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

B. PEART, D. S. WALTON and K. T. DOLDER
Department of Atomic Physics, University of Newcastle upon Tyne
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Abstract. Cross sections of the reaction $H^- + e \rightarrow H^+ + 3e$ have been measured for interaction energies between threshold (14·4 eV) and 850 eV. The cross section reaches a maximum value $5{\cdot}0 \times 10^{-17}$ cm^2 at 70 eV. Comparison with previous measurements shows that, for energies greater than 100 eV, the ratio of cross sections for single and double detachment is almost constant and equal to $39 \pm 10\%$. The present measurements are compared with similar results for helium and Li^+.

1. Introduction

Multiple ionization by electron impact has not been extensively studied and almost all of the theoretical work has been confined to the double ionization of helium. The theory of multiple ionization encounters three major difficulties. As in the case of single ionization, approximations must first be made to render the equations soluble, but two further problems remain. Byron and Joachain (1966) demonstrated that calculations of multiple ionization are extremely sensitive to the choice of target wave function and particularly to the terms involving electron correlation. Moreover, the Coulomb field of the product ion, which acts on the ejected electrons, is partially screened by these electrons to an extent which depends on their individual momenta (D. J. Moores and R. Tweed, private communication).

The 'sudden approximation', suggested by Mittelman (1966) for the double ionization of helium, avoids most of these difficulties. It assumes that a projectile ejects one electron from helium in a time short compared with the orbital period. The remaining electron is therefore left in a state which is not an eigenstate of He^+ so that it may make a transition to the continuum. It follows that the ratio of cross sections for single and double ionization σ_+/σ_{2+} is constant and independent of the projectile energy. Peek (1967) has shown that the sudden approximation is equivalent to the high energy limit of the first Born approximation.

The extreme sensitivity of theory to the initial state wave functions led Byron and Joachain (1966, 1967) to suggest that comparisons of calculated and measured cross sections might eventually provide sensitive checks for correlation terms in atomic wave functions. It is, however, not yet clear whether multiple ionization will converge to the limit of the first Born approximation and it may prove necessary to include higher terms in the Born series (McDowell and Coleman 1970).

Several measurements of cross sections for the double ionization of helium have been published (e.g. Schram *et al.* 1966, Gaudin and Hagemann 1967, Van der Wiel *et al.*, 1969) and similar results for Li^+ have been reported by Peart and Dolder (1969). The present paper describes measurements for H^-. It is hoped that experimental results for three two-electron systems with different nuclear charges will provide useful checks for theory. In particular, it may suggest the screened nuclear charge which should be assumed to act on the two ejected electrons.

2. Apparatus and method

General principles of experiments with colliding charged-particle beams have been described by Harrison (1968), Dolder (1969) and Dunn (1969).

The apparatus used for this experiment was developed from that previously employed to measure cross sections for single detachment from H^- (Peart *et al.* 1970 to be called I). For the present experiment changes were only made to that part of the apparatus through which ions passed after colliding with the electron beam.

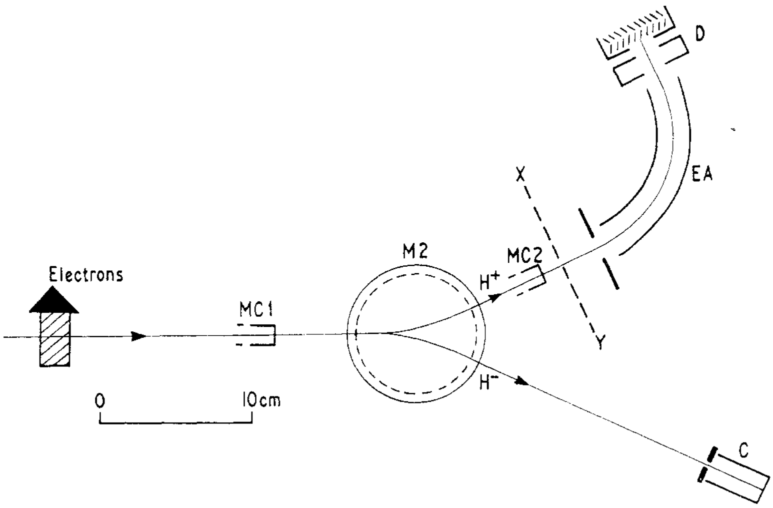

Figure 1. Schematic plan of the apparatus used to separate and collect ions. The plane of the electrostatic analyser EA and particle detector D has been rotated about XY to show the ions deflected horizontally, and not vertically as in the apparatus. The magnetic separator M2, two movable collectors MC1 and MC2, and one fixed collector C are also shown.

Figure 1 illustrates the separation of H^- (parent) and H^+ (product) ions in the magnetic field M2 between tapered cylindrical polepieces. After separation, the H^- ions were collected by a deep Faraday cup and their current was measured by an electrometer. When the H^+ ions emerged from the field they were deflected vertically on a mean radius of 8 cm by an electric field between cylindrical electrodes EA. They then struck the first dynode of the particle detector D to produce electrical pulses which were counted individually. The detector (E.M.I. type 9643) was described in I and, in the present experiment, its efficiency Ω was measured by comparing count rates produced by proton beams with the currents ($\sim 10^{-15}$ A) indicated by an electrometer when the same beams were collected in a movable Faraday cup MC2, which could be moved into the ion beam path at the position shown in figure 1. The transmission efficiency of the electrostatic analyser EA was shown to be $(98 \cdot 5 \pm 1)\%$ by a further experiment in which the detector was replaced by a Faraday cup with the same entrance aperture. The transmission remained within these limits when the potential of either analyser electrode was varied by ± 50 eV. These tests indicated that $(88 \pm 3)\%$ of 8 keV protons which emerged from M2 were counted and this agrees with the measurement reported in paper I where further details of the calibration procedure were given.

The cross section for double detachment σ_{2+} is expressed in terms of measurable quantities by

$$\sigma_{2+} = \frac{R_s}{IJ} \frac{e^2 v V}{(v^2+V^2)^{1/2}} \frac{F'}{\Omega}$$

where R_s is the rate of production of protons by electron impact and the remaining symbols are defined in I. The detector also responded to extraneous signals so that the beam modulation technique described in I was needed to resolve the counting rates R_s due to signal and R_b due to backgrounds.

Typical values for these experiments were, $R_s \sim 8\ s^{-1}$, $R_b \sim 200\ s^{-1}$, $I \sim 3 \times 10^{-10}$ A, $J \sim 10^{-3}$ A, $F'/h = 0{\cdot}96$ where ($h \sim 3{\cdot}3$ mm) is the ion beam height. The electron energies ranged from 14 to 850 eV whilst, except for the checks mentioned in § 3, the ion energy was 8 keV.

3. Results and discussion

In experiments of this type it is strongly advisable to plot the ratio $R_s F'/I$ against the electron current J. A linear relation indicates that most of the possible sources of systematic error are absent (see, for example, Dolder). The cross section can then be deduced from the gradient of the ensuing straight line and confidence limits of this slope can be taken to represent random errors of the measurement. A further important check is to ensure that the measured cross section is zero below the ionization threshold. This was impractical for the experiment described in I, because the threshold for single detachment from H^- is only 0·75 eV, but it was possible in the present reaction which had a threshold of 14·35 eV.

Figure 2 illustrates the measurement of $R_s F'/I$ plotted against J for three interaction energies. The interaction energy is the energy of the colliding particles in centre of mass coordinates. Further checks showed that the results were independent

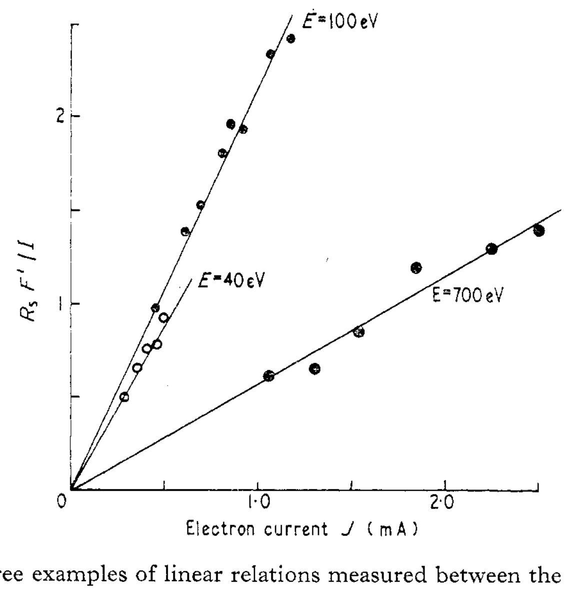

Figure 2. Three examples of linear relations measured between the ratio $R_s F'/I$ and the electron current, J. These refer to interaction energies of 40, 100 and 700 eV.

of variations of the ion beam energy between 6 and 9 keV and upon wide variations of the ion beam current or form factor F'.

The table summarizes the results and the limits of random and systematic errors, which were estimated as described in I. The measured cross sections σ_{2+} are plotted

Table 1

Interaction energy (eV)	Measured cross section ($\times 10^{-17}$ cm^2)	Random error† ($\pm$%)	Maximum systematic error ($\pm$%)
32·4	3·24	11	8
42·4	4·19	7	8
52·4	5·20	5	8
62·4	4·65	11	8
77·4	4·98	9	8
102	4·27	4	8
127	3·86	11	8
152	3·22	9	8
177	3·48	11	8
220	2·72	10	8
250	2·34	12	8
300	2·13	12	8
400	1·45	10	8
500	1·38	11	8
600	1·12	10	8
700	0·99	12	8
850	0·80	17	8

† The random errors are 90% confidence limits at each electron energy.

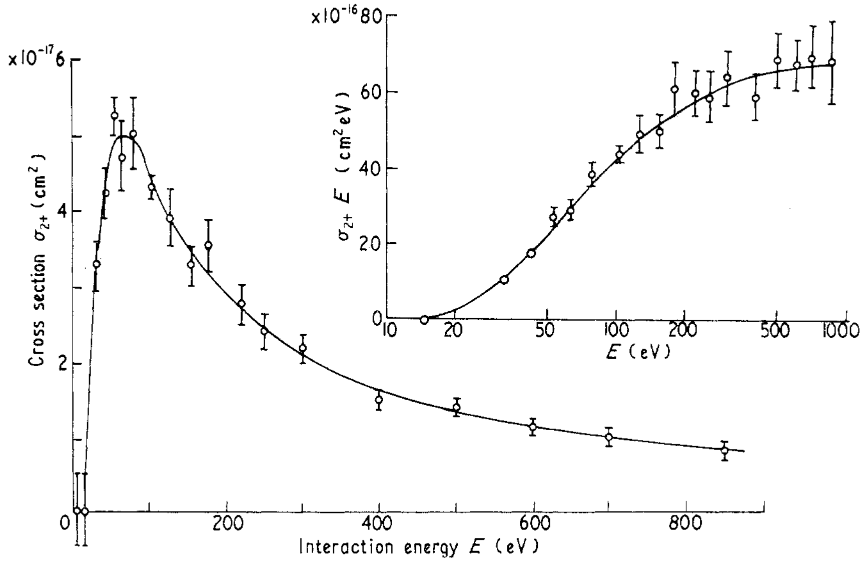

Figure 3. Measured cross sections σ_{2+} for double detachment from H^- plotted against the interaction energy E. The bars represent 90% confidence limits of random error and the uncertainties in energy. The inset illustrates the relation found between $\sigma_{2+}E$ and lg E.

against interaction energy E in figure 3. The brackets represent 90% confidence limits of random error and the uncertainties (± 2 eV) in the interaction energies. For energies greater than 25 eV, σ_{2+} lies within 30% of the cross section for the single ionization of atomic hydrogen. The inset of figure 3 shows the relation between $\sigma_{2+}E$ and $\lg E$. A similar functional dependence was previously noted for helium (e.g. Van der Wiel *et al.*) and Li^+ (Peart and Dolder).

Contrary to the prediction of the sudden approximation, the ratio σ_+/σ_{2+} does not tend to a constant value at high energies for helium, Li^+ or H^-. However, it can be seen from figure 4 that σ_+/σ_{2+} is a slowly varying function over quite a wide range

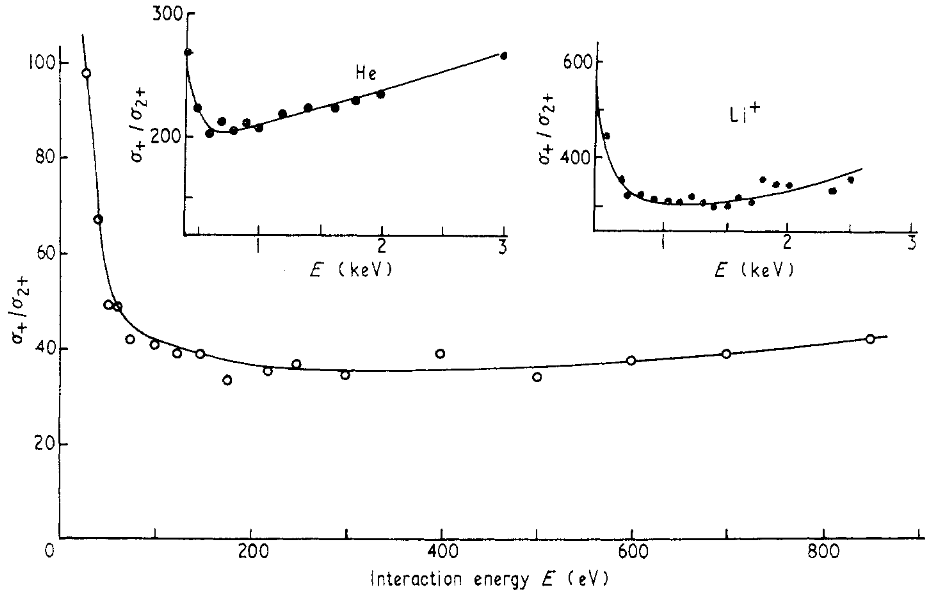

Figure 4. The ratio of cross sections for single and double detachment of electrons from H^- plotted against interaction energy. The insets show similar measurements for helium and Li^+.

of energy and this is particularly so for H^-. The assumptions of the sudden approximation are likely to be more closely realized for H^- because the ratio of its first and second ionization energies is small. An almost negligible perturbation would therefore be sufficient to eject the first electron.

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