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Collisions between electrons and H_2^+ ions III. Measurements of proton production cross sections at low energies

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Abstract. Inclined beams of electrons and H_2^+ ions have been used in measurements of cross sections for proton production with interaction energies between 3·45 and 31·5 eV. A source was used which produced the ions under clearly defined conditions. The cross section was $11{\cdot}6\,\pi a_0^2$ at 3·45 eV and decreased, with increasing energy, over the whole energy range. There is some evidence of structure between 10 and 20 eV which is not predicted by an extension of the theoretical work of Peek, and Peek and Green to lower interaction energies.

1. Introduction

Previous communications (Peart and Dolder 1971, 1972, hereafter called I and II, respectively) described measurements of cross sections for proton production (σ'_p) and dissociative excitation (σ_e) with an apparatus in which beams of electrons and H_2^+ ions intersected at right angles. A surprising result was the agreement at energies as low as 28 eV, between the measurements of σ_e and theoretical predictions derived from the Bethe–Born approximation by Peek (1967) and Peek and Green (1969). As it was impossible to extend these measurements to appreciably lower energies without a serious loss of accuracy, the technique of inclined beams has now been applied to collisions between electrons and H_2^+. It was then possible to measure σ'_p for interaction energies as low as 3·45 with a resolution of about 0·25 eV. It will be remembered (see II) that σ'_p is defined by $\sigma'_p = \sigma_e + \sigma_i$ where σ_e and σ_i respectively represent cross sections for dissociative excitation and ionization. Almost all of the results presented in this paper were obtained at energies below the ionization threshold (≈ 30 eV) so that, under these conditions, $\sigma'_p = \sigma_e$.

The technique of inclined electron–ion beams was introduced and described by Walton *et al* (1971). For very light ions it enables collisions to be observed at much lower energies, and with much better energy resolution, than can be attained in experiments in which beams intersect at right angles.

2. Apparatus and method

With the exception of the electron gun and its associated components, the apparatus was the same as that represented by figures 2 and 3 of I. The present experiment used a gun which has already been described by Walton *et al.* It produced a well collimated electron beam which intersected the ion beam at an angle of 20°. Protons formed by these collisions were deflected by the field of a magnet M to a particle detector D as illustrated by figure 2 of I.

The cross section for proton production (σ'_p) is related to the rate of formation of protons in electron–ion collisions (R_s) by,

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

These symbols, and the procedures used to deduce σ'_p from the measurements, have been explained in the earlier papers. The beam modulation technique used previously was needed to separate the signal R_s, from backgrounds R_B due primarily to protons formed by collisions between H_2^+ and residual gas. The following values were typical of these experiments; $R_s = 3\ s^{-1}$, $R_B = 8 \times 10^3\ s^{-1}$, $\Omega = 90\,\%$, $I = 3 \times 10^{-10}$ A, $J = 8 \times 10^{-6}$ A, $E_i = 20$ keV, $p = 5 \times 10^{-10}$ Torr.

3. Results and discussion

Table 1 summarizes the results and the estimates of systematic and random errors. The latter were expressed as 90 % confidence limits at each energy.

Table 1

Interaction energy (eV)	Cross section (πa_0^2)	Random error ($\pm$ %)	Systematic error ($\pm$ %)
3·45	11·6	20	10
5·0	10·4	13	10
5·9	10·2	8	10
7·0	9·89	16	10
7·8	9·11	5	10
8·5	9·02	6	10
8·7	8·68	10	10
9·45	8·45	6	10
10·0	7·99	10	10
10·6	7·23	10	10
11·4	7·12	11	10
13·0	6·99	9	10
14·5	6·40	6	10
16·0	5·70	12	10
17·7	5·14	12	10
19·5	5·02	10	10
21·0	5·04	8	10
24·4	4·87	10	10
31·5	4·26	9	10

In figure 1 these results are plotted as $\sigma'_p E$ against E (logarithmic scale) and they are compared with four theoretical predictions of the dissociative excitation cross section, σ_e. Two alternative sets of assumptions, which will be outlined below, were made in the theory and these led to cross sections which will be denoted by σ_e^+ and σ_e^*. Peek (private communication) has then averaged both results over vibrational populations

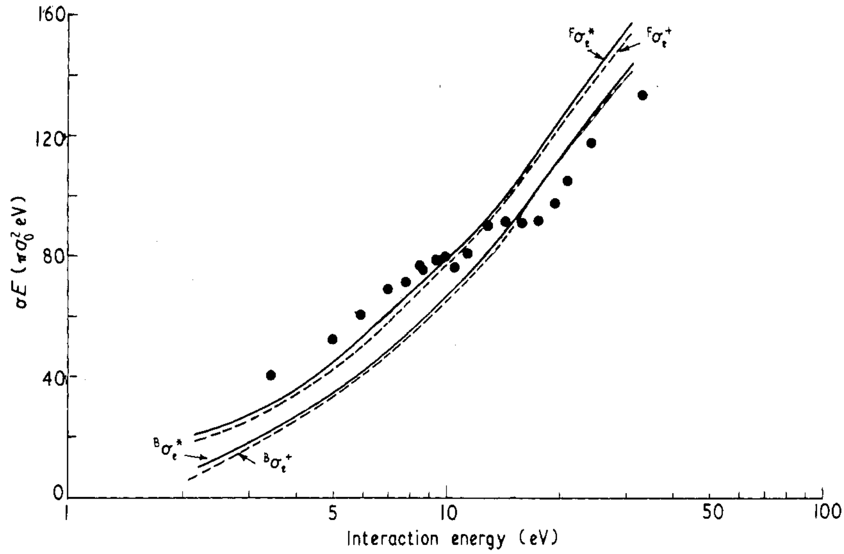

Figure 1. Measured proton production cross sections (σ_p') and four calculated excitation cross sections (σ_e) plotted as σE against the interaction energy, E (logarithmic scale). The superscripts which identify the theoretical curves are explained in the text.

deduced either from Franck–Condon factors (Villarejo 1968) or from measurements of the photodissociation of H_2^+ by von Busch and Dunn (1972). Consequently, there are four theoretical curves which are represented by ${}^{F}\sigma_e^+$, ${}^{F}\sigma_e^*$, ${}^{B}\sigma_e^+$ and ${}^{B}\sigma_e^*$ where the superscripts, F and B respectively denote the two vibrational populations. The importance of defining the vibrational population, and the precautions which were taken to design a suitable ion source, were discussed in our two previous papers.

These theoretical predictions both assume that excitation occurs only from the ($1s\sigma_g$–$2p\sigma_u$) and ($1s\sigma_g$–$2p\pi_u$) transitions. Since the latter contribution is not very sensitive to the assumed vibrational population, it could be calculated satisfactorily in a manner similar to that discussed by Peek (1967), who assumed 'classical limits' for the energies of inelastic transitions. This procedure may slightly over-estimate the cross section for the dissociation of high vibrational states of H_2^+ ($1s\sigma_g$) because it ignores the possibility that a small fraction of the H_2^+ ($2p\pi_u$) can be formed in a non-dissociative state. A significant modification of the published theory was, however, needed because the present paper is concerned with energies which are too low for the Bethe–Born approximation to be valid. Peek (private communication) therefore re-cast his published work in terms of Born's approximation to obtain the estimates of σ_e which are given here, and which are hitherto unpublished.

The differences between σ_e^+ and σ_e^* lie solely in the approximations made to evaluate contributions from the $2p\sigma_u$ state. The σ_e^* cross sections were obtained by assuming classical energy limits. The σ_e^+ cross sections, on the other hand, were given by a 'reflection approximation' which was discussed in this context by Peek and Green (1969) who suggested that it may be in error for the highest ($v \gtrsim 15$) vibrational states of H_2^+. They demonstrated that $\sigma_e^+ \leqslant \sigma_e^*$ and showed, by numerical example, that the correct Born cross sections are not bounded by these two approximations.

It can be seen from figure 1 that, at these energies, the experimental results do not indicate that any of the four theoretical estimates is to be preferred. The present theory cannot, however, be expected to be reliable at such low energies because, in addition to the limitations of Born's approximation, it is inevitable that coulomb distortion will become appreciable for slow electrons. Moreover, at low energies the higher vibrational states will make a larger relative contribution and, not only are there greater difficulties in calculating cross sections from these states, but there are inevitable uncertainties in their populations in the beams of H_2^+ produced in the laboratory.

A further hint of a limitation in the present theory is illustrated by the pronounced flattening of the experimental results which is seen for $10 < E(\mathrm{eV}) < 20$. The magnitudes of the random error prevent this evidence from being entirely conclusive, but it suggests that structure exists which is not found in the theoretical curves. This may simply arise from maxima in the dissociative cross sections of higher electronic states, or it may be partly due to autoionization structure which has been broadened by the vibrational distribution. It must also be remembered that the initial rotational excitation of H_2^+ has been ignored, and this may be significant at low energies.

4. Conclusions and future experiments

Several of the conclusions drawn from the first three papers of this series are summarized by figure 2. This shows measurements of σ_p' (paper I), σ_e (paper II) and the present results for σ_p' plotted as σE against E (logarithmic scale). Three theoretical comparisons are included which each assume a Franck–Condon population of vibrational states.

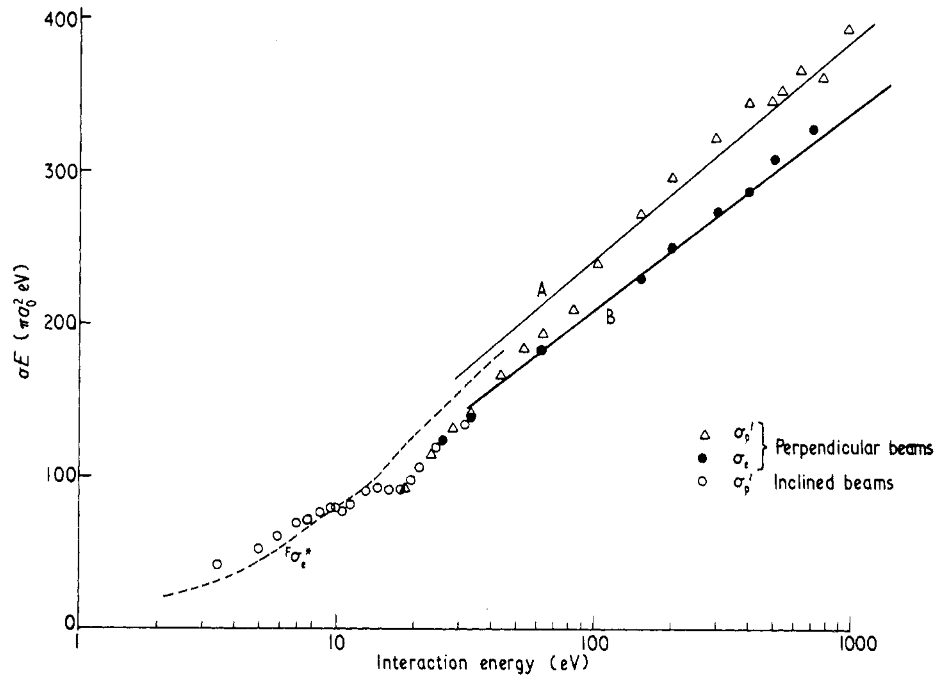

Figure 2. Comparisons of measured cross sections for proton production (σ_p') and dissociative excitation (σ_e) with relevant theoretical results, based on Bethe–Born theories, which are represented by the lines A and B, respectively. The broken line shows a Born approximation for σ_e which is explained in the text. Note, below the ionization threshold (≈ 30 eV) $\sigma_p' = \sigma_e$.

This distribution was chosen for the present illustration because results averaged in this way agree a little more closely with the measurements than when the von Busch–Dunn distribution is assumed. At high energies, $\sigma'_p E$ merges with theory (Peek 1967, curve A) only when $E \gtrsim 200$ eV. On the other hand, $\sigma_e E$ agrees with the relevant theory (curve B, see II) at much lower energies.

It was suggested in II that the contribution of dissociative ionization to σ'_p (note, $\sigma'_p = \sigma_e + \sigma_i$) only follows the functional dependence of the Bethe approximation when $E \gtrsim 200$ eV; this is plausible in view of the high threshold (≈ 30 eV) for ionization. In future experiments an attempt will be made to measure cross sections for dissociative ionization to test this suggestion.

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