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Electron impact ionisation of metastable atomic hydrogen

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Abstract. This paper reports on measurements of the electron impact ionisation cross section of metastable atomic hydrogen in the energy range 6·3–998·3 eV. Crossed electron and atom beams are used in a new method where the more usual intensity modulation is replaced by a 'see-saw' motion of the electron beam across the atom beam. The main advantage of the method is that it obviates the problem of the density distribution in the beams. Absolute results, with 10% accuracy, are obtained for the difference (σ_{2s}–σ_{1s}) between the cross sections of the atom in the metastable and ground states. At high energies, the results are consistent with the Bethe formula, in contrast with earlier experimental data. At low energies large discrepancies subsist with all theoretical predictions.

1. Introduction

The study of excited atoms is important for the understanding of the mechanisms occurring in astrophysical and fusion plasmas. Excited atoms are formed in large amounts by charge exchange reactions of energetic ions. They are much more reactive than their ground-state parents and are therefore likely to play a prominent part in the formation and destruction of plasmas. For thermonuclear plasmas, the study of hydrogen is obviously of major importance.

In this paper, absolute cross section measurements are reported of the electron impact ionisation cross section for atomic hydrogen in the energy range 6·3–998·3 eV. This process has been investigated experimentally by Koller (1969) and Dixon *et al* (1975) in the energy ranges 3·4–10 and 8·5–498·5 eV respectively. However, large error bars affect their data, particularly at the low- and high-energy sides, and the measurements suffer from a lack of data regarding the metastable population of the atom beam. It was therefore felt that this process could usefully be investigated again using a new experimental method recently developed in our laboratory. Advantage was also taken of our earlier studies on the fraction of metastable atoms produced by charge exchange of protons in caesium (Brouillard *et al* 1977).

2. Experimental method and apparatus

The experimental method is essentially a crossed beam method where an electron beam intersects a beam of atomic hydrogen at 90°. However, the interaction is modulated by a periodic movement of the electron beam, that moves across the atom beam in a 'see-saw' motion. Figure 1 shows the experimental set-up.

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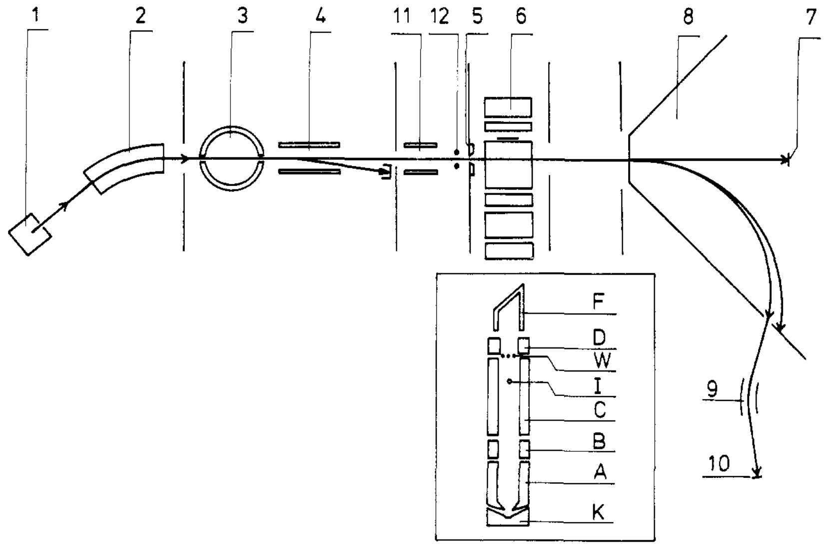

Figure 1. Schematic diagram of the apparatus. 1, colutron ion source; 2, sector magnet; 3, caesium cell; 4, electrostatic deflector; 5, beam defining diaphragm; 6, high-vacuum chamber; 7, neutral beam collector (secondary emission probe and bolometer); 8, analysing magnet; 9, electrostatic analyser; 10, proton detector; 11, quenching field; 12, field ioniser. For the electron gun, an upper and a side view are given. K, cathode; A, anode; B, focusing and deflecting electrodes; C, collision electrodes; D, suppressing electrodes; F, electron beam collector; W, set of three wires; I, atom beam.

The beam of atomic hydrogen is produced by charge exchange of protons in caesium. A beam of hydrogen ions, extracted from a Colutron ion source (1) is accelerated to some 3125 eV and mass analysed by the sector magnet (2). The proton component is passed through a caesium vapour cell (3) where some 10% of the beam is charge exchanged. The remaining protons are deflected out of the beam by means of a weak electric field (4). The atomic beam is then 'skimmed' down to 1 mm diameter by the circular diaphragm (5) at the entrance of the high-vacuum chamber (6) that contains the electron gun.

The total intensity of the atomic beam is measured by means of a secondary emission probe (7) which can also be used as a bolometric detector for calibration. The measurement of the metastable content of the beam has been described in an earlier paper (Brouillard *et al* 1977). The electron gun has been described elsewhere (Defrance *et al* 1980). It produces a ribbon electron beam, some 16 mm wide, that is focused on the atomic beam and then collected in a Faraday cup (F). The region where the beams intersect is located between two large electrodes (C) belonging to the electron gun lens system, and is therefore at the electric potential of those electrodes. This potential, called hereafter the 'collision potential', makes it possible to eliminate the largest part of the ionisation on residual gas, as it gives the protons created in the crossing region an increased kinetic energy and so provides a method of sorting them out from the protons formed along the path of the atom beam by ionisation on residual gas in the subsequent magnetic analyser (8). The beam reaching the detector (10) still contains, besides protons formed in collisions with electrons, a contribution of ionisation on residual gas in the crossing region. But this region is short (9 cm) and is well evacuated by powerful differential pumping. The residual pressure in the crossing region, in working conditions, is below 10^{-9} Torr.

To distinguish between electron impact ionisation and ionisation on residual gas, the electron beam is given a deflection movement, perpendicular to the atom beam in order to sweep it in a 'see-saw' motion. The counting rate on the proton detector (10) is then recorded as a function of time in a multichannel analyser, synchronised with the electron beam motion. The amplitude of the deflection must be large enough that, at the extreme positions, the beams practically no longer interact. The recorded spectrum then consists of one peak (electron impact ionisation) on a pedestal (ionisation on residual gas). This method has a major advantage over the usual intensity modulation. It lets off the difficult measurement of the density profiles in the beams.

It can indeed be shown (see Defrance *et al* 1980) that the number K of ionisations produced by an electron beam of intensity I_e during one passage across an atom beam of intensity I_a is given by the simple relation:

$$K = \sigma I_e I_a (v_e^2 + v_a^2)^{1/2} / u v_e v_a$$

where σ is the cross section, v_e and v_a the velocities of the electrons and atoms respectively and u is the sweep velocity of the electron beam. The velocity u is measured by means of a set of three wires (W) across the electron beam. The geometrical correction, necessary to take into account the fact that the wires are not located at the crossing of the beams has been discussed by Defrance *et al* (1980).

The efficiency of the detector, which is of the Daly-type (Brouillard and Godart 1969) has been measured and found equal to 89%. The multichannel analyser has a 10% dead time. The overall efficiency of the proton detection is therefore equal to 80%.

3. Measurement of the ionisation cross section of H(2s)

The proportion p_{2s} of metastable atoms in the hydrogen beam formed in the caesium target is well known from previous investigations (Brouillard *et al* 1977). At 3125 eV, $p_{2s} = 20\%$. The corresponding intensity I_{2s} is

$$I_{2s} = p_{2s} I_a$$

where I_a is the total measured intensity of the atom beam. The proportion of ground-state atoms is practically $(1 - p_{2s})$ so that their intensity I_{1s} is

$$I_{1s} = (1 - p_{2s}) I_a.$$

Metastable atoms, on the other hand, are easily quenched by an electric field. In the present measurement, a quenching field of $250\ \mathrm{V\ cm^{-1}}$ was periodically applied between the plates of the condenser (11). The transit time of the metastable atoms in that field was 4×10^{-8} s, enough to ensure an almost complete quenching. The field was alternately switched, 2·56 s off, 2·56 s on (2·56 s being the time for 1000 passages of the electron beam across the atom beam) and the corresponding proton yields K_1 and K_2 were recorded separately. The difference $(K_1 - K_2)$ is directly related to the difference $(\sigma_{2s} - \sigma_{1s})$ of the cross sections for atoms in the metastable and in the ground state respectively. The measurements thus provide an absolute value for $(\sigma_{2s} - \sigma_{1s})$.

A problem arises owing to the presence of highly excited long-lived states in the beam. Although the population of excited states formed in charge exchange decreases as n^{-3} with the principal quantum number n, this is overcompensated by the increase of the ionisation cross section. In fact, the contribution of highly excited states has been observed to be dominant. Furthermore, it is not fully eliminated in the differential measurements as it is affected by the quenching field that field ionises the highest excited states. This problem has been solved by the use of a field ioniser (12). This ioniser consists of two 1 mm diameter parallel rods, 3 mm apart, one on each side of the atom beam and between which a voltage is applied to create a field of some 1000 V cm^{-1}. This field is strong enough to field ionise the excited states with $n > 28$ but is short enough that a large fraction of the metastable states can survive. The situation is very similar to the one prevailing in the experiment by Dixon *et al* (1975) and discussed there. The exact proportion of the metastables quenched in this field has been established using the usual relaxation method to calculate the electric potentials and fields. It was found equal to 59·9%. The same method has been used to calculate the fractions quenched in the deflector field (4) and in the voltage gradient created by the collision potential. These fractions were 2·3% and 21% respectively. The metastable fraction in the beam in the crossing region was therefore 6% of the total atom beam.

Another problem that must be considered is the trapping of slow ions in the electron beam. Slow ions can indeed contribute to the formation of H^+ in the atomic beam by charge exchange reactions:

$$H(2s) + X^+ \rightarrow H^+ + X.$$

Slow ions are created by the electron beam in the residual gas and on metallic surfaces. If they are trapped in the electron beam, their density can become large enough to have a significant part in the counting rate observed. Trapping of residual gas ions in electron beams reduces the space-charge effects and has been studied in this respect by Linder and Hernqvist (1950). They showed that the time required for the ionic cloud to be formed depends mainly on gas pressure and electron energy. At 10^{-9} Torr, and in the

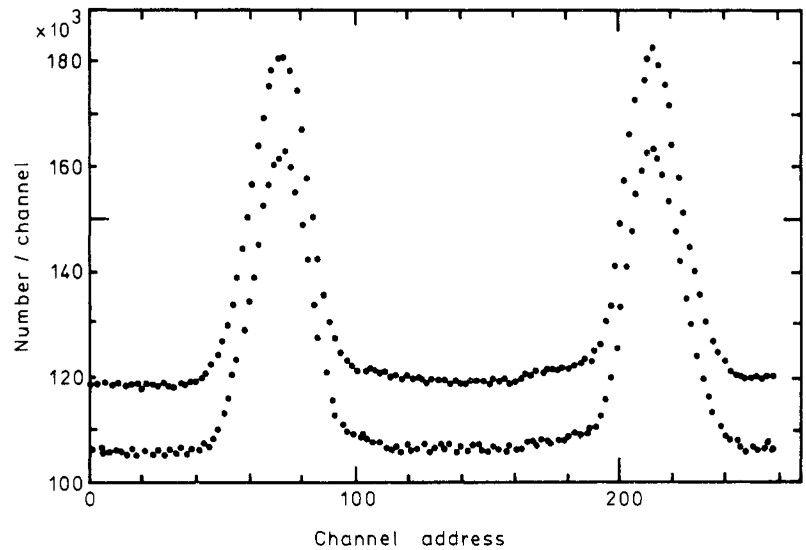

Figure 2. Typical superimposed spectra taken at 33·5 eV electron energy, the lower one, with quenching field on, and the upper one, without quenching field.

energy range considered here, the minimum time is about 50 ms. This suggests that ion trapping will be minimised if the electron beam is swept at a frequency in excess of 20 Hz. The frequency used in the present measurements was 390 Hz. It has been verified that the signal was not dependent on the sweep frequency, in the range 100–1000 Hz, nor on the residual gas pressure.

Ions ejected from the collector F are prevented from flying back to the crossing region by a suitable polarisation of the collector and the suppressing electrodes (D). The electron collector is usually given a positive bias voltage, relative to the crossing region, in order to hold the secondary electrons. However, this drains secondary ions towards the atomic beam. To solve this dilemma, use is made of the suppressing electrode (D), on which a positive voltage of 30 V is applied while the collector is biased to 25 V. In addition, a small negative voltage of 5 V is applied on the set of wires (W).

Typical working conditions in the present measurements were:

$I_a = 10^{-8}$ A
$I_e =$ from 10^{-5} A at 6·3 eV to 5×10^{-3} A at 1000 eV
$I_{2s} = 6\times10^{-10}$ A
$u = 4\times10^{2}$ cm s^{-1}
$K_2 = 1$ count/sweep
$K_2 - K_1 = 0{\cdot}1$ count/sweep.

A typical display of the multichannel analyser is shown in figure 2.

Table 1.

Centre of mass energy (eV)	$\sigma_{2s}-\sigma_{1s}$ (10^{-16} cm^2)	Standard error (%)	σ_{2s} (10^{-16} cm^2)
6·3	5·94	27	5·94
8·3	8·75	21	8·75
10·3	10·5	18	10·5
12·3	7·67	16	7·67
14·3	7·94	10	8·06
18·3	7·31	7·5	7·56
23·3	5·82	25	6·22
25·3	6·47	9·5	6·92
31·8	6·06	18	6·63
33·3	4·82	12	5·39
38·3	4·33	10	4·93
48·3	3·41	6·5	4·08
68·3	2·49	6·5	3·14
98·3	2·33	5·5	2·91
148·3	1·45	4	1·93
198·3	1·35	4·5	1·75
218·3	1·24	5·5	1·61
248·3	1·20	4	1·54
298·3	0·959	3	1·26
348·3	0·877	10	1·15
398·3	0·791	5	1·04
498·3	0·654	5·5	0·867
748·3	0·508	8	0·655
998·3	0·364	8	0·482

4. Results

The results are presented in table 1. The energies listed in the first column are the centre of mass energies, as obtained from the measurement of the acceleration voltages and corrected for contact potentials. The experimental data for the difference ($\sigma_{2s}-\sigma_{1s}$) of the electron impact ionisation cross sections of H(2s) and H(1s) together with the related statistical standard deviation are given in the two next columns. The last column contains the figures obtained for σ_{2s} when the Lotz formulae are used for σ_{1s} (Lotz 1966). The absolute accuracy of our data is believed to be better than $\pm 10\%$. This quotation takes into account the uncertainty of $\pm 5\%$ concerning the metastable fraction in the atomic beam.

Our results for σ_{2s} are shown in figure 3 for comparison with the experimental data by Koller (1969) and Dixon *et al* (1975) and with theoretical predictions: the Born-B and Born-exchange calculation of Prasad (1966), the Born-A results of B Piraux and C Joachain (1980, private communication) and the Bethe approximation calculated by Vriens and Bonsen (1968).

Below 100 eV, all experimental data are in mutual agreement and all the theoretical cross sections are much higher than the experimental ones, a situation similar to that of the ground-state cross section. It appears that theory is not yet in a position to give a

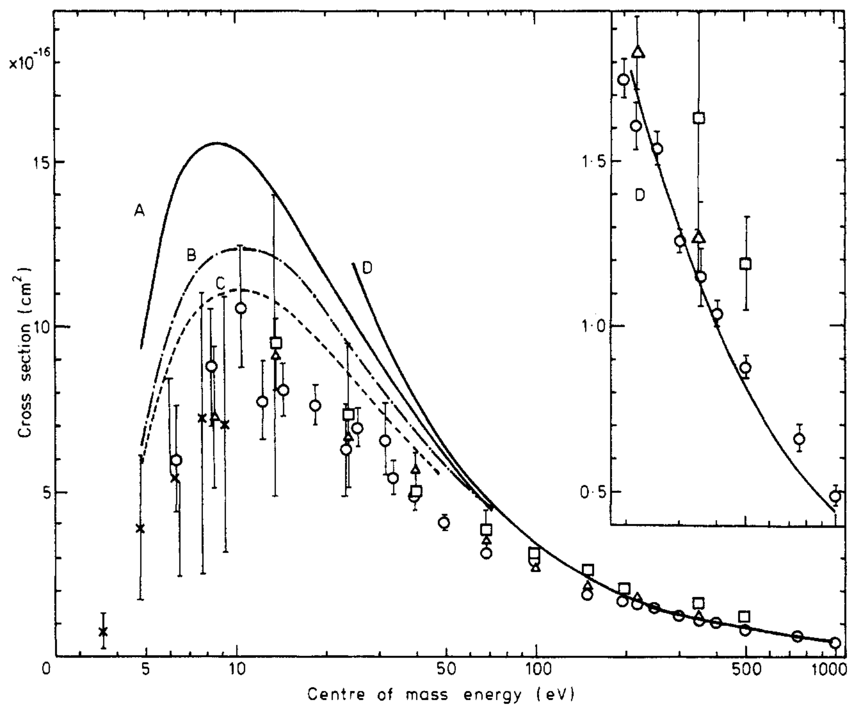

Figure 3. Cross section for ionisation of metastable hydrogen atoms as a function of centre of mass energy. Open circles are our results, open triangles and squares are the results of Dixon *et al* (1975) and crosses are those of Koller (1969). Curves are predictions of theoretical approximations: A, the Born-A of B Piraux and C Joachain (1980, private communication), B, the Born-B and C, the Born-exchange of Prasad (1966) and D, the Bethe calculation of Vriens and Bonsen (1968). In an expanded scale are shown high-energy experimental results compared with the Bethe approximation.

reliable description of the ionisation process. The fact that the Born-B and Born-exchange calculations produce a result closer to the experimental data than the Born-A approximation is even more confusing.

Above 100 eV, our results are systematically below those of Dixon *et al* (1975). This is presumably due to ion trapping effects in the measurements of Dixon *et al*, as was pointed out by these authors themselves in a later paper (Dixon *et al* 1976).

Above 200 eV, our data are in good accord with the Bethe formula.

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