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Report

THE MEASUREMENT OF THE EFFICIENCY OF A HELIUM GAS CELL FOR THE CONVERSION OF A BEAM OF ENERGETIC ATOMIC HYDROGEN INTO A PROTON BEAM

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THE MEASUREMENT OF THE EFFICIENCY OF A HELIUM GAS CELL FOR THE CONVERSION OF A BEAM OF ENERGETIC ATOMIC HYDROGEN INTO A PROTON BEAM

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ABSTRACT

A proton beam was sent through the stripping cell with various pressures of helium in the stripping cell, and the fluxes of protons and atomic hydrogen emerging from the cell were measured. From this measurement values for the stripping cross section σ_{01}, the recombination cross section σ_{10} and the scattering cross section σ_S were deduced, which were in reasonable agreement with previous measurements. The efficiency of the stripping cell was calculated from these cross sections.

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1. INTRODUCTION

Neutral particle detectors have been used both in this laboratory[1,2] and elsewhere[3] to measure the flux and energy distribution of neutral hydrogen particles, produced by charge exchange, emerging from a heated plasma, and so to determine the density and ion energy distribution of the plasma. These detectors usually use a gas stripping cell to ionize the energetic neutral particles and form a proton beam, and by analysing this proton beam the energy spectrum of the incident neutral particle beam can be deduced, provided the conversion efficiency of the gas stripping cell is known over the range of energies analysed.

It is assumed that only three cross sections are of importance in determining the conversion efficiency of the stripping cell. These are the ionization cross section for atomic hydrogen σ_{01}, the recombination cross section for protons to atomic hydrogen σ_{10}, and the scattering cross section σ_s, which is assumed to be the same for H^o and H^+. Values of σ_{01} and σ_{10} are available from published papers[4,5,6] for a limited energy range. As has been discussed by Amdur and Mason[7], it is not, in general, possible to represent the results of scattering in terms of a single cross section σ_s. If, as is done here, the scattering is expressed in terms of such a cross section, then the value to be ascribed to this cross section will be different for different geometries. The value of σ_s for a particular geometry is difficult to calculate.

Since the cross section data is incomplete and the effect of scattering difficult to estimate, it is necessary to calibrate the apparatus using particle beams of known energy and intensity. We have used a monoenergetic proton beam from an RF ion source; by measuring the variation of the ratio of H^o to H^+ which emerges after passage through the stripping cell for different gas pressures it is possible to deduce values of σ_{01}, σ_{10}, and σ_s. It was found that σ_{01} and σ_{10} agreed well with earlier measurements and that the energy variation of σ_s is as previously measured. Thus the experiment confirms that these three cross sections describe the behaviour of the stripping cell with reasonable accuracy. The efficiency for the conversion of an incident beam of atomic hydrogen into a proton beam is given by an expression involving these three cross sections. Curves for the variation of this calculated efficiency with beam energy and with gas pressure in the stripping cell are obtained from the cross sections.

2. CALCULATION INVOLVING CROSS SECTIONS

The stripping cell, a sketch of which is given in Fig.1., consists of a long thin cylinder. The stripping gas was leaked in at a point roughly half way along, where the pressure was measured, and pumped away at each end. The pressure of this flowing gas was assumed to vary linearly from the point where it was admitted to zero at the ends where it was rapidly pumped away. The beam of protons and/or atomic hydrogen passed along the axis of the tube.

Writing q – Flux of protons (particles/cm^2/sec),

r – Flux of atomic hydrogen (particles/cm^2/sec),

n – Stripping gas density (particles/cm^3),

p – Stripping gas pressure at point of entry to cell (Torr),

x – Distance measured from entrance of stripping cell (cm),

σ_{01}, σ_{10}, σ_s – Cross sections (cm^2).

Then the spatial variations of the fluxes of protons and atomic hydrogen are given by the equations

$$\frac{dq}{dx} = r\,n\,\sigma_{01} - q\,n\,\sigma_{10} - q\,n\,\sigma_s \qquad \ldots (1)$$

$$\frac{dr}{dx} = -r\,n\,\sigma_{01} + q\,n\,\sigma_{10} - r\,n\,\sigma_s \qquad \ldots (2)$$

Writing
$$dh = n\,dx$$
$$h = \int_0^x n(x')\,dx'.$$

Eqs. (1) and (2) become

$$\frac{dq}{dh} = r\,\sigma_{01} - q\,\sigma_{10} - q\,\sigma_s \qquad \ldots (1)'$$

$$\frac{dr}{dh} = -r\sigma_{01} + q\,\sigma_{10} - r\,\sigma_s \qquad \ldots (2)'$$

Solving these equations

$$q = \exp(-\sigma_s h)\left\{A + B\,\exp(-|\sigma_{01} + \sigma_{10}|h)\right\},$$

$$r = \exp(-\sigma_s h)\left\{A\,\frac{\sigma_{10}}{\sigma_{01}} - B\,\exp(-|\sigma_{01} + \sigma_{10}|h)\right\},$$

with constants A and B to be determined by the boundary conditions.

Writing q_1 and r_1 for the values of q and r on leaving the stripping cell and

$$h_1 = \int_0^\ell n(x')\,dx',$$

and assuming a linear variation of $n(x)$ with x,

$$h_1 = \frac{\ell[n(x)]\ max}{2} .$$

but $$[n(x)]_{max} = C_1 p$$

where $$C_1 = \frac{\rho_{Hg}.g.10^{-4}}{kT} ,$$

ρ_{Hg} = Density of mercury (gm/cm²)

g = Acceleration due to gravity (cm/sec²)

k = Boltzmann's Constant (erg/°k)

T = Absolute temperature (°k)

p = Gas pressure (Torr)

and for $T = 25^{o}C$, $$C_1 = 3.243 \times 10^{13}$$

$$\therefore\ h_1 = \frac{\ell C_1}{2} p .$$

Starting with a proton beam

$$h = 0, \quad q = q_o, \quad r = 0$$

$$q_1 = q_o \frac{1}{\sigma_{01} + \sigma_{10}} \exp(-\tfrac{1}{2}\ell C_1 p\ \sigma_S) \left\{\sigma_{01} + \sigma_{10} \exp(-\tfrac{1}{2}\ell C_1 p|\sigma_{01} + \sigma_{10}|)\right\} \quad \ldots (3)$$

$$r_1 = q_o \frac{\sigma_{10}}{\sigma_{01} + \sigma_{10}} \exp(-\tfrac{1}{2}\ell C_1 p\sigma_S) \left\{1 - \exp(-\tfrac{1}{2}\ell C_1 p|\sigma_{01} + \sigma_{10}|)\right\} \quad \ldots (4)$$

$$\frac{r_1}{q_1} = \frac{\sigma_{10}}{\sigma_{01}} \quad \frac{1 - \exp(-\tfrac{1}{2}\ell C_1 p|\sigma_{01} + \sigma_{10}|)}{1 + \frac{\sigma_{10}}{\sigma_{01}} \exp(-\tfrac{1}{2}\ell C_1 p|\sigma_{01} + \sigma_{10}|)} \quad \ldots (5)$$

Starting with an atomic hydrogen beam

$$h = 0, \quad q = 0, \quad r = r_o$$

Efficiency of stripping cell

$$= \frac{q_1}{r_o} = \frac{\sigma_{01}}{\sigma_{01} + \sigma_{10}} \exp(-\tfrac{1}{2}\ell C_1 p\sigma_S) \left\{1 - \exp(-\tfrac{1}{2}\ell C_1 p|\sigma_{01} + \sigma_{10}|)\right\}$$

3. METHOD OF MEASUREMENT

A schematic diagram of the apparatus used is shown in Fig. 2. The analysing magnet shown was used to separate protons from atomic hydrogen, H_2^+ and H_3^+ produced by the RF ion source. After passing through the helium cell the flux of protons was measured using the detector of Mason and Schofield[1]. Electrostatic deflection plates were included in the system to ensure that only charged particles were detected when the detector was in use. An arrangement of grids in front of the detector selected particles within a given energy band. To calibrate the detector in terms of proton flux a Faraday cup as shown was used.

For the measurement of the efficiency of the stripping cell, the electrostatic plates and detector were removed and replaced by a simple secondary emission detector, to be described, which measured the fluxes of both protons and atomic hydrogen from the stripping cell.

The RF ion source does not produce a mono-energetic beam of protons, due to a noise voltage across the sheath where the ions are accelerated. Previous workers have measured this noise voltage and none have given a value greater than 40V. For the range of particle energies over which measurements were made (300-3500 eV) this spread of energy is not important.

With the secondary emission detector in position a proton beam was directed into the stripping cell and the proton flux q_1 and atomic hydrogen flux r_1 emerging from the cell were measured. The measurement was performed for a range of pressures in the stripping cell from zero up to a maximum pressure of the order of 50 μ. When the ratio r_1/q_1 was plotted against the pressure p, curves as shown in Fig. 3 were obtained. The form of this curve is consistent with Eq. (5). From Eq. (5) for large $p, r_1/q_1 = \sigma_{10}/\sigma_{01} = R$, thus values for the ratio R can be read directly from the curve. Transposing Eq. (5)

$$\tfrac{1}{2}\ell C_1(\sigma_{01}+\sigma_{10})\cdot p = \log\left\{\frac{\frac{\sigma_{10}}{\sigma_{01}}\left(\frac{r_1}{q_1}+1\right)}{\frac{\sigma_{10}}{\sigma_{01}} - \frac{r_1}{q_1}}\right\} = \text{function}\left(\frac{r_1}{q_1}\right).$$

When the function of (r_1/q_1) given above was plotted against the pressure p a straight line was obtained, and from the slope of this line the sum $(\sigma_{01}+\sigma_{10})$ can be deduced. The cross sections are then obtained from the relations

$$\sigma_{10} = \frac{R(\sigma_{01}+\sigma_{10})}{1+R}$$

$$\sigma_{01} = \frac{\sigma_{01}+\sigma_{10}}{1+R}$$

As shown in Fig.3 when the pressure is zero in the stripping cell the measured ratio r_1/q_1 is not zero. This is because there is some recombination in the residual gas in the apparatus. However this does not invalidate the measurement of $(\sigma_{01}+\sigma_{10})$ from the slope of the curve of $f(r_1/q_1)$ against p.

A secondary electron detector, a sketch of which is shown in Fig.4, was used to measure the fluxes of protons and atomic hydrogen. This is basically the same as the detector already described by Chambers[8]. Deflection plates can be used to deflect the proton beam and confine the measurement to the atomic hydrogen beam. The secondary electrons were collected by the can which surrounds the secondary emitting electrode, the can being biased positive to collect the electrons. A mask is placed in front of the detector to reduce the beam cross section so that all the beam particles passing the mask go to the secondary emitting electrode and not to the surrounding can. In order to prevent secondary electrons from the secondary emitting electrode being drawn out to the mask it was found necessary to interpose a ring electrode as shown and charge this to a negative potential.

The proton current can be deduced by subtracting the secondary electron current collected by the can from the total current to the secondary emitting electrode. In order to deduce the atomic hydrogen flux it is necessary to know the secondary emission coefficient for atomic hydrogen for the energy in question. This could have been done using the results of Chambers. However it seemed more satisfactory to use the result obtained by Chambers that the ratio of the atomic hydrogen secondary emission coefficient to that for protons was a constant $= 1.10$ which did not vary much with energy. The proton secondary emission coefficient was obtained directly from the measurement after subtracting the secondary electron current produced by atomic hydrogen.

The scattering coefficient σ_s was obtained by directing a proton beam into the stripping cell and measuring the proton flux leaving the cell over a wide range of gas pressure in the stripping cell. Since σ_{10}/σ_{01} is small, for $\frac{1}{2}\ell C_1(\sigma_{01}+\sigma_{10})\, p >. 2$ Eq.(3) becomes

$$\frac{q_1}{q_0} = \frac{\sigma_{01}}{\sigma_{01}+\sigma_{10}} \exp(-\tfrac{1}{2}\ell C_1\, \sigma_s\, p) \ .$$

Thus σ_s is obtained from the slope of the straight line obtained by plotting $\log\ q_1$ against the pressure p.

4. EXPERIMENTAL RESULTS

Fig.5 shows a plot of experimental values of $(\sigma_{10}+\sigma_{01})$ against beam energy. The measurements were confined to beam energies between 1000 V and 3500 V. The higher limit was set by design of the apparatus. The lower limit was set by the fact that there was recombination of the beam in the apparatus so there was not a sufficiently large change in the ratio of atomic hydrogen to protons in the beam on passing through the stripping cell to make reliable measurements.

Fig.6 shows a plot of experimental values of σ_{10}/σ_{01} against the beam energy. In this case it was possible to obtain values down to beam energies of 400 V. This is because only the limiting ratio of atomic hydrogen to protons for high pressures was measured.

Fig.7 shows a plot of measured values of the cross section σ_{01} against particle energy, showing the results obtained in this experiment together with results obtained by Williams(6) and by Fleischmann(9). Fig.7 shows a plot of the cross section σ_{10} obtained in this experiment together with the results of Williams and Dunbar(5). No experimental values of σ_{10} are available for particle energies of less than 1000 V. However values may readily be deduced using the values of σ_{01} obtained by Fleischmann and the ratio σ_{10}/σ_{01} obtained in this experiment.

Fig.9 shows a log-log plot of the cross section σ_s against particle energy. The straight line drawn corresponds to $\sigma_s \propto (\text{Energy})^{-0\cdot 58}$, which is the relation obtained from the measurements of Amdur and Mason(7).

Considerable difficulty was experienced in this experiment from impurities present in the helium. These impurities had the effect of apparently making the recombination cross section σ_{10} too large by a factor of between ten and one hundred. It was not found satisfactory to pass the gas through a trap surrounded by liquid nitrogen. A 'molecular sieve' of calcium aluminium silicate immersed in liquid nitrogen was however satisfactory. It was presumed that the impurity was water vapour, which passed through the trap when the liquid nitrogen evaporated. However, the percentage of water vapour revealed by an analysis of the gas used was too small by a factor of at least 100 to account for the discrepancy observed. No other impurities were revealed in the analysis to account for discrepancy.

5. CONCLUSION

Fig.10 shows the variation of the efficiency of the stripping cell with particle energy for different gas pressures in the stripping cell, calculated from the cross sections given by the smooth curves of Figs.7,8 and 9. This indicates that it should be possible to use the stripping cell down to particle energies of 100-200 eV, if stripping cell efficiencies of 1-2% are acceptable.

The above measurements could have been made more directly using the calorimetric methods described by Chambers. However such methods require reasonably high beam densities which might have been difficult to produce in the present rather long (3 metres) apparatus. It would also have been more direct to start with a beam of atomic hydrogen rather than a proton beam. This would have meant designing a recombination cell to convert the proton beam to an atomic hydrogen beam.

6. ACKNOWLEDGEMENT

The authors are indebted to Professor J.B. Hasted for helpful discussion and suggestions.

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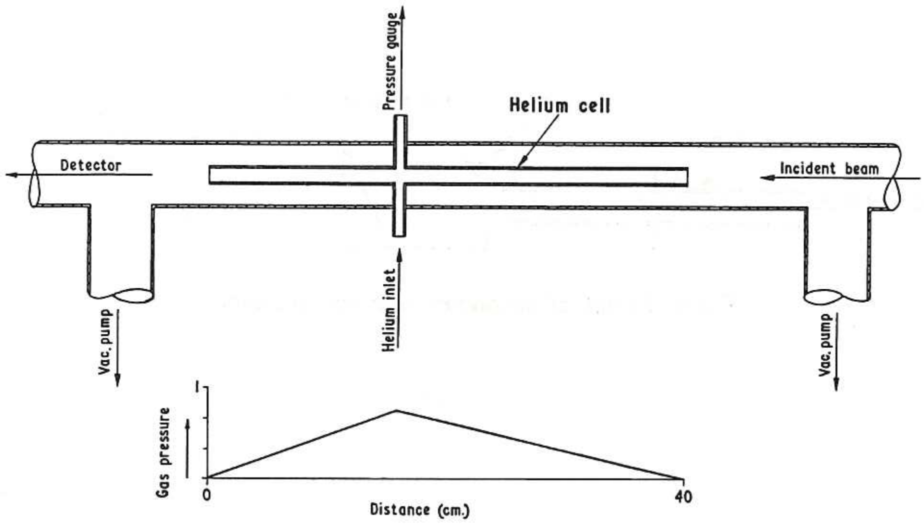

Fig. 1 Sketch of stripping cell

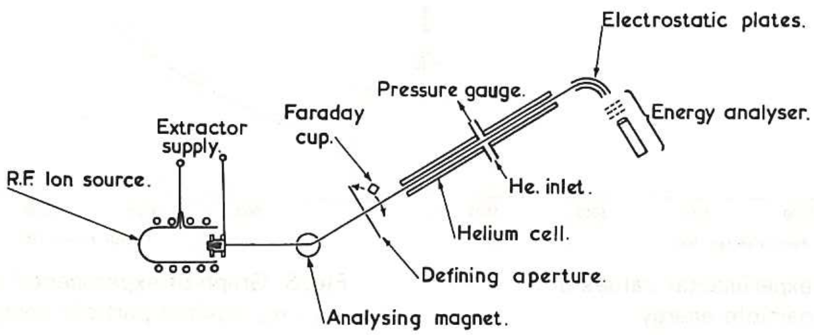

Fig. 2 Schematic diagram of apparatus

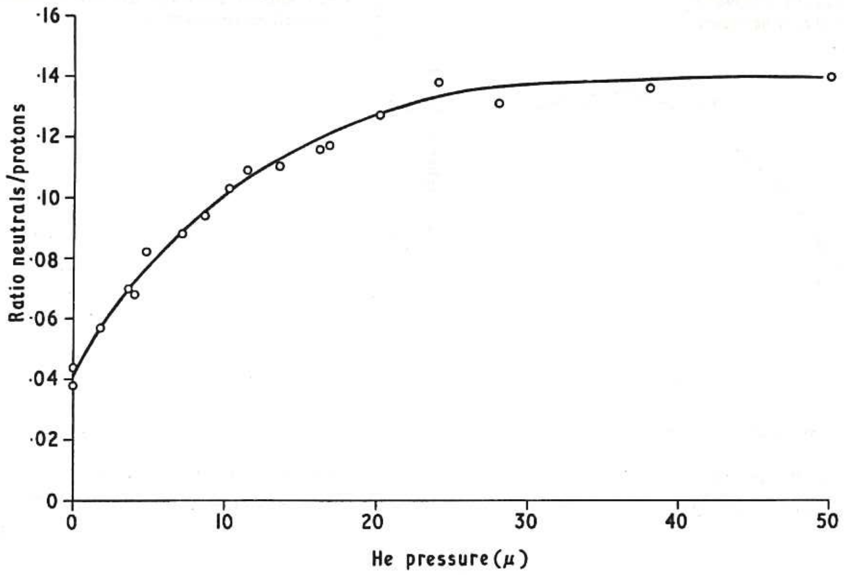

Fig. 3 Graph of measured ratio of atomic hydrogen flux to proton flux against pressure in the stripping cell.

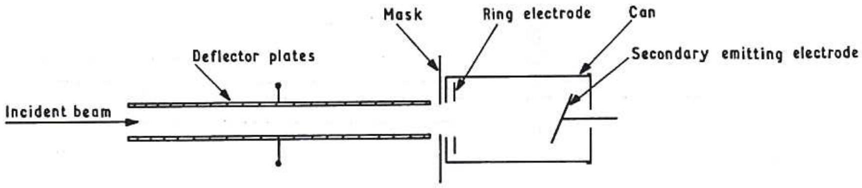

Fig. 4 Sketch of secondary electron detector

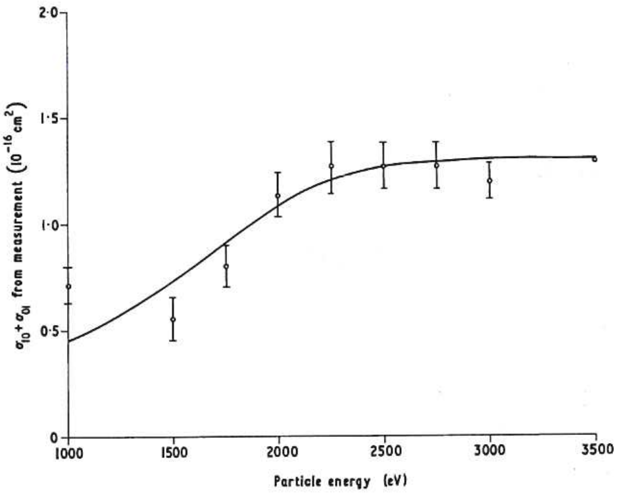

Fig. 5 Graph of experimental values of $\sigma_{10}+\sigma_{01}$ against particle energy.

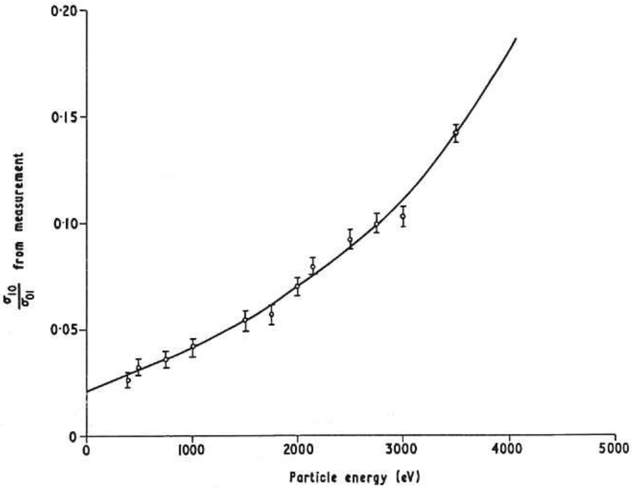

Fig. 6 Graph of experimental values of σ_{10} / σ_{01} against particle energy.

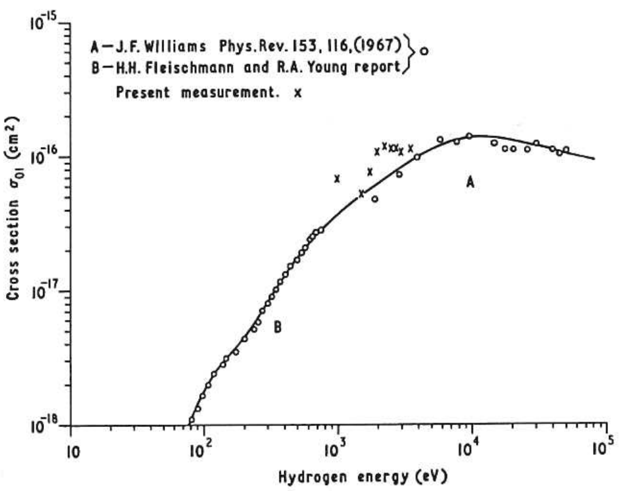

Fig. 7 Graph of measured values of σ_{01} against particle energy.

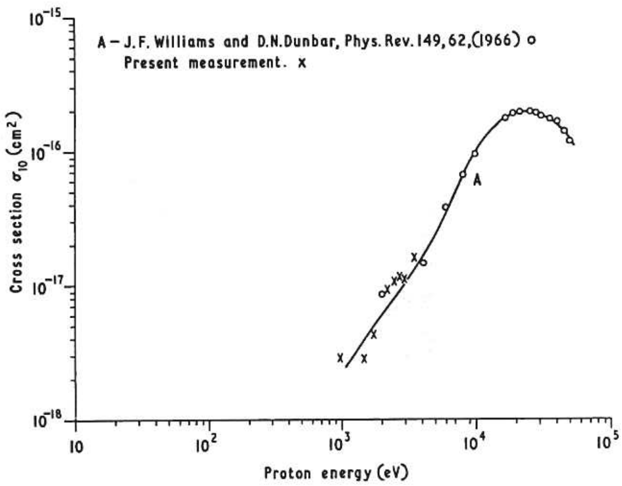

Fig. 8 Graph of measured values of σ_{10} against particle energy.

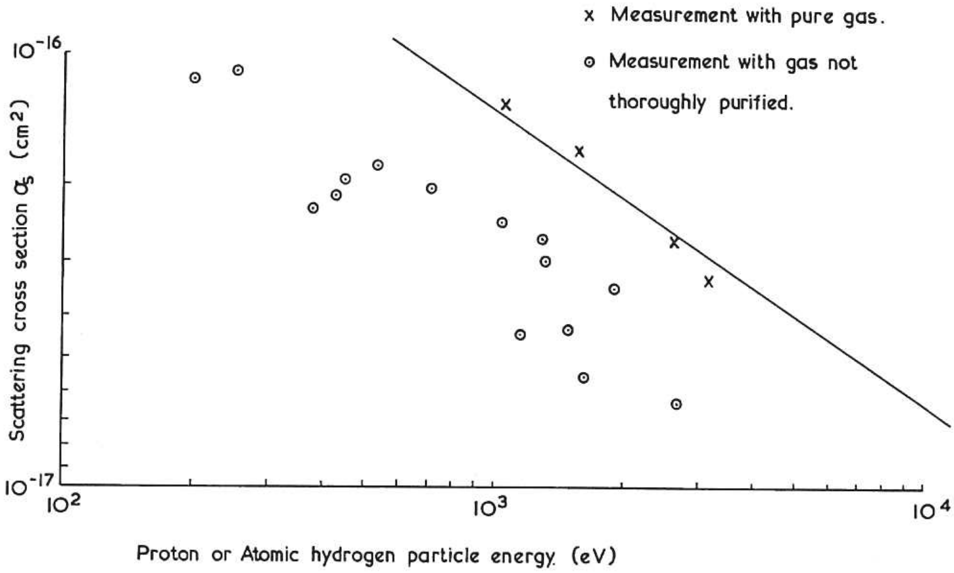

Fig. 9 Log-log plot of scattering cross section σ_s against particle energy.

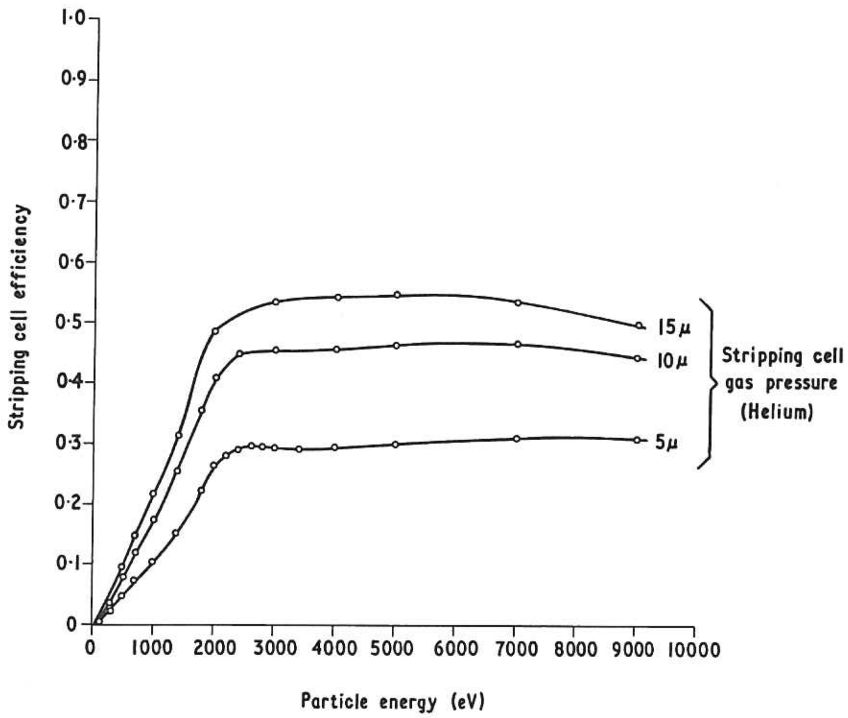

Fig. 10 Graph of calculated efficiency of stripping cell against particle energy.

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