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A MEASUREMENT OF THE CROSS SECTION FOR PROTON PRODUCTION IN COLLISIONS BETWEEN ELECTRONS AND H_2^+ IONS

by

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A B S T R A C T

A crossed beam method has been used to measure the cross-section for proton production in single collisions between H_2^+ ions and electrons at incident electron energies from 5·0 eV to 1000 eV. The measured cross section is the sum of the dissociative excitation cross section plus twice the dissociative ionization cross section. Its magnitude is in good agreement with other experimental data and with theory, but there is some disagreement over the rate of fall-off of the cross section at high energies. The present data at electron energies above 40 eV can be represented approximately by

$$Q = \frac{255}{E} \log \frac{E}{13 \cdot 8}$$

where Q is in units of πa_0^2, and in E in eV. The measured cross section was found to be independent of ion source pressure over a wide pressure range, and the implications of this with regard to the vibrational state population distribution of the H_2^+ ions are discussed.

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CONTENTS

1. INTRODUCTION

Dissociation of molecules by electron impact occurs commonly through dissociative excitation and dissociative ionization. Experimentally it is difficult to detect the two neutral fragments from dissociative excitation of a neutral molecule, and little quantitative work has been done on such processes (Massey and Burhop, 1952). However, this detection difficulty does not occur for dissociative excitation of an ionized molecule, because one of the fragments is charged. Dissociation of ionized molecules can conveniently be studied using an adaption of the crossed beams technique for measuring electron impact ionization cross sections of atomic ions (Dolder, Harrison, and Thonemann, 1961).

The simplest molecule is the hydrogen molecular ion, H_2^+. A study of its dissociation processes has the advantage that a more accurate and detailed theoretical description is possible than for any other molecule. The processes are also of practical interest in high temperature plasma devices where H_2^+ may be injected directly into a containment system or used as one step in producing excited atomic hydrogen for such injection.

Classical theory calculations following the methods of Gryzinski (1959, 1965) have been applied to electron impact dissociative excitation and ionization of H_2^+ by Alsmiller (1962). The Born approximation has been used to calculate the cross section for dissociative excitation from the $1s\sigma_g$ ground electronic state of H_2^+ to the $2p\sigma_u$ electronic state by Kerner (1953) and by Ivash (1958). Ivash has also used the Born-Oppenheimer approximation to estimate the effects of electron exchange. In each of these calculations the approximation of a fixed internuclear separation was used. Peek (1964) has used the Born approximation to calculate dissociative excitation cross sections from the $1s\sigma_g$ state to the $2p\sigma_u$, $2p\pi_u$, and $2s\sigma_g$ states with fixed internuclear separation; this work has recently been extended to give cross sections from each vibrational state of the $1s\sigma_g$ electronic state to the $2p\sigma_u$ and $2p\pi_u$ states, without the assumption of fixed internuclear separation (Peek, 1965). Peek (1967) has also made a Born approximation calculation for the high energy region, in which he uses a closure argument to take into account all possible final states.

An experimental study of proton production in collisions between electrons and H_2^+ ions has recently been made by Dunn and Van Zyl, (1967) using a crossed beam method. The present paper describes a measurement of the same cross section over a wider range of electron energies.

2. FORMATION AND DISSOCIATION OF H_2^+

Fig.1 is a simplified potential energy diagram for H_2, H_2^+, and H_2^{++}. For clarity, highly excited states of H_2^+ and all excited states of H_2 are omitted.

In the experiment described here, the parent H_2^+ ions were obtained from an oscillatory electron bombardment source. The processes yielding H_2^+ in an ion source of this type are direct ionization of ground state H_2 and, possibly, electronic excitation of H_2 followed by autoionization (Briglia and Rapp 1965, McGowan and Fineman 1965, Doolittle and Schoen 1965). Both processes take place within the Franck-Condon region of internuclear separation of the neutral molecule, and, because the excited electronic states of H_2^+ are effectively repulsive (see below), ionization to any state of H_2^+ other than the $1s\sigma_g$ ground state results in dissociation. Since the electron energy used was greater than 18 eV, all vibrational levels of the $1s\sigma_g$ ground electronic state of H_2^+ could be populated. Making the assumption that direct ionization is the only process involved, several investigators have derived vibrational state population distributions for H_2^+ formed by electron impact on H_2 (e.g. Wacks 1964, McGowan and Kerwin 1964, Dunn 1966). The results for ionization from the ground vibrational level of H_2 indicate that the fractional population of the H_2^+ levels (with vibrational quantum number v) is 0·09 for v = 0, and attains a maximum of 0·18 for v = 2; the total for all levels with v > 10 is less than 0·05. The vibrational states are metastable in a homonuclear molecule such as H_2^+, but the distribution of these states may possibly be modified by secondary collisions. It is thus apparent that there must be some uncertainty in the vibrational distribution of H_2^+ ions extracted from an electron bombardment source.

Dissociation of H_2^+ by electron impact can also be discussed with reference to Fig.1. Excited electronic states of H_2^+ shown are the $2p\sigma_u$, leading to $H^+ + H(n = 1)$ at infinite separation, and the eight states that lead to $H^+ + H(n = 2)$. Two excited states, $2p\pi_u$ and $3d\sigma_g$, have very shallow potential minima at rather large internuclear separation. It is possible for excited stable molecular ions to be formed in these states by electron impact excitation of H_2^+ initially in high vibrational levels of the $1s\sigma_g$ state (Bates and Holt, 1965), but sufficiently high vibrational levels are almost certainly sparsely populated. It is unlikely that higher electronic states have significant potential minima. Electronic excitation of

H_2^+ in this experiment can thus be assumed to result entirely in dissociation.

The processes leading to significant production of protons collisions between electrons and H_2^+ ions are

$$H_2^+ + e \rightarrow (H_2^+)^* + e \rightarrow H + H^+ + e \quad \text{(dissociative excitation)}$$

$$H_2^+ + e \rightarrow H_2^{++} + 2\,e \rightarrow 2H^+ + 2\,e \quad \text{(dissociative ionization)},$$

where the hydrogen atom may be excited.

If the rate of proton production is measured, the cross section obtained is

$$Q_p = Q_e + 2Q_i \ ,$$

where Q_e and Q_i are the dissociative excitation and dissociative ionization cross sections respectively.

The energy imparted to the fragments in the dissociation process is shared equally as kinetic energy. This energy depends on the initial vibrational state of the H_2^+ ion and on the electronic state to which it is excited. The maximum energy which can be imparted is about 50 eV, and this can occur when H_2^+ in the highest vibrational level is dissociatively ionized. An apparatus for measuring the rate of proton production should strictly be capable of collecting protons that share the maximum energy, although in practice this criterion can be lowered, because relatively few dissociations release energy approaching this maximum. A calculation by Dunn and Van Zyl (1967) indicates that less than 1% of the dissociations will give particles with energy above 10 eV.

3. APPARATUS

The experimental apparatus is similar to that described by Dolder, Harrison, and Thonemann (1961), and is shown schematically in Fig.2. A mass-analysed beam of H_2^+, with an energy of 20 keV, is collimated by a pair of apertures S1 and S2 (0·26 cm high by 0·10 cm wide). It then traverses a magnetically shielded collision region where it is intersected at right angles by an electron beam of variable energy. A slotted shutter can be scanned through the beams in this region in order to measure their height and vertical current density distribution. Upon leaving the collision region, protons resulting from dissociation are separated from the parent H_2^+ ions by the field of the beam separator magnet M2.

The electron and H_2^+ currents were typically 10^{-3} A and 10^{-6} A respectively. The H^+ current was typically 10^{-14} A and was measured with a vibrating reed electrometer. A background of about 10^{-12} A of proton current was also present. This was caused predominantly by dissociation of H_2^+ ions in collision with residual gas near the collision region, where the pressure was typically 2×10^{-9} torr.

The effects of contributions to the pressure from outgassing of the electron gun and collector were avoided by means of the coincidence and anti-coincidence beam pulsing scheme described by Dolder et al (1961). In the coincidence mode, the electrometer measured the average of the signal proton current plus the background current, whereas in the anti-coincidence mode, it measured the average background current alone. The difference between these average currents is the average signal current. In this experiment the pulsing period was 600 μsec, the ion and electron beam pulse lengths were 300 μsec and 280 μsec respectively. These times are very short compared with the time constant for pressure changes in the vacuum system, which was of the order of 0·1 sec. The mode was changed every 30 seconds, and each reading of signal current was the average of ten differences between coincidence and anti-coincidence currents.

The dissociation fragments separated with velocities dependent upon the energy imparted by the dissociation process, thereby causing the proton beam to diverge. The dimension that limited the maximum divergence acceptable by the apparatus was the pole gap (23 mm) of magnet M2. This limit corresponds to 35 eV shared by the fragments, assuming that the parent ion beam had an energy of 20 keV and was parallel.

The cross section for proton production expressed in terms of experimental parameters in the manner described by Harrison (1966) is

$$Q_p(E) = \frac{S_p}{I_d J_p} \frac{Vv}{(V^2 + v^2)^{\frac{1}{2}}} heF \; . \qquad \ldots (1)$$

where S_p is the mean pulsed signal current, I_d is the instantaneous value of the parent ion current when the beam is pulsed on, J_p is the mean pulsed electron current, V and v are the ion and electron velocities, h is the height of the ion beam in the interaction region, e is the electronic charge and F is a dimensionless factor that allows for non-uniformities in the beams.

Accurate values were obtained for all quantities in equation (1), and the cross section was evaluated absolutely.

The incident electron energy E is given by

$$E = E_e + (m_e/m_i)\, E_i \; ,$$

where E_i, m_i, E_e and m_e are the kinetic energies and masses of the ions and electrons respectively. Thus, for a parent H_2^+ ion energy of 20 keV, 5·44 eV must be added to each electron energy to give the true incident electron energy.

4. BACKGROUND EFFECTS

Harrison (1966) has described the mechanisms by which space charge of the beams can modulate the background currents and so produce spurious signals. These effects are usually investigated at electron beam energies below the threshold energy of the collision process being studied, but in this experiment it was not possible to obtain an electron beam with sufficiently low energy.

The electron beam did not produce a measurable background but a background current of about 10^{-12} A of protons was produced by the passage of the parent ion beam through the apparatus. This background was pressure dependent and it was necessary to ensure that the diffusion pumps maintained a steady pressure substantially free from sudden fluctuations. To investigate the effects of electron beam space charge upon this background, the cross section was measured as a function of ion beam energy, at several electron energies, and was found to be independent of energy in the range 10 to 20 keV. Over the same energy range the background, normalised to unit ion beam current, varied appreciably. Results for 150 eV electrons are shown in Fig.3. The invariance with energy of the measured cross section indicates that, when the H_2^+ ion energy is greater than 10 keV, the apparatus is capable of collecting virtually all the energetic protons from electron impact dissociation, and that there is negligible modulation of the background current by the electron beam space charge.

A further source of background can arise if photons or neutral particles formed when the parent ion beam strikes its collector C2 can reach the proton collector C3 and produce secondary electrons (Dolder et al, 1961). The focussing effect of electron space charge on the parent ion beam can produce a modulated component in this background. Initially, such a modulation, comprising about 10% of the signal, was observed. This background effect was virtually eliminated by avoiding the use of any surfaces and slits that could scatter the parent ions, and by altering the apparatus so that particles or photons from C2 could not readily enter C3.

5. TECHNIQUES AT HIGH ELECTRON ENERGIES

In the present experiment, particular care was necessary at electron energies much in excess of 100 eV. At such energies, electrons which strike surfaces in the vicinity of the interaction region have a high probability of producing one or more slow secondary electrons, some of which may pass through the primary ion beam. In contrast with previous electron-ion collision cross-sections studied with this apparatus, the present cross-section is large for electrons of a few eV; thus a small fraction of slow secondaries in the electron beam would cause the apparent cross-section to be significantly larger than its true value.

In order to study this effect, the electron gun configuration was altered when data was to be taken at high electron energies. Fig.4a shows the original configuration, used for the low energy region of the cross section; here the electron path length was kept as short as possible in order to maximise the usable electron beam current, and thus the signal to background ratio. The high energy configuration is shown in Fig.4b. The electron beam path length was increased, and a secondary electron suppression electrode was added in the form of a rectangular box surrounding the interaction region. The apertures in this box were made sufficiently large so that both beams would pass cleanly through it. By putting a negative potential of a few tens of volts on this box, slow secondary electrons produced at either the anode of the electron gun or the defining aperture in front of the electron collector were suppressed.

Such suppression was indeed found to be necessary at high electron energies. At 1000 eV, for example, proper secondary electron suppression reduced the apparent cross section by about 20%.

A second spurious effect was discovered at high electron energies, and was attributed to the electron beam outgassing surfaces in its collector. The double beam pulsing scheme described in section 3 is effective for avoiding an increase in the background current of protons due to electron outgassing only if gas molecules knocked off of surfaces have a chance to become randomized; that is, if they undergo a number of collisions with surfaces or other gas molecules before they pass through the ion beam. A high flux of energetic electrons striking the back of the collector can knock off gas molecules, some of which would stream back through the collector entrance and through the ion beam without being randomized. Their transit time is short compared with the pulsing period, and hence the background would be slightly larger when the electrons were on than when they were off, giving a spuriously large cross section. This effect would be particularly significant at high electron energies for three reasons: the cross section, and hence the signal to background ratio, is becoming smaller; high energy electrons are more efficient at outgassing surfaces; and the electron beam was more sharply focussed, producing a greater flux of electrons over the area of collection.

This effect could be avoided by placing a negative potential on the front segment of the electron collector. This served to defocus the electron beam and so reduced both the flux of electrons to any given area of the collector and the average solid angle of the ion beam as viewed from where the electrons struck the collector. The apparent cross section (at electron energies greater than 500 eV) as a function of this potential decreased up to a potential equal to 30% of the electron energy, and remained constant for potentials greater than this. At 1000 eV the reduction was about 5%.

6. DEPENDENCE ON ION SOURCE CONDITIONS

Peek (1965, 1966) predicts that the cross section for dissociative excitation of H_2^+ by electron impact is strongly dependent on the initial vibrational state of the H_2^+ ion. There is evidence (Dunn 1964) that the vibrational population of H_2^+ ions extracted from an electron bombardment source is a function of ion source pressure. It was therefore an essential first step in this experiment to see if any change in the measured cross section could be observed when the source parameters were altered.

Fig.5 shows the effect of changing the ion source pressure. No significant change in the measured cross section was observed over a range of 3 to 130 millitorr. In practice the pressure was maintained at about 8 millitorr. Implications of the invariance of the cross section with ion source pressure are discussed in section 9.

No significant change in the measured cross section was observed when the electron accelerating potential in the ion source was varied from 50 to 200 V. The potential normally used in the experiment was 100 V.

7. DETERMINATION OF THE CROSS SECTION

For each electron beam energy, the signal current of protons as a function of electron beam current was measured for a number of electron beam currents from zero to a maximum value limited by the space-charge divergence of the electron beam. This divergence was monitored by measuring the current to the defining plate D (Fig.4). The current to plate D was normally a few per cent of the total electron beam current except at the lowest electron energies used, where it was allowed to rise to a maximum of ten per cent. This current, corrected for loss of secondary electrons, was added to the electron collector current to give the total electron current J_p.

At each energy the mean value of $S_p/I_d J_p$ was determined from the least squares slope of S_p/I_d plotted against J_p. The factor F and ion beam height h were determined in the manner described by Harrison (1966). The value of F was always between 0·97 and 1·00. The mean electron energy was determined to an accuracy of ± 0·3 eV by passing a Ne^{+} beam through the apparatus and comparing the appearance potential of Ne^{++} with the spectroscopic value of the ionization energy. The energy distribution was determined from retarding potential measurements and the full width at half height was found to vary between 0·5 and 1·5 eV. At incident electron energies above 13 eV, an H_2^+ ion energy of 20 keV was used. To obtain incident electron energies below 13 eV, the ion energy was reduced to 10 keV, when its contribution to the incident electron energy was only 2·7 eV. Cross sections measured at 13 eV using the two different ion energies were in good agreement, which provided additional evidence for complete ion collection.

8. RESULTS

The measured cross section is shown as a function of incident electron energy by the circles in Fig.6. Error bars indicate the random errors at each electron energy, and corresponds to the 90% confidence limits of $S_p/I_d J_p$. The absolute magnitude may be subject to additional systematic errors due to uncertainties in the measurement of the quantities given in Table 1. These systematic errors have been added linearly and are estimated to be less than + 7% and - 9½%. At electron energies below 10 eV, a further uncertainty due to the velocity distribution of the electrons becomes significant. The cross section data together with these errors are listed in Table 2.

9. DISCUSSION

It is possible that the present experimental data indicate some structure in the cross section at energies up to 15 eV, but the magnitude of the confidence limits and the spread in electron velocities do not permit a definite identification of maxima. However, if a smooth curve (M in Fig.6) is drawn through the points, there is indication that a new reaction process becomes significant at about 13 eV, probably dissociative excitation to the $2p\pi_u$ state. There is also some slight indication that a contribution from dissociative ionization appears in the region of 30 eV. It is clear that many of the parent ions were vibrationally excited because a considerable yield of protons was still present at incident electron energies down to the dissociation threshold energy of the $v = 5$ vibrational state.

The curve T1 in Fig.6 is a calculation of the cross section for proton production given by

$$Q_p = \sum_v p_v \left[Q_v(2p\sigma_u) + Q_v(2p\pi_u) \right] + Q(2s\sigma_g) + 2Q(ION)$$

where the Frank Condon factors P_v for ionization from the lowest vibrational level of $H_2(1\,^1\Sigma_g^+)$ to the v^{th} vibrationally excited level of ground state H_2^+ are taken from Dunn (1966), the excitation cross sections $Q_v(2p\pi_u)$ and $Q_v(2p\sigma_u)$ for each vibrational level, v, are taken from Peek (1966), and the excitation cross section $Q(2s\sigma_g)$ and ionization cross section Q(ION), both at a fixed internuclear separation of $2a_o$, are taken from Peek (1964) and Alsmiller (1962) respectively. Curve T2 represents a high energy calculation by Peek (1967) in which an attempt has been made to include in the cross section the effects of excitation to all possible final states. Peek has calculated values for $Q(2p\sigma_u)$, $Q(2p\pi_u)$ and $Q(\Sigma'')$, where $Q(\Sigma'')$ is the cross section for transitions to all excited states other than the $2p\sigma_u$, and is obtained by means of a closure argument. Since the experimental cross section includes a double contribution from ionization, curve T2 has been obtained by taking

$$Q_{T2} = \sum_{v} Pv \left[Q_v(2p\sigma_u) + 2Q_v(\Sigma'') - Q_v(2p\pi_u) \right]$$

This assumes that contributions from states other than $2p\sigma_u$, $2p\pi_u$, and ionization are negligible.

Also shown in Fig.6 are the data of Dunn and Van Zyl (1967). These data agree well with the present results at high energies; at intermediate energies, however, the two experiments tend to diverge, and at the lowest energy there is some considerable disagreement. The source of the disagreement at intermediate energies seems to be the slight 'hump' or inflection point in the data of Dunn and Van Zyl, centred around 50 eV. (However, in a preliminary report by Dunn, Van Zyl and Zare (1966), the data presented do not show this inflection point, and in fact agree extremely well over the intermediate energy range with the data of the present experiment.) It should be noted that for electron energies above 15 eV, the two experiments differ nowhere by more than 10%.

The Born approximation predicts that at high electron energies, the functional form of the cross section should approach

$$Q = \frac{A}{E} \log \frac{E}{B}$$

In order to test this prediction, QE was plotted as a function of log E, and the results are shown in Fig.7. The linear relationship between these variables at energies above 40 eV indicate that the prediction is indeed satisfied. The deviation from linearity below 40 eV is probably caused by the Coulomb attraction between ion and electron, which tends to increase the cross section, particularly at low energies.

Also shown in this figure is the high energy Born approximation calculation of Peek (curve T2 in Fig.6). When plotted in this manner, the calculation shows serious disagreement with the experimental results. The best straight-line fit to the experimental data above 40 eV gives

$$Q = \frac{255}{E} \log \frac{E}{13 \cdot 8}$$

while the theory predicts

$$Q = \frac{156}{E} \log \frac{E}{1 \cdot 69}$$

The data of Dunn and Van Zyl, also shown in Fig.7 seem to show a linear relationship between QE and log E down to 15 eV. This is somewhat surprising, since one might expect a Coulomb increase in the cross section at higher energies than this. The best straight-line fit to their data at all energies above 15 eV gives

$$Q = \frac{216}{E} \log \frac{E}{6 \cdot 97}$$

However, it should be noted that the slope derived from their data points above 200 eV agrees extremely well with the slope derived from the data of the present experiment.

The good agreement between the two experiments is particularly significant, in view of the fact that there were extensive differences in experimental methods and apparatus, and that the theory predicts a strong dependence of the cross section upon the vibrational state population distribution of the H_2^+ ions.

Dunn and Van Zyl operated their ion source at a pressure of 1 millitorr, and claim that at this pressure no significant vibrational de-excitation was caused by collisions between H_2^+ ions and

H_2 molecules in their source. They also present data indicating an invariant cross section for ion source pressures between 1 and 20 millitorr. In the present experiment, the normal operating pressure in the ion source was 8 millitorr, where it might be expected that some de-exciting collisions would occur; but it was shown that a change in this pressure over the range from 3 to 130 millitorr produced no significant change in the cross section measured at 150 eV. Evidence for collisions between H_2^+ ions and gas molecules in this pressure range was found by measuring the yield of H_3^+ ions from the source. H_3^+ ions are usually formed by the process,

$$H_2^+ + H_2 \rightarrow H_3^+ + H \ .$$

The cross section for H_3^+ production, measured by Reuben and Friedman (1962), is about 4×10^{-16} cm^2 at an average ion energy of 8 eV and this can be regarded as typical for the conditions in the present ion source. At an ion source pressure of 130 millitorr, the yield of H_3^+ ions was about 11 times the yield of H_2^+ ions; thus it is clear, even allowing for the possibility of different transmission characteristics of the H_3^+ and H_2^+ ion beams through the mass spectrometer, that an appreciable number of collisions occurred. Bauer and Cummings (1962) have calculated vibrational de-excitation rates for $N_2 - N_2$ collisions; their model for such collisions predicts that the most probable transitions are those for which $\Delta v = 1$. Applying this assumption to $H_2^+ - H_2$ collisions, and assuming the rate of vibrational de-excitation of each level in such collisions to be the same as that for H_3^+ production, Peek's calculated cross sections predict a reduction of about 10% in the measured cross section when the ion source pressure is varied from 3 to 130 millitorr. In the experiment, no such reduction was observed.

There are two possible explanations for this invariance of measured cross section with ion source pressure. The first is that the rate of vibrational de-excitation in $H_2^+ - H_2$ collisions is in fact much smaller than that for H_3^+ formation. If the rate of vibrational de-excitation were ten times smaller, the variation in the measured cross section caused by varying the ion source pressure would not have been detected. Such a small de-excitation cross section would explain the invariance of cross section with ion source pressures observed both here and by Dunn and Van Zyl, but is in contradiction to the interpretation of the pressure dependence of the measured photodissociation cross section of H_2^+ made by Dunn (1964). However, in Dunn's experiment the maximum photon energy was only sufficient to dissociate H_2^+ ions in the $v \geqslant 5$ levels, so that the degree of correspondence between the two experiments is not clear.

The other possible explanation is that the proton production cross section is in fact less sensitive to vibrational state distribution than is predicted. Peek (1965) makes comment that his cross sections for high vibrational states may be unreliable, but makes no prediction about the magnitude of this uncertainty.

At present, it is not possible to determine which explanation for the observed invariance of cross section with ion source pressure is correct. Vibrational de-excitation cross sections for $H_2^+ - H_2$ collisions are not known, either experimentally or theoretically, and the effect upon vibrational state sensitivity of certain approximations in the calculations of Peek have not yet been evaluated.

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TABLE 1

SOURCE OF POSSIBLE ERROR		MAXIMUM SYSTEMATIC ERROR IN CROSS SECTION
THE MEASUREMENT OF	S_p	± 2·5%
	I_d	+ 0·2%, - 1·2%
	J_p	+ 1·25%, - 2·25%
	V	+ 0%, - 0·1%
	v	± 0%*
	h	± 0·4%
	F	± 0·5%
POSSIBLE MODULATED COMPONENT OF BACKGROUND		± 2%
UNCERTAINTY IN ANGLE OF BEAM INTERSECTION		+ 0%, - 0·5%
TOTAL		+ 6·85%, - 9·45%

*ABOVE 20 eV ELECTRON ENERGY

TABLE 2

Mean Incident Electron Energy† (eV)	Qp (πa_0^2)	Random Error* (±%)	Maximum Systematic Error (%)
5·0	6·08	24	+ 17, - 19½
7·0	6·82	11	+ 10, - 12½
9·0	5·93	9	+ 8½, - 11
11·0	5·93	5	+ 8, - 10½
13·7	4·94	9	+ 8½, - 11
15·7	4·91	8	+ 8, - 10½
18·7	4·95	5	+ 7½, - 10
21·2	4·42	6	+ 7, - 9½
23·7	4·37	5	+ 7, - 9½
28·7	4·34	4	+ 7, - 9½
33·7	3·78	6	+ 7, - 9½
43·7	3·35	4	+ 7, - 9½
53·7	3·02	3	+ 7, - 9½
63·7	2·67	4	+ 7, - 9½
83·7	2·36	2	+ 7, - 9½
103·7	2·17	4	+ 7, - 9½
128·7	1·91	6	+ 7, - 9½
153·7	1·77	3	+ 7, - 9½
203·7	1·45	3	+ 7, - 9½
253·7	1·25	3	+ 7, - 9½
303·7	1·10	3	+ 7, - 9½
403·7	0·91	2	+ 7, - 9½
503·7	0·80	5	+ 7, - 9½
603·7	0·71	3	+ 7, - 9½
753·7	0·58	4	+ 7, - 9½
1003·7	0·47	4	+ 7, - 9½

† ± 0·3 eV *90% CONFIDENCE LIMITS

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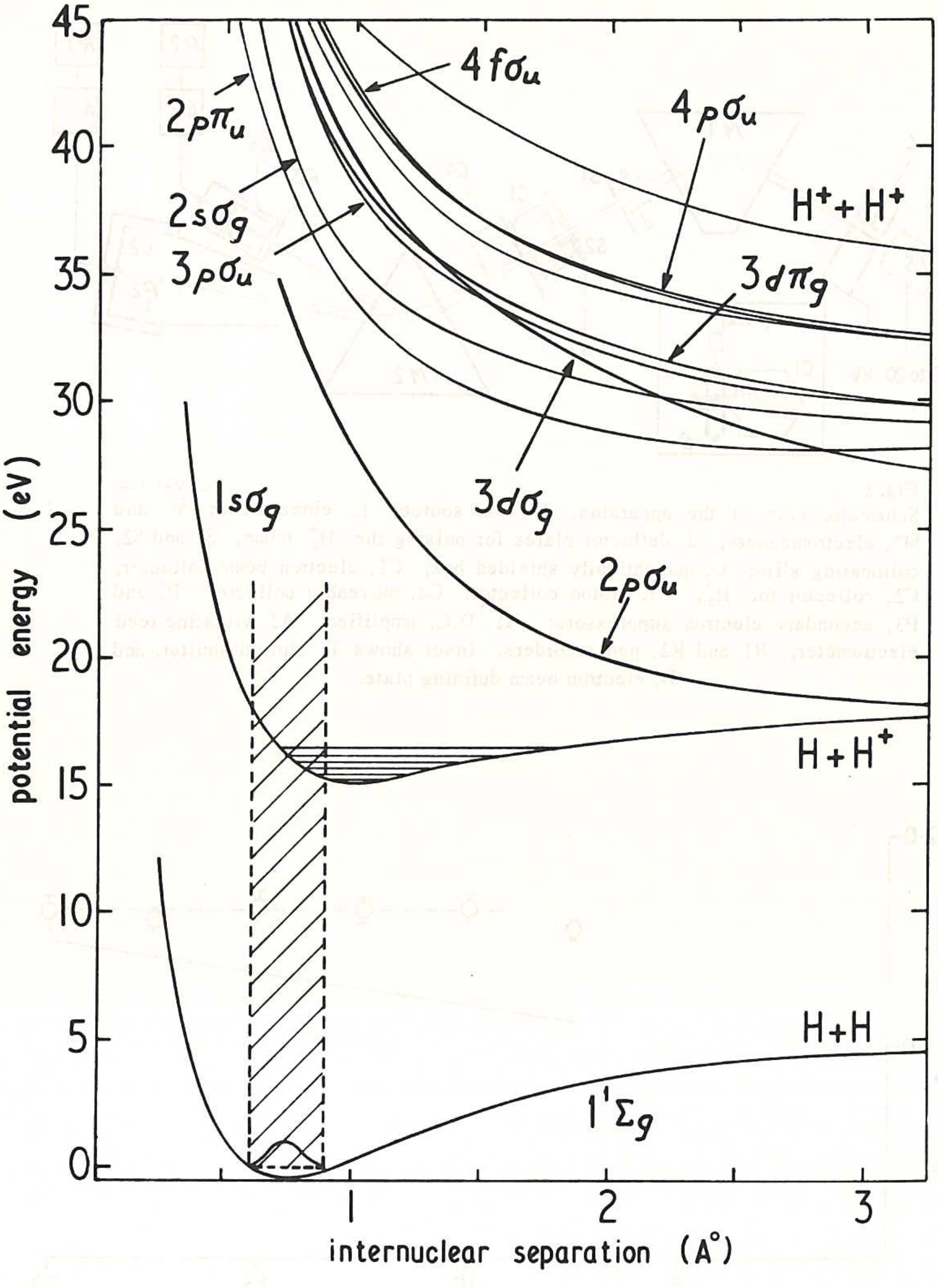


Fig. 1 (CLM-P 149)

Potential energy diagram for H_2, H_2^+ and H_2^{++}. The Franck-Condon Region for transitions from the ground vibrational state of H_2 is shown shaded.

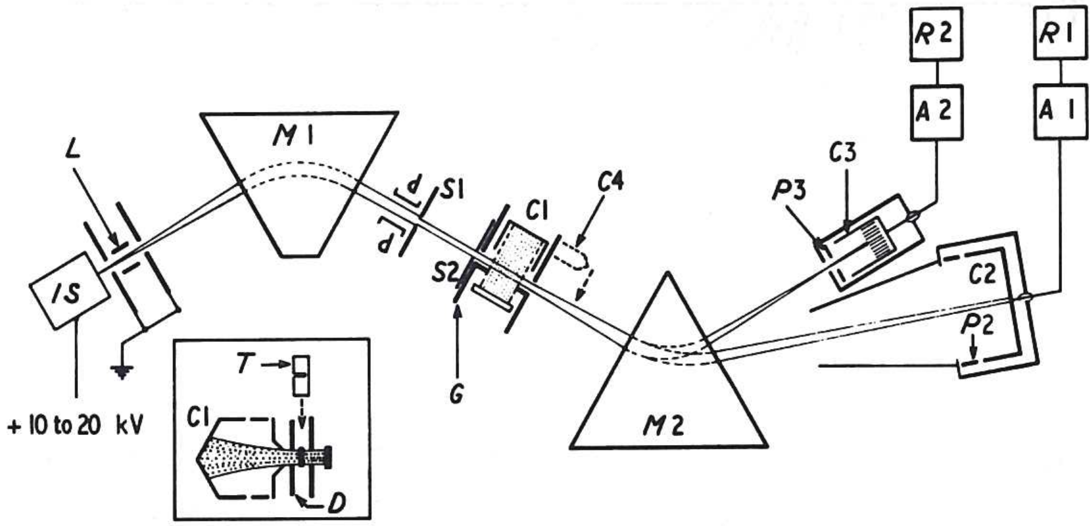


Fig. 2 (CLM-P 149)

Schematic view of the apparatus. IS, ion source; L, einzel lens; M1 and M2, electromagnets; d, deflector plates for pulsing the H_2^+ beam; S1 and S2, collimating slits; G, magnetically shielded box; C1, electron beam collector; C2, collector for H_2^+; C3, proton collector; C4, moveable collector; P2 and P3, secondary electron suppressors; A1, D.C. amplifier; A2, vibrating reed electrometer; R1 and R2, pen recorders. Inset shows T, slotted shutter, and D, electron beam defining plate.

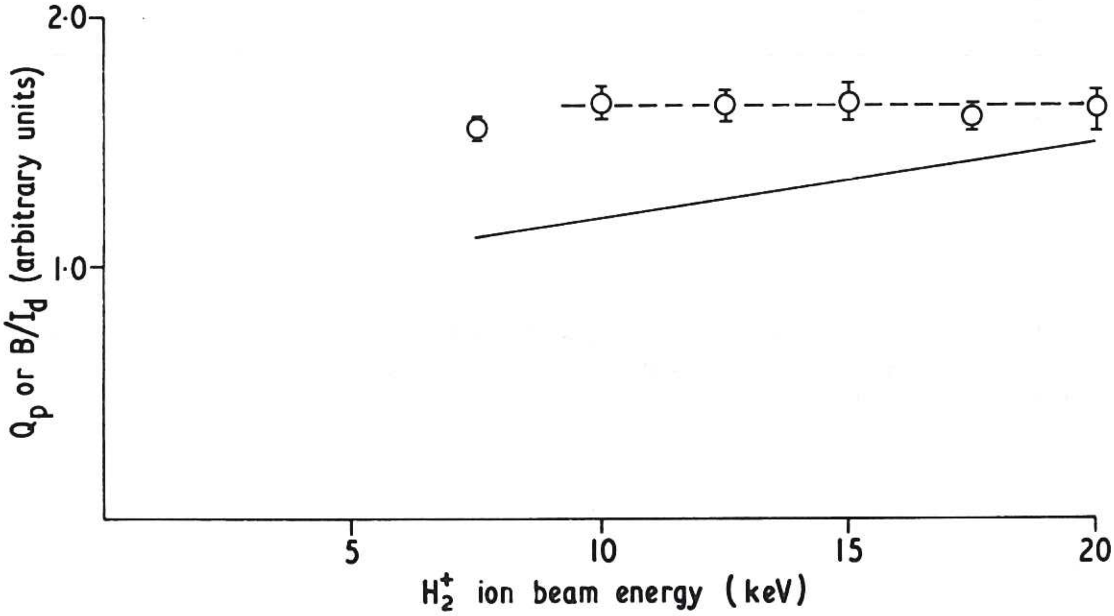
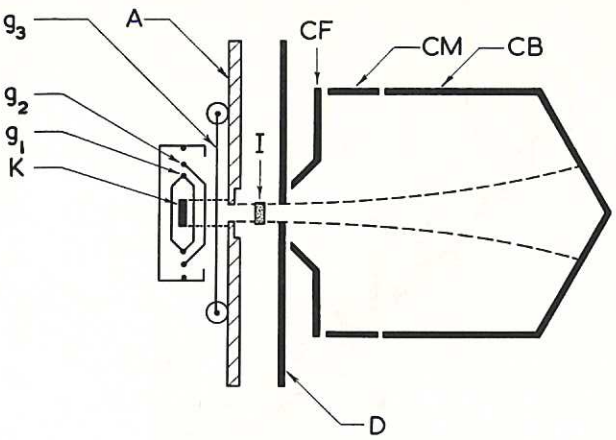


Fig. 3 (CLM-P 149)

Variation of measured cross section with H_2^+ ion energy at incident electron energy of 150 eV. 90% confidence limits are indicated by brackets. The background, normalised to unit H_2^+ ion current, is shown by a solid line.



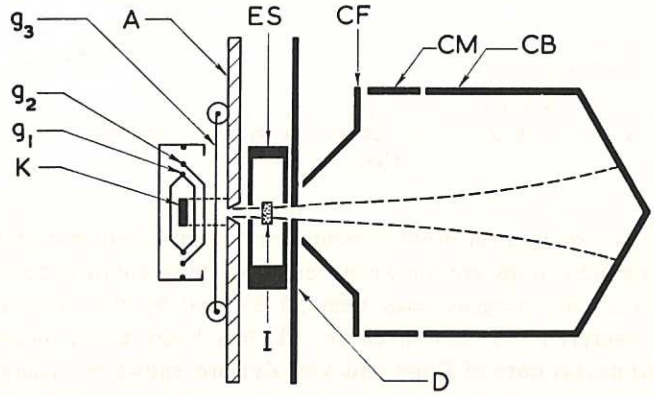


Fig. 4 (CLM-P 149)
Schematic view of the electron gun and collector configurations used for low energies (a) and high energies (b). K, cathode; g_1, control grid; g_2 and g_3, accelerating and focussing grids; A, anode; I, ion beam; ES, secondary electron suppressor electrode; D, defining plate; CF, CM, CB, front, middle, and back collector segments.

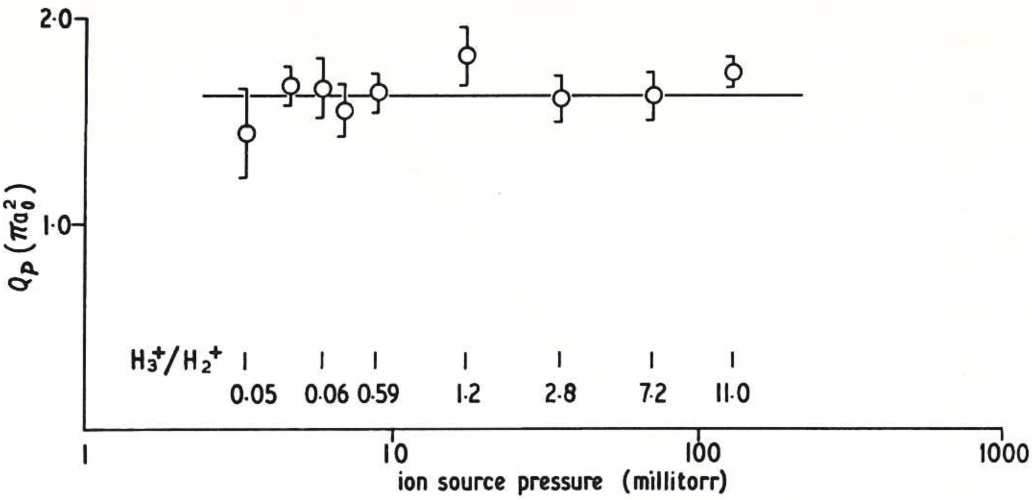


Fig. 5 (CLM-P 149)
Variation of measured cross section with ion source pressure at an incident electron energy of 150 eV. 90% confidence limits are indicated by brackets. The ratios of the yields of H_3^+ and H_2^+ from the ion source are also shown.

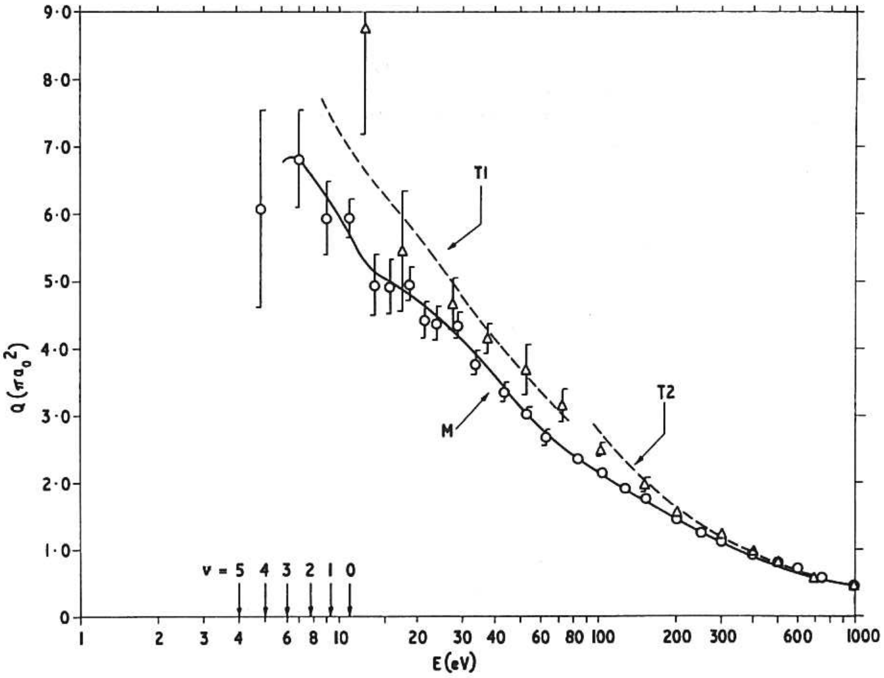


Fig. 6 (CLM-P 149)

Variation of the cross section for proton production with incident electron energy. The present experimental data are shown by circles; 90% confidence limits are indicated by brackets at energies less than 50 eV and by the diameter of the circles at higher energies. A smooth curve M has been drawn through these points. The experimental data of Dunn and Van Zyl are shown by triangles; the brackets represent standard deviations, which are equivalent to confidence limits of about 65%. Curves T1 and T2 are derived from calculations by Peek as explained in the text. The threshold energies for dissociation of the first six vibrational levels of H_2^+ are indicated.

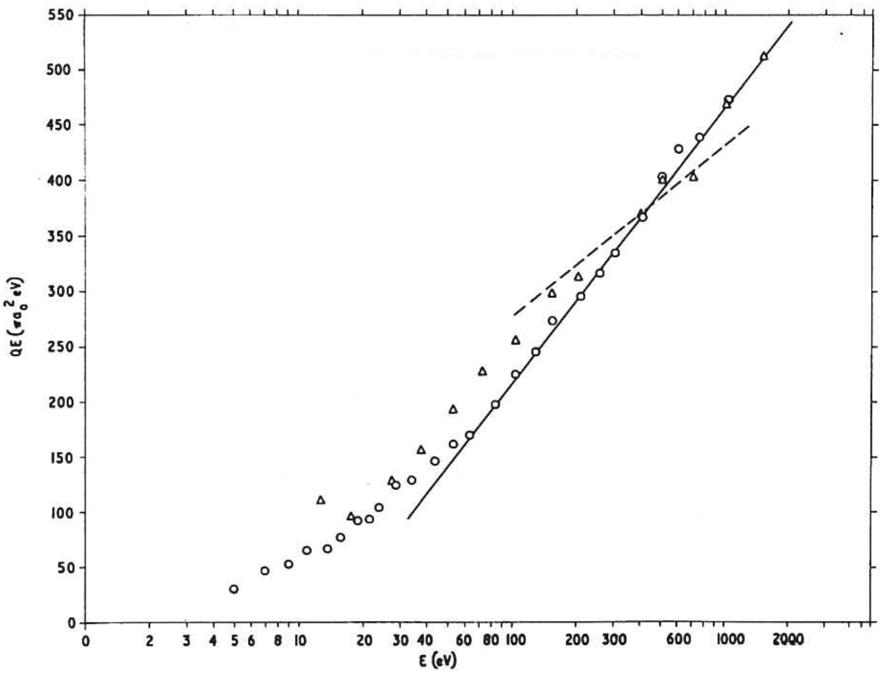


Fig. 7 (CLM-P 149)

Experimental data and theoretical calculations, with QE plotted as a function of log E. The results of the present experiment are shown by circles, and the results of Dunn and Van Zyl by triangles. A solid line has been drawn through the linear region of the present data. The dotted line is a high-energy Born approximation calculation by Peek and corresponds to curve T2 in Fig.6.