross section.

The maximum systematic error is estimated to be less than 12% at the lowest energy. The contributions to this figure are the translation velocity u (5%), the electron current intensity (2%), the ion current intensity (1%), the detector efficiency (3%). In addition, 1% is assumed to the kinematic factor of formula (1).

3. Positive ion trapping in the electron beam

Influence of positive ions formed by electron impact on residual gas has already been previously recognised (Dixon *et al* 1976, Defrance *et al* 1981b). These positive ions, once formed, cannot escape laterally because they are trapped in the space charge of the electron beam. The concentration of these ions in the interaction region depends upon the electron density and upon the voltage distribution along the electron beam path. They contribute to the signal through following reaction:

$$H^- + X^+ \rightarrow H^+ \ldots.$$

The top part of figure 2 shows schematically the electron gun. The full curve in the lower part shows the corresponding voltage distribution along the electron beam axis in a situation where one tries to avoid secondary electrons moving back from the Faraday cup into the interaction region (voltage is increasingly positive from interaction region to Faraday cup). In our experimental set-up plates (B) in figure 2 are usually kept positive. This voltage distribution concentrates in the interaction region the positive ions trapped in the electron beam. On the other hand, when a negative voltage is applied on the wires W (broken curve in lower part of figure 2), trapped ions are removed from the interaction region and secondary electrons are still retained by the Faraday cup. Varying the voltage of the wires (W) is a good way to explore the relative importance of this ion trapping effect on a cross section measurement. For H^+ formation from H^- by electron impact, measurements of apparent cross sections have been made at 300 eV for different wire voltages. The results are shown

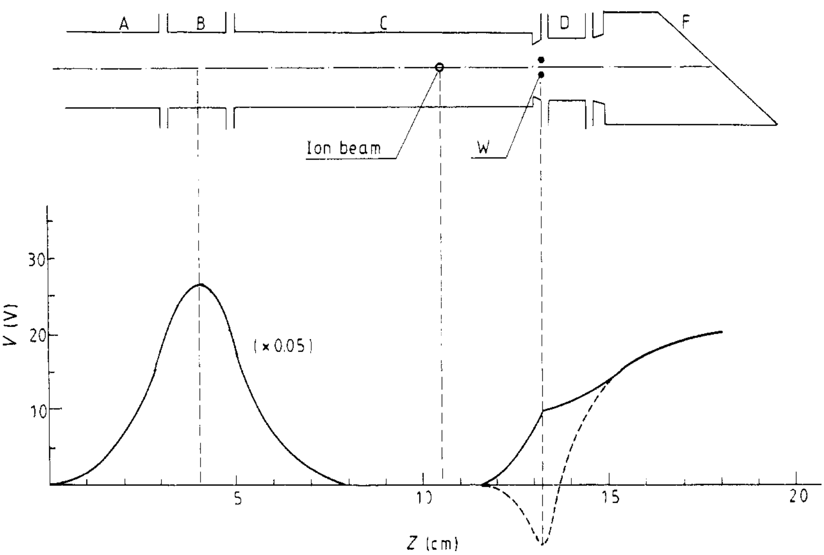

Figure 2. Upper part shows a vertical cut in the electron gun. The notation is the same as in figure 1. The lower part shows the voltage distribution along the electron beam axis in two different situations: full curve, when a positive voltage is applied to the wires; broken curve, when a negative voltage is applied. The voltage difference is measured with respect to plates C.

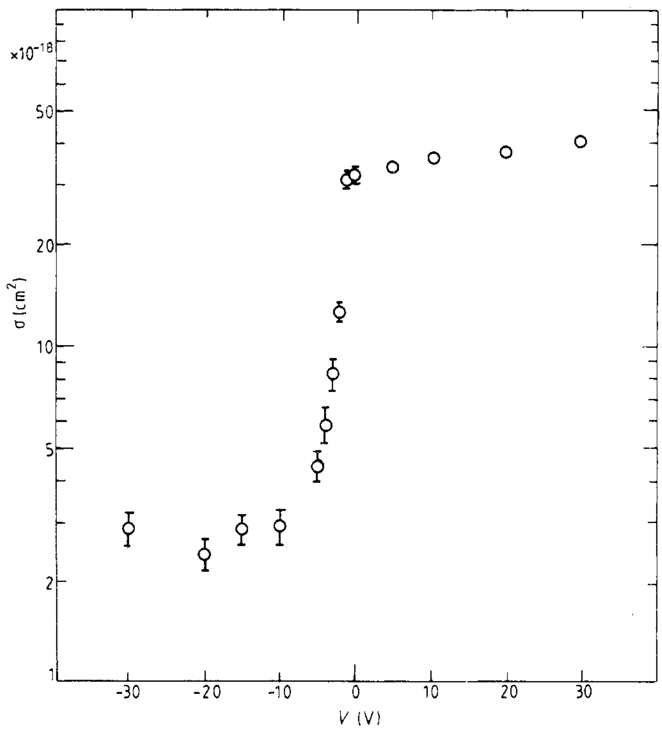

Figure 3. Apparent cross section for reaction $H^- + e \rightarrow H^+ + 3e$ at 300 eV for different wire voltages in the electron gun. Evidence of the influence of positive ion trapping is seen in the drop of measured cross section as the wire voltage goes from positive to negative.

in figure 3. The apparent cross section drops by a factor of 12 when one passes from a positive wire voltage (positive ions concentrated in interaction region) to a negative wire voltage (positive ions extrated from interaction region, corresponding to broken curve in figure 2). This shows how positive ions can drastically influence results. Another significant way to show this influence is by varying the electron density. The cross section of proton formation from H^- by electron impact has been measured at 330 eV for different electron beam intensities in two different situations: +15 and −15 V on electron gun wires. The results are shown in figure 4. The electron current is varied from 2.4 mA down to 50 μA. When a positive voltage is applied to the wires (open circles), the cross section drops rapidly for intensities below 100 μA. At this intensity, the depth of the potential well of the electron beam is still too small to trap the formed positive ions significantly. When a negative voltage is applied to the wires (full circles in figure 4) no change in cross section is observed as a function of electron intensity.

Finally, a good way to detect the influence of positive ion trapping in electron impact cross section measurements, is to measure below threshold. Unfortunately, in the case of the reaction $H^- + e \rightarrow H^+ + 3e$, the threshold (14.35 eV) lies close to or below the threshold for positive ion formation by electron impact on residual gas (i.e. ionisation energy $\simeq$ 15.4 eV for H_2). Consequently, proton formation from H^- by electron impact and positive ion formation from electron impact on residual gas vanish for almost the same electron energy.

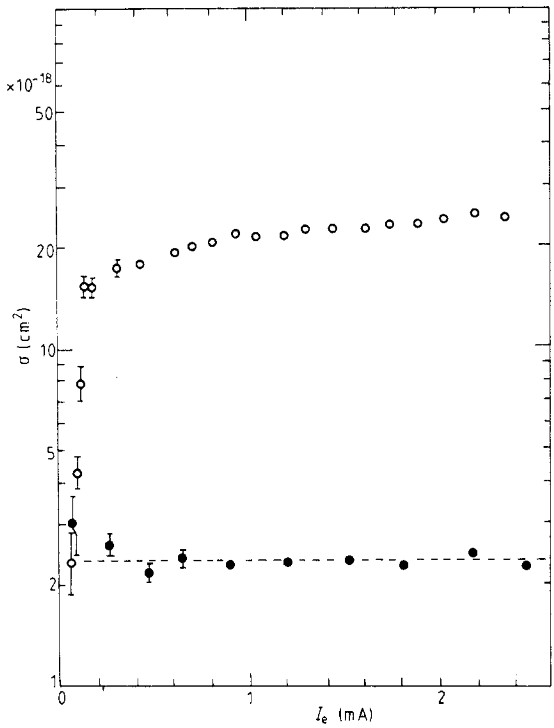

Figure 4. Apparent cross section for reaction $H^- + e \rightarrow H^+ + 3e$ at 330 eV for two different wire voltages in the electron gun as a function of electron beam intensity. Open circles show the results when a positive voltage is applied, full circles, when a negative voltage is applied.

4. Results and discussion

Present results are listed in table 1. Figure 5 shows them together with those of Peart *et al* (1971). The discrepancy ranges from a factor of four at low energies to a factor of 12 at high energies. A possible explanation of this difference could be the presence of trapped positive ions in the electron beam of Peart *et al*'s experiment, contributing to the production of too high cross sections. The experimental set-up used by Peart *et al* is described in another paper (Peart *et al* 1970) on electron detachment from H^- by electron impact. In this paper it is seen that one of the author's concerns is to avoid slow secondary electrons moving back to the interaction region synchronously with the intensity modulated electron beam. To prevent this, the interaction region is surrounded by negative electrodes. In such a situation positive ion trapping can certainly occur. On the other hand, checks of signal linearity with respect to electron beam intensity in the case of the reaction $H^- + e \rightarrow H^+ + 3e$ were not conducted at sufficiently low intensities to reveal the presence of trapped positive ions.

A crude estimation of the contribution of trapped ions to the apparent cross section can be made, if we assume that the density of trapped ions is equal to the density of electrons.

The number K of electron impact ionisation over one sweep is taken from formula (1):

$$K = \sigma n_e n_i \frac{(v_e^2 + v_i^2)^{1/2}}{u S_e S_i}$$

Table 1.

Centre of mass energy (eV)	σ (10^{-18} cm^2)	Standard error (%)
17.8	1.97	21
19.8	2.78	10.3
22.8	4.39	7.7
30.8	7.07	4.7
40.8	8.49	4.0
50.8	10.2	3.0
60.8	9.56	1.5
70.8	10.2	2.2
80.8	9.60	1.5
90.8	7.89	4.3
100.8	7.39	2.6
125.8	6.39	2.3
150.8	5.43	2.4
200.8	3.96	1.6
250.8	3.09	3.1
300.8	2.69	1.0
330.8	2.32	1.7
400.8	1.58	2.9
500.8	1.23	3.4
600.8	0.983	5.2
700.8	0.785	4.7
800.8	0.700	4.4
900.8	0.532	5.3
1000	0.496	4.0

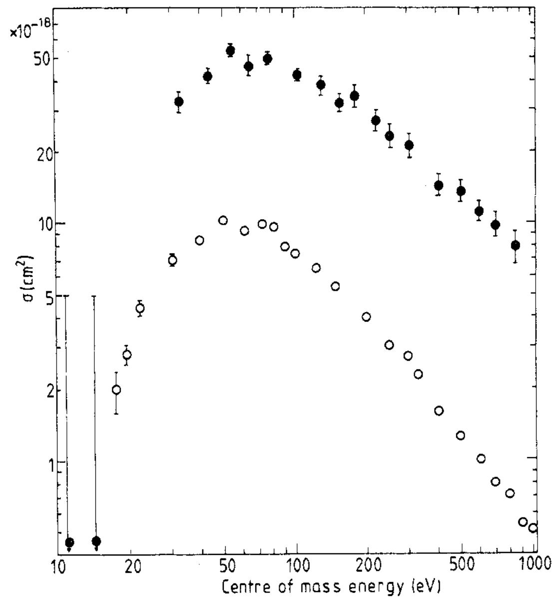

Figure 5. Cross section for H^+ formation from H^- by electron impact: open circles are present results, full circles are the results of Peart *et al* (1971). Error bars stand for statistical error: standard deviation for present results and 90% confidence limit for the results of Peart *et al.*

where n_e, S_e; n_i, S_i are the densities and geometrical sections of the electron beam and the H^- beam, respectively. Similarly, the number K' of ionisations produced by the trapped ions is

$$K' = \sigma' n_t n_i \frac{v_i}{u S_t S_i}$$

where n_t and S_t relate to the trapped ion beam and σ' is the cross section for ionisation of H^- by the trapped ions.

Now, if $n_e = n_t$, $S_e = S_t$ and $v_i \ll v_e$, we get:

$$\frac{K'}{K} = \frac{\sigma'}{\sigma} \frac{v_i}{v_e}.$$

At 60 eV CM energy, $v_i = 8 \times 10^7\ \mathrm{cm\ s^{-1}}$ and $v_e = 4.6 \times 10^8\ \mathrm{cm\ s^{-1}}$. Taking

$$\sigma = 10^{-17}\ \mathrm{cm}^2 \text{ and } \sigma' = 10^{-16}\ \mathrm{cm}^2$$

we get

$$K'/K = 1.74$$

thus yielding an apparent cross section enhanced by a factor of 2.74. Conversely, taking a value of five for the ratio of apparent to true cross section , i.e. $K'/K = 4$, we obtain

$$\sigma' = 2.3 \times 10^{-16}\ \mathrm{cm}^2$$

a figure which is not absurd.

Reliable theoretical predictions are unfortunately missing. Only one theoretical prediction is available to our knowledge (Tweed 1973a, b). However its validity is questionable, as some basic issues are still unresolved (Byron *et al* 1973, Tweed 1973c).

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References

Byron F W and Joachain C J 1966 *Phys. Rev. Lett.* **16** 1139–42
Byron F W, Joachain C J and van der Wiel M J 1973 *J. Phys. B: At. Mol. Phys.* **6** L375–7
Defrance P, Brouillard F, Claeys W and Van Wassenhove G 1981a *J. Phys. B: At. Mol. Phys.* **14** 103–10
Defrance P, Claeys W, Cornet A and Poulaert G 1981b *J. Phys. B: At. Mol. Phys.* **14** 111–17
Dixon A J, Harrison M F A and Smith A C H 1976 *J. Phys. B: At. Mol. Phys.* **9** 2617–31
Peart B, Walton D S and Dolder K T 1970 *J. Phys. B: At. Mol. Phys.* **3** 1346–56
—— 1971 *J. Phys. B: At. Mol. Phys.* **4** 88–93
Tweed R J 1973a *J. Phys. B: At. Mol. Phys.* **6** 256–69
—— 1973b *J. Phys. B: At. Mol. Phys.* **6** 270–85
—— 1973c *J. Phys. B: At. Mol. Phys.* **6** L378–80