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A measurement of cross sections for detachment from H^- by a method employing inclined ion and electron beams

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Abstract. A technique employing inclined beams of electrons and ions has been developed and used to measure cross sections of the reaction $H^- + e \rightarrow H + 2e$ for interaction energies between threshold (0·75 eV) and 30 eV. The magnitudes of the cross sections agree closely with results which Peart *et al.* obtained, for energies greater than 12·5 eV, with normally inclined beams. At energies close to 14·2 eV a pronounced structure has been observed in the detachment cross section. This could be attributed to the formation of a state of H^{2-} with a lifetime of order 10^{-15} s.

1. Introduction

It has now been established that detachment from H^- by electron impact, that is, $H^- + e \rightarrow H + 2e$, is relatively unimportant in maintaining the equilibrium concentration of H^- in stellar photospheres (see Schmeltekopf *et al.* 1967 and Branscomb 1967). It has also been shown that, for electron energies above 200 eV, there is harmony between measured cross sections and those calculated, for example, by Kim and Inokuti (1971). Interest in this reaction can now shift to much lower energies where one might hope to observe the characteristic threshold behaviour of a negative ion and any structure which exists in the detachment function. There is also technical interest in verifying that the measured cross section is in fact zero below threshold (0·75 eV), because this is a valuable check in experiments with colliding beams of charged particles (Dolder 1969).

The previous measurements of this cross section by Tisone and Branscomb (1966, 1968), Dance *et al.* (1967) and Peart *et al.* (1970, to be called I) employed beams which intersected at right angles, but it was impractical to make accurate measurements at energies less than about 10 eV. An inclined beam technique has therefore been developed and used to obtain cross sections between threshold and 30 eV, with an energy resolution of approximately 0·25 eV. A brief account of the results between 12 and 17·5 eV has already appeared (Walton *et al.* 1970) but the present paper includes details of the technique and results obtained over the wider range of energies.

2. Apparatus and method

With the following exceptions, the apparatus was the same as that illustrated by figure 1 of I.

(*a*) The electron gun (G), collector (Ce), and their associated components, were replaced by the assembly which is described below and illustrated by figure 1 of the present paper.

(*b*) The magnet M1 was replaced by a much smaller magnet which deflected the H^- ions through 10° on a radius of 23 cm. This was done to reduce the magnetic fringe field which had to be screened from the electron gun.

(*c*) The 60 ° electrostatic deflector was removed from the tank T1 and replaced by a pair of magnetically shielded collimating slits which were 3 mm high and 0·5 mm wide.

(*d*) The ions entered T1 through a new port so that they were initially directed towards the detector D.

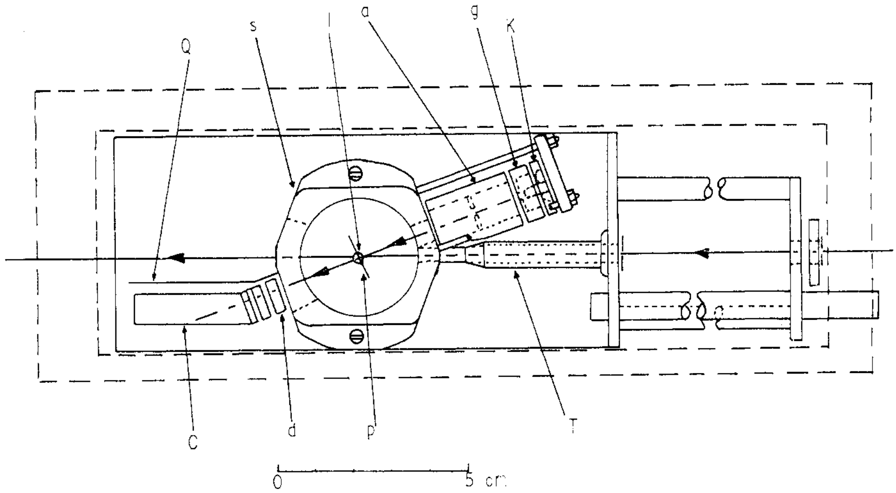

Figure 1. Scale plan of the interaction region showing the electron gun and ion collimators. The grid electrode (g), and anode (a) of the electron gun were supported by the cylinder (S) which also held the electron collector (C) and defining plate (d). The earthed electrodes (T and Q) used to shield the ion beam and the scanning plate (P) are also shown.

Figure 1 is a scale plan of the new electron gun and interaction region. Electrons were obtained from an indirectly heated cathode (Philips type BP1A) which was held by the support K. The beam passed through a 1 mm diameter hole in the grid electrode (g) and was focused by the positive potential of the electrode (a), which contained a stop of 1 mm diameter. The earthed aperture in the cylindrical support (s) formed the final element of the lens which focused the electrons at the point I. The support (s) also held the deep electron collector (C) which was biased 15 V positive to retain secondary electrons. Before entering the collector, the electrons passed through the 3 mm diameter aperture in the defining plate, d, and, by focusing the beam to produce minimum current at this plate, it was possible to check that the collected electrons had passed through the ion beam with the correct inclination. At the very lowest energies (which corresponded to an interaction energy of only 3 eV) about 10% of the electron current was drawn by the defining plate. As a result, there was some uncertainty in the cross section at these energies and this has been included in the estimates of experimental error. At higher energies the defining slit intercepted about 2% of the electron beam. Even at the lowest energies, the gun produced beams with perveances greater than $10^{-7}\,AV^{-3/2}$ with a semi-angular convergence of $\frac{1}{2}$°. This was about 30% of the space charge limit.

It was essential to shield the gun very carefully from stray magnetic fields and this was accomplished with the two concentric mumetal boxes represented by broken lines in figure 1. This arrangement attenuated stray fields by a factor 5×10^3, without saturation. It was noted that a field of 0·2 Wb m^{-2} could be tolerated in the analyzer magnet gap before there was any perceptible deflection of a 10 eV electron beam. The plate (p), bearing a horizontal slit 0·2 mm high, was used in the determination of current density distributions in the colliding beams.

After collimation, the ion beam was shielded from the potentials of the gun and collector electrodes by an earthed tube (T) and plate (Q). The interaction assembly was made almost exclusively from 'Immaculate 5' stainless steel and the gun electrodes were located and insulated by 2·00 mm diameter ruby spheres. The assembly could be baked between 350 and 400 °C by heaters mounted between the mumetal boxes.

3. Experimental method

The detachment cross section can be expressed in terms of measurable quantities by,

$$\sigma(E) = \frac{R_s e^2 v V \sin\theta}{IJ(V^2+v^2-2vV\cos\theta)^{1/2}} \cdot \frac{F'}{\Omega} \tag{1}$$

where θ (= 20 °) is the angle at which the beams collide. The remaining symbols were defined in I. The interaction energy (i.e. the collision energy in centre of mass coordinates) is given in terms of the laboratory electron (E_e') and ion (E_i') energies by,

$$E = \frac{M}{m+M}\left\{E_e' + m\left(\frac{E_i'}{M}\right) - 2m^{1/2}\left(\frac{E_i'}{M}\right)^{1/2} E_e'^{1/2}\cos\theta\right\}. \tag{2}$$

For a constant angle of intersection and ion energy, the resolution of the interaction energy is,

$$\delta E = \left\{1 - m^{1/2}\left(\frac{E_i'}{M}\right)^{1/2} E_e'^{-1/2}\cos\theta\right\}\delta E_e' \tag{3}$$

provided that $\Delta E \ll E$. In practice, the spread is broadened by nonuniformities in the ion energy and, more particularly, by variation in θ. The latter effect reduces the resolution by an amount,

$$\delta E = 2m^{1/2}\left(\frac{E_i'}{M}\right)^{1/2} E_e'^{1/2}\sin\theta\,\delta\theta. \tag{4}$$

In the present experiment, $E_i' = 8$ keV, $\delta E_e' \simeq \pm 0{\cdot}5$ eV, $\theta = 20$ ° and $\delta\theta \simeq \pm\frac{1}{2}$ ° so that, for an interaction energy of 15 eV, one estimates $\delta E \simeq \pm 0{\cdot}25$ eV.

The method used to obtain cross sections and estimate errors was described in I. Inherent in this procedure is the measurement, at each interaction energy, of linear relations between $R_s F'/I^+$ and the electron current, J. This is not only an important experimental check, but the cross sections are deduced from the gradients of these lines. It was also possible, on this occasion, to verify that the measured cross section fell to zero at threshold. This demonstrates that subtle errors which are associated with modulated backgrounds (Dolder 1969), were insignificant. A further check is possible in experiments with merged or inclined beams because the interaction energy is a function of the laboratory energies of both beams. Results were therefore obtained with three different ion energies and the fact that these lie on a smooth curve (figure 2) gives confidence that the observed resonance structure was not of instrumental origin.

4. Results and discussion

Table 1 summarizes the results and estimates of error, whilst the closed symbols in figure 2 show these measurements plotted against the interaction energy. The 90% confidence limits of random error, which were assessed as described in I, are

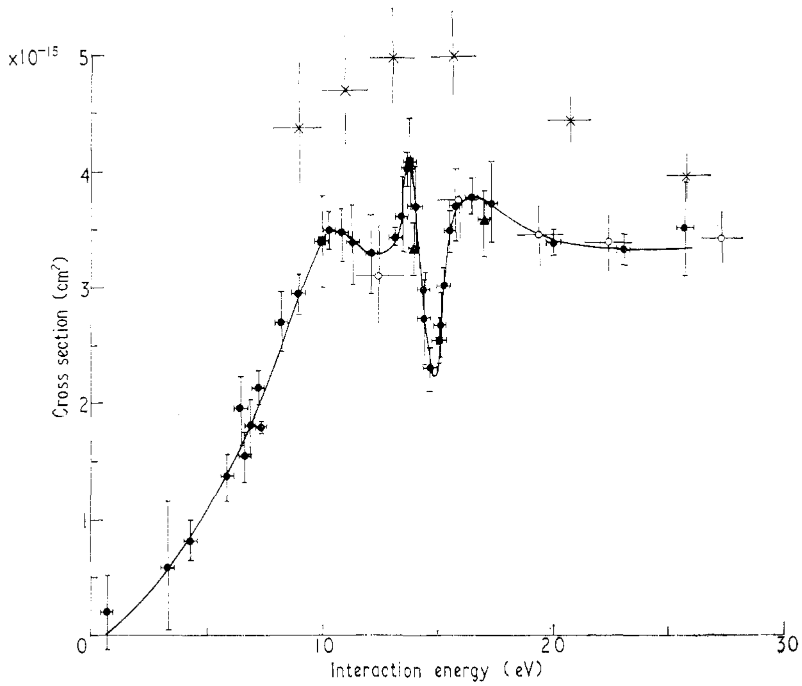

Figure 2. Measured detachment cross sections plotted against interaction energy. The brackets illustrate estimates of random error and energy spread. ○ Peart *et al.* 1970; × Dance *et al.* (1967); ▲, ● and ■ present results obtained with laboratory ion beam energies of respectively 7, 8 and 10 keV.

also shown. The nonlinear rise from threshold (which contrasts with the ionization function of positive ions) and the structure near 14·2 eV can clearly be seen. The figure also includes the five results which were obtained in this energy range by Peart *et al.*, working with normally inclined beams. The close agreement between these two independent, absolute measurements suggests that the results of Dance *et al.*, which are also shown in the figure, may be too high. Some relevant comments on these results were given in I. The measurements at different ion energies, which were made in the region of the resonance, are identified in the legend.

The cause of the structure in the detachment function has not yet been established. It may be relevant that the calculated s wave phase shift (η_0) for the elastic scattering of electrons by H^- (McDowell 1968) almost passes through π at about 15 eV. Although this calculation indicates a fairly slow variation of η_0 with energy, it seems possible (McDowell 1970 private communication) that a new calculation with improved wavefunctions might show behaviour characteristic of a resonance. It has also been tentatively suggested by Taylor (1971 private communication) that the structure might be due to a cusp (e.g. Newton 1966) associated with the opening of the channel for double detachment at 14·35 eV. Clearly there is scope for further calculations.

Table 1

Interaction energy (eV) ($\pm 0{\cdot}25$ eV)	Cross section ($\times 10^{-16}$ cm^2)	Random error† ($\pm$ %)
3·4	5·90	100
4·4	8·18	20
5·9	13·6	15
6·5	19·6	15
6·6	15·4	15
6·9	18·0	12
7·3	21·4	8
7·4	18·0	2
8·3	27·0	10
9·0	29·5	6
10·0 (10)	34·0	12
10·3	34·9	5
10·8	34·7	8
11·3	33·8	11
12·1	33·0	9
13·2	34·4	2
13·5	36·3	8
13·7	40·2	4
13·8 (10)	41·0	10
13·9 (7)	33·4	10
14·0	37·0	10
14·4	29·9	2
14·6	27·3	14
14·7	23·0	9
15·1 (10)	25·3	13
15·1	26·8	13
15·2	30·0	5
15·5	34·9	5
15·8	37·3	8
16·5	38·0	4
17·0 (7)	35·7	8
17·4	37·5	10
20·1	34·0	4
23·1	33·4	4
25·7	35·3	12

Numbers in brackets indicate the ion beam energy (keV) when this differed from 8.

† The random errors refer to the 90% confidence limits at each electron energy.

Maximum systematic errors are estimated to be $\pm 10\%$.

5. Some comments on experiments with merged or inclined beams

Experiments with merged ($\theta = 0$) beams of electrons and ions have very briefly been described by Mahadevan (1969), but they do not yet appear to have yielded any precise results. Merged beams give access to the highest energy resolution and lowest interaction energies, and they have been brilliantly exploited in experiments with heavy particles (e.g. Neynaber 1968). However, it does not follow that this method can be applied so easily to collisions between electrons and ions, because space charge forces will make it difficult to keep two charged beams in confluence over an appreciable path length without radically altering their current density distributions. The very different forces exerted by stray magnetic fields on electrons and ions of comparable velocity will add to these difficulties. In addition, there are the problems of alignment and definition of path length, which are common to all merged beam experiments.

The inclined beam method sacrifices energy range and resolution and, because the beams interact only over a short path, it yields smaller signals. On the other hand, the collision geometry is well defined so that precise measurements are readily obtained. A further advantage, which was relevant to the experiments of Rundel *et al.* (1969) on collisions between H^+ and H^- ions, was that the parent ion is effectively 'labelled' by the direction of its trajectory so that its products can easily be identified.

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