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THE YIELD OF EXCITED ATOMS IN A BEAM FORMED BY CHARGE EXCHANGE IN A PARTIALLY IONIZED GAS TARGET

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A B S T R A C T

Beams of excited hydrogen atoms are commonly produced for neutral injection experiments by charge exchange in a gas target. The passage of the beam through the target also ionizes the gas and the amount of ionization will increase as beam intensities are increased. Measurements have been made of the effect of ionization of the gas in a charge exchange cell on the yield of excited atoms. The results are compared with calculations of the effect based on the best available experimental, theoretical or estimated collision cross section values in that order of preference. The agreement between calculation and experiment is considered to be satisfactory and the method of calculation is used to predict the effect at higher ion densities in the cell. It is found that the population of a given excited level falls to a very small value when the ion density is greater than a critical value.

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CONTENTS

INTRODUCTION

Energetic beams of highly excited hydrogen atoms are now commonly used as a means of forming a plasma in magnetic mirror machines[1]. The highly excited hydrogen atoms are dissociated by the Lorentz force $(eV \times B)$ into protons and electrons which are then trapped in the magnetic field.

Excited atoms are produced by charge exchange and dissociation of a focussed beam of H^+ or H_2^+ ions as they pass through a gas or vapour cell. In collisions with the neutral gas, the excited atoms are destroyed by re-ionization. Since the probability for this process does not depend on the beam intensity such collisions with the gas molecules do not in themselves set a limit on the excited atom intensity obtainable. However, collisions which lead to ionization of the gas itself occur about as often as charge exchange. As a result a plasma is formed which could have, for example, a density of 10^{10} to 10^{12} ions cm^{-3} for an input ion beam intensity of 10 mA cm^{-2}. The exact value will depend on the geometry of the beam and cell, the ionization cross section, the molecular weight of the gas, and the gas density. The existence of this plasma in the gas cell has the effect of adding loss processes which are dependent on the beam intensity and, for a given level n, it is shown that there is a limit to the beam intensity that can be used.

In the first part of this paper we describe an experiment to measure the effect of the degree of ionization on the yield of excited atoms from a gas target[2]. In the second part we present predictions for the effect in terms of the best available or estimated cross sections and compare these results with the measurements.

EXPERIMENTAL METHOD

(a) Neutral gas in charge exchange cell

The general arrangement of the experiment was similar to that used in previous studies on the production of excited hydrogen atoms[3] and is shown schematically in Fig.1. All measurements were carried out at a proton energy of 25 keV. The proton beam first passed through the 11 cm long charge exchange cell. The apertures of the cell were 2.0 mm in diameter and the outer region was pumped by a conventional 6" oil diffusion pump baffled with a liquid nitrogen trap. Both hydrogen (target thickness 7 to 14×10^{15} cm^{-2}) and argon (1.5 to $4 \times 10^{15} cm^{-2}$) gas were used. These were of a commercial high purity cylinder grade and were passed through a cold trap at liquid nitrogen and solid CO_2/acetone temperatures respectively. The pressure was measured with a Pirani gauge in conjunction with gas sensitivity factors previously determined by calibration against a McLeod gauge.

The beam leaving the cell consisted of ions and neutral atoms of which some were in excited levels. The population of the highly excited levels was determined by measuring the fraction of the beam which was ionized by a known electric field. Before reaching the electric field region used for the measurements, the beam passed first through a pre-ionizing electric field to establish a known threshold for the field ionization effect and then through a transverse electric field to remove all the ions present. The electrode system used for the measurement of population was similar to that used previously but with the principal dimensions:

gap between electrodes	= 4 mm
diameter of aperture in electrodes	= 2 mm
diameter of aperture defining maximum beam diameter	= 1 mm.

With these dimensions and proportions the maximum field seen by an atom moving along the axis of the electrode system was 0.94 of the field given by the electrode voltage divided by the gap between the electrodes. The focussing effect of the gap was such that the maximum voltage which could be applied before particles were deflected outside the acceptance of the detectors was 0.25 times the original

proton accelerating voltage for particles ionized in the mid-plane of the gap. These properties were determined by standard digital computer techniques.

After passing through the electrode system the neutral atoms were detected by a faraday cup covered with an 8 μgm cm^{-2} carbon foil to convert a known fraction of the neutrals to ions. Protons produced in the electric field or by collision with background gas molecules were deflected by a sector magnet onto a CsI (Tℓ) crystal detector.

The distribution of population in the high levels was obtained by the modulated field technique described earlier[3]. For this method the d.c. potential on the electrodes increased slowly and linearly with time, reaching its maximum value in about 15 minutes. A fraction of this voltage was applied to the X amplifier of an X-Y pen recorder. A small amplitude, 800 c/s voltage was added to the d.c. potential applied to the electrodes with the effect that the fractional ionization of the atom beam in the field also varied at 800 c/s as well as slowly increasing with the increase in d.c. potential. The 800 c/s component of the proton detector signal was then amplified and passed through a phase sensitive detector. Due to the relatively long period of recording a single trace it was found that it was necessary to correct for variations in the neutral beam intensity. This was done by an electronic dividing circuit which effectively divided the phase sensitive detector output by the neutral beam intensity. The quotient was then supplied to the Y amplifier of the XY recorder. The kind of record obtained is illustrated in Fig.2.

(b) Ionized gas in charge exchange cell

The gas in the charge exchange cell was partially ionized by passing currents of 7.5 A to 15 A between an oxide coated cathode and the metallic cell walls which acted as the anode. The cathode was placed in the cell about 5 cm above the beam. Five double Langmuir probes[4], spaced 2 cm apart along the beam line and 5 mm below the beam axis, were used to measure the ion density. The probe data was analysed by the method described by Bohm[5]. Typical central ion densities ranged

from 5×10^{10} cm^{-3} to 5×10^{11} cm^{-3}; the uncertainty in density measurements, based on reproducibility, was ±30 per cent. The relative density distribution parallel to the beam axis as measured by the probes, was 0.6 : 1 : 1.4 : 1 : 0.6.

With the discharge on, the temperature of the cell walls rose to 250°C and, although the walls were made of stainless steel, some impurities would be released at this temperature. Since the purpose of the measurements was to study the effect of the plasma it was decided to accept some level of impurity and avoid errors due to this by pulsing the discharge on and off at intervals of 0.1 sec. This period was much shorter than the estimated time of 3 sec required to change the gas in the cell and the impurity level was assumed to remain reasonably constant. Records of 800 c/s signal versus electric field strength were taken simultaneously for the discharge on and discharge off conditions by appropriate electronic switching combined with the use of integration times of a few seconds on each channel.

The observed decrease in the populations of n = 20 to 15 in an argon discharge is illustrated in Fig.2; the top traces are the differential ionization signal recorded when the discharge was off (target thickness $\equiv n^0 \cdot \ell = 1.8 \times 10^{15} cm^{-2}$), the lower traces were recorded when the discharge was on (ion target thickness $= n^+ \cdot \ell = 2.9 \times 10^{12} cm^{-2}$). The curves are the results of consecutive sweeps of the gap voltage and demonstrate the reproducibility of the results.

ANALYSIS

(a) Weakly ionized hydrogen target

In the gas target incident protons capture electrons from the hydrogen molecules; as a result, fast hydrogen atoms, with a population distribution covering all excited states, are produced. The population distribution is then modified by radiative decay and by collisions (ionization, excitation, and de-excitation) with hydrogen molecules and, in the case of the weakly ionized gas target, with ions or electrons. In the present experiment no particular collision process can be isolated as the dominant one, and we cannot use the experimental results to

verify any one cross section calculation. We can, however, use the best measured, calculated, or estimated cross sections available at this time to calculate the effect of the ionized target on the excited levels, and compare the prediction of this aggregate of cross sections with the experimental results.

For the hydrogen component of the target we consider electron capture and ionization but neglect excitation, since first Born approximation (FBA) calculations by Pomilla and Milford[6] for the processes

$$H(n) + H(1s) \rightarrow H(n+1) + H(1s)$$
$$H(n) + H(1s) \rightarrow H(n+1) + H(2p)$$

indicate that the cross section for excitation of a level n to $n+1$ (a) is much smaller than that for ionization and (b) decreases rapidly with increasing n at 25 keV. The electron capture cross sections used in the analysis are the FBA results for atomic hydrogen of Bates and Dalgarno[7], extrapolated as n^{-3} for $n > 4$, and normalized to the experimental total capture cross section (4.6×10^{-16} cm^2/molecule)[8] in molecular hydrogen. The ionization cross section is estimated to be that for ground state ionization (1.2×10^{-16} cm^2/molecule)[8], increasing linearly with n until it takes on the value of the total electron scattering cross section in H_2 (7×10^{-16} cm^2/molecule)[9] and taken to be constant for larger n [3,10].

The ions and electrons in the target are considered to be cold, so that the velocity of the incident protons is the relative collision velocity, and cross sections for collisions with ions are taken to be the same as those for electron collisions at the same velocity. The following is a summary of the cross sections which have been used:

Excitation ($\sigma^+_{n,n+1}$ and $\sigma^+_{n,n+2}$): Bethe approximation results of McCoyd and Milford[11], statistically averaged over substates, and extrapolated as n^4 for $n > 10$.

Ground state excitation ($\sigma^+_{1,n}$): FBA results of May[12] for proton excitation. Electrons are near threshold for excitation from the ground state and their contribution has been neglected.

De-excitation ($\sigma^+_{n,n-1}$ and $\sigma^+_{n,n-2}$): obtained from the ratio of statistical weights and the excitation cross section; e.g.

$$\sigma^+_{n+1,n} = \left(\frac{n}{n+1} \right) \sigma_{n,n+1} \quad .$$

Ionization ($\sigma^+_{n,c}$) for $n > 1$: the FBA results of Omidvar[13] extrapolated as n^2 for $n > 5$.

Ionization ($\sigma^+_{n,c}$) for $n = 1$: experimental results of Fite et al[14] for ionization by protons.

Radiative decay from a level n to all levels is also included in the analysis. We assume that collisions with the ions and electrons assure a statistical distribution over substates and use statistical averages of the radiative transition probabilities of Hiskes, Tarter and Moody[15].

The cross sections for ion, electron and hydrogen collisions and the transition probabilities can be assembled into four matrices $\underset{\sim}{\Sigma}^+$, $\underset{\sim}{\Sigma}^-$, $\underset{\sim}{\Sigma}^o$, and $\underset{\sim}{A}$. The population of a level n is determined by an infinite set of coupled equations which can be expressed as:

$$\frac{d\underline{N}(x)}{dx} = \left[n^+(x)\, \underset{\sim}{\Sigma}^+ + n^-(x)\, \underset{\sim}{\Sigma}^- + n^o(x)\, \underset{\sim}{\Sigma}^o + v^{-1}\, \underset{\sim}{A} \right] \cdot \underline{N}(x) \qquad \ldots (1)$$

where n^+, n^-, n^o are the ion, electron, and molecule densities in the target

v is the speed of the incident protons

x is the distance along the target

$\underline{N}$ is a vector whose components are the populations of all levels of the hydrogen atom and the continuum.

This infinite set of equations must be truncated if we hope to get a solution. We have somewhat arbitrarily chosen a twenty-five level system since the highest level observed in our experiment is $n = 20$. The populations of the excited levels are tightly coupled by the very large electron excitation and de-excitation cross sections, and an arbitrary termination, for example, a reflector or a sink at the cutoff, has drastic effects on the populations of all levels. We have

found (see Appendix B) that for a system of k levels the introduction of the following ionization cross sections for the last two levels result in a smooth termination:

$$\sigma^{+}_{k-1,c} = \sigma^{+}_{k-1,c} + \left(1 - \left(\frac{k-1}{k+1}\right)^{6} \right) \sigma^{+}_{k-1,k+1} \qquad \ldots (2)$$

$$\sigma^{+}_{k,c} = \sigma^{+}_{k,c} + \left(1 - \left(\frac{k}{k+1}\right)^{6} \right) \sigma^{+}_{k,k+1} \; . \qquad \ldots (3)$$

With this termination, for example, the solution for the population of $n = 24$ obtained from a 25 level system agrees to within 1 per cent with the solution from a 31 level system.

(b) Weakly ionized argon target

Although no calculations for argon excitation cross sections are known to us, we assume that, as in the case of hydrogen they are small and can be neglected. For the capture cross section we use the relative hydrogen capture cross sections of Bates and Dalgarno normalized to the experimental total capture cross section $(6.4 \times 10^{-16}\ \mathrm{cm}^2)$[16]. As for hydrogen, the ionization cross section was estimated to be that for ground state ionization $(3.8 \times 10^{-16}\ \mathrm{cm}^2)$[16] increasing linearly with n to the value of the total electron scattering cross section $(2.35 \times 10^{-15}\ \mathrm{cm}^2)$[9] and then remaining constant.

(c) Flow cross section concept

The complete set of equations (1) describing the populations of the excited levels can be solved numerically but give little insight as to the relative importance of various cross sections in the depletion of the population of an excited level by the presence of charged particles in the target. The equations (1) can be uncoupled by introducing an "effective flow" cross section $\sigma^{+}_{flow}(n)$, which represents the net population flow out of a level n due to collisional excitation to and de-excitation from neighbouring levels. The population N_n of a given level n is then approximately described by the relation

$$\frac{dN_n(x)}{dx} = - N_n(x) \left[(\sigma^{+}_{flow}(n) + \sigma^{+}_{n,c})\, 2n^{+} + \sigma^{o}_{n,c}\, n^{o} \right] + N^{+}(x)\, \sigma^{o}_{c,n}\, n^{o} \qquad \ldots (4)$$

where

$2n^+$ is the total (ion + electron) charge density

N^+ is the proton population

$\sigma^o_{c,n}$ is the cross section for capture into level n.

For most neutralizers the proton population is determined mainly by capture into and ionization of the ground state; for such a two level system we have the solution

$$N^+(x) = \frac{1}{\sigma^o_{1,c} + \sigma^o_{c,1}} \left[\sigma^o_{1,c} + \sigma^o_{c,1} \exp\left(- n^o(\sigma^o_{1,c} + \sigma^o_{c,1})x\right) \right] \qquad \ldots (5)$$

Combining equation (4) and (5) and solving for N_n we obtain, for a thick target, an expression for the fractional decrease in the population of a level n due to the presence of ions and electrons in the neutraliser

$$\text{Fractional decrease} \equiv 1 - \frac{N_n(n^+)}{N_n(n^+ = 0)} = \frac{(\sigma^+_{flow}(n) + \sigma^+_{n,c}) \frac{2n^+}{n_o}}{(\sigma^+_{flow}(n) + \sigma^+_{n,c}) \frac{2n^+}{n_o} + \sigma^o_{n,c}} \qquad \ldots (6)$$

From this expression we can see that the depletion of the population of an excited level in a weakly ionized target depends not only on the charge density but also on the ionization cross section for collisions with the gas.

In Appendix A we show that an approximate expression for the flow cross section is

$$\sigma^+_{flow}(n) = (27n - 143 + 504n^{-1})A \qquad \ldots (7)$$

where A is defined by the relation

$$\sigma^+_{n,n+1} = A\, n^4 \ .$$

Some numerical values for the cross sections $\sigma^+_{n,n+1}$, $\sigma^+_{flow}(n)$, and $\sigma^+_{n,c}$ are listed in Table I for 25 keV H atoms colliding with cold electrons. Note that, for large n, the effective flow cross section is much smaller (of order n^{-2}) than that for excitation and has a much weaker dependence on n. The loss from an excited state is a function of the sum of the flow and ionization cross sections (see equation (6)), and it can be seen from Table I that ionization is slightly more important than flow. This is quite different from plasma trapping of injected atoms in a mirror machine, where Lorentz ionization of a particular excited level

(typically n = 12) provides a sink, and the excitation-de-excitation flow becomes a cascade into the continuum[17]. Excitation is then much more important than ionization.

TABLE I

Some Cross Sections for 25 keV H Atoms Colliding with Cold Electrons

(10^{-16} cm^2)

	$\sigma^+_{n,n+1}$	$\sigma^+_{flow}(n)$	$\sigma^+_{n,c}$
n = 10	2.1×10^4	380	500
15	1.1×10^5	640	1200
20	3.4×10^5	910	2100

RESULTS AND DISCUSSION

The fractional population decrease is plotted in Fig.3 against central ion density in both hydrogen discharges (on the left) and argon discharges (on the right) for n = 17 and n = 20 and at two different pressures. These results were taken from a set of curves such as those shown in Fig.2. The solid line is the numerical solution to equation (1); the dashed line is the solution to the flow approximation (equation (6))[18].

Although there is considerable scatter in the experimental data, the results are consistent with the numerical solutions to equation (1) which reflect our present knowledge of collision cross sections. The thick target requirement, invoked in the derivation of equation (6), is only satisfied for Figs.3a and 3c, for which the agreement between the flow and numerical solutions is quite good; for the other cases one would expect, and finds, that the flow approximation result is too large.

Our results indicate that ion densities up to 5×10^{11} cm^{-3} in a charge exchange chamber will not significantly lower the yield of excited hydrogen atoms. In Fig.4 we show the fractional population decrease predicted by the flow approximation (equation (6)) over a wider range of ion density and compare this with the

numerical solution to equation (1) for n = 10 in H_2. These results assume an equilibrium target thickness and the agreement is quite good. The line for Na in Fig.4 illustrates the fact that the fractional decrease in population is a strong function of the type of neutralizer as well as the degree of ionization. It can be seen from these results that with a sufficiently large fraction of the gas ionized the population of the high levels will fall to a very small value.

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18. For the numerical solution a roughly triangular ion density distribution, as given by the probe measurements, was used. For the flow approximation an equivalent uniform ion density was used.

APPENDIX A

The population flow out of a given level n due to excitation and de-excitation collisions is given by

$$\frac{1}{2n^+}\left(\frac{dN_n}{dx}\right)_{exc.} \equiv N_n\,\sigma^+_{flow}(n) = \sum_{\substack{j=n-2 \\ j\neq n}}^{n+2} (N_n\,\sigma^+_{n,j} - N_j\,\sigma^+_{j,n}) \quad \ldots (A1)$$

To derive an approximate expression for the flow cross section, we assume that the population N_n of a level n, like the capture cross section, is proportional to n^{-3}. We also make use of the fact[12] that $\sigma^+_{n,n+1} \simeq A\,n^4$ and $\sigma^+_{n,n+2} \simeq 0.1\,A\,n^4$, and that $\sigma^+_{j,n} = (\frac{n}{j})^2\,\sigma^+_{n,j}$. When we substitute these expressions into equation (A1) and expand terms of the form $(1 - cn^{-1})^m$ in a Taylor series, we obtain

$$\sigma^+_{flow}(n) = A\,(27n - 143 + 504n^{-1} + O(n^{-2})) \,. \quad \ldots (A2)$$

APPENDIX B

To approximate the infinite set of equations (1) by a set of k equations, we need two termination loss cross sections, $\sigma^{+}_{term}(k)$ and $\sigma^{+}_{term}(k-1)$, which will simulate the normal flow condition when the levels k and $k-1$ are no longer fed from levels $n > k$. To obtain the first of these cross sections we use the expression for $\sigma^{+}_{flow}(k)$ (equation (A2)) on the left hand side of equation (A1) and, on the right hand side, we make the substitutions

$$\sigma^{+}_{k,k+1} + \sigma^{+}_{k,k+2} = \sigma^{+}_{term}(k)$$

$$\sigma_{k+1,k} = \sigma_{k+2,k} = 0 \ .$$

Expanding terms of the form $(1 - cn^{-1})^{m}$ in a Taylor series and solving for $\sigma^{+}_{term}(k)$ we have

$$\sigma^{+}_{term}(k) = A(6n^3 - 21n^2 + 63n + \ldots) \ .$$

In equation (3) of the text we have approximated this by

$$\left(1 - \left(\frac{k}{k+1}\right)^{6}\right) \sigma^{+}_{k,k+1}$$

which, when expanded in a Taylor series, is

$$A\,(6\,n^3 - 21\,n^2 + 56\,n + \ldots) \ .$$

Similarly, to obtain the cross section $\sigma^{+}_{term}(k-1)$ we use the expression for $\sigma^{+}_{flow}(k-1)$ (equation (A2)) on the left hand side of equation (A1), make the substitution

$$\sigma^{+}_{k-1,\,k+1} = \sigma^{+}_{term}(k-1)$$

$$\sigma_{k+1,\,k-1} = 0$$

on the right hand side, and obtain

$$\sigma^{+}_{term}(k-1) = A(k^3 - 9k^2 + 43k + \ldots) \ .$$

This we have approximated (see equation (2)) by

$$\left(1 - \left(\frac{k-1}{k+1}\right)^{6}\right) \sigma^{+}_{k-1,\,k+1}$$

which expands to

$$A(1.2k^3 - 12k^2 + 64.9k + \ldots) \ .$$

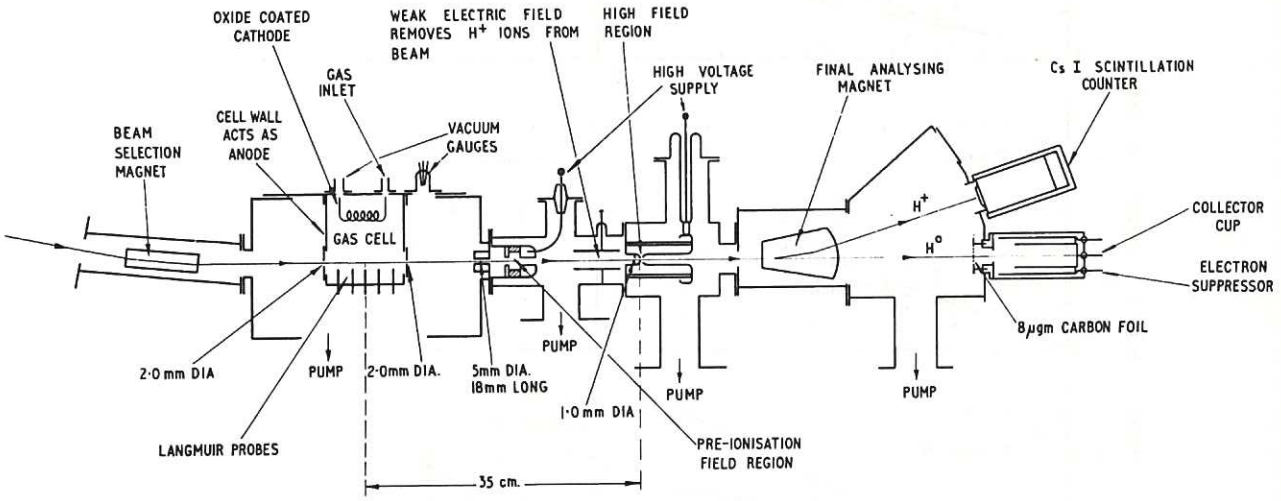

Fig. 1 The experimental arrangement (CLM-P 122)

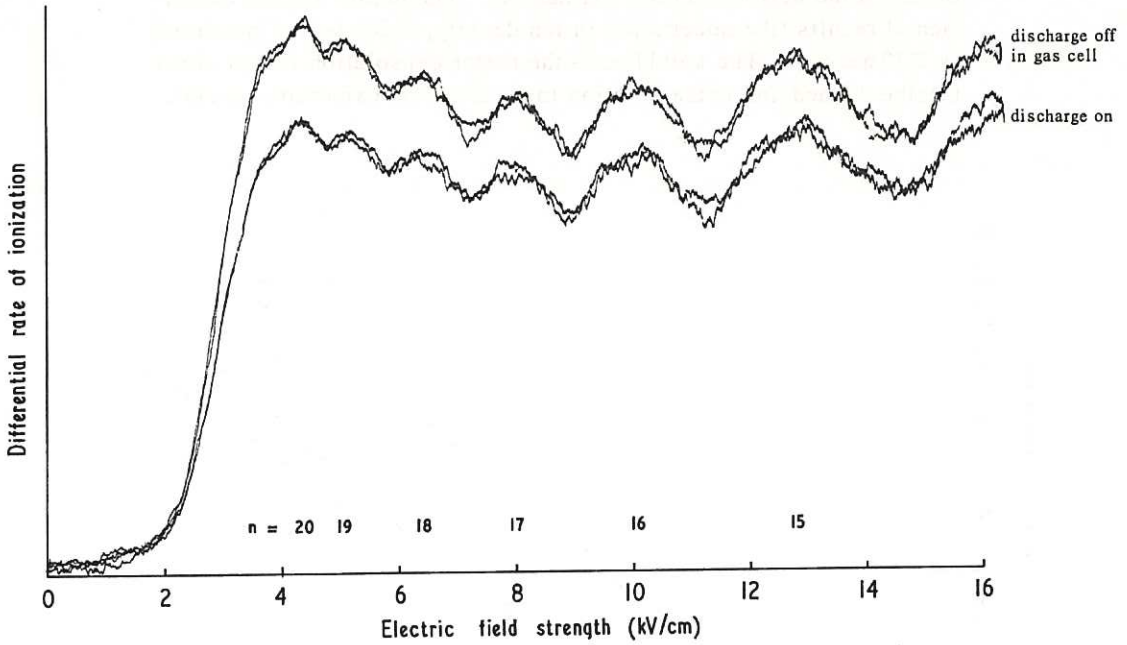

Fig. 2 (CLM-P 122)

Differential ionization curve for H atoms produced from 25 keV H^+ passing through an 11 cm long argon neutralizer

Top traces: discharge off (target thickness $\equiv n^0\ell = 1.8 \times 10^{15}\ cm^{-2}$);

Lower traces: discharge on ($n^0\ell = 1.8 \times 10^{15}\ cm^{-2}$, $n^+\ell = 2.9 \times 10^{12}\ cm^{-2}$)

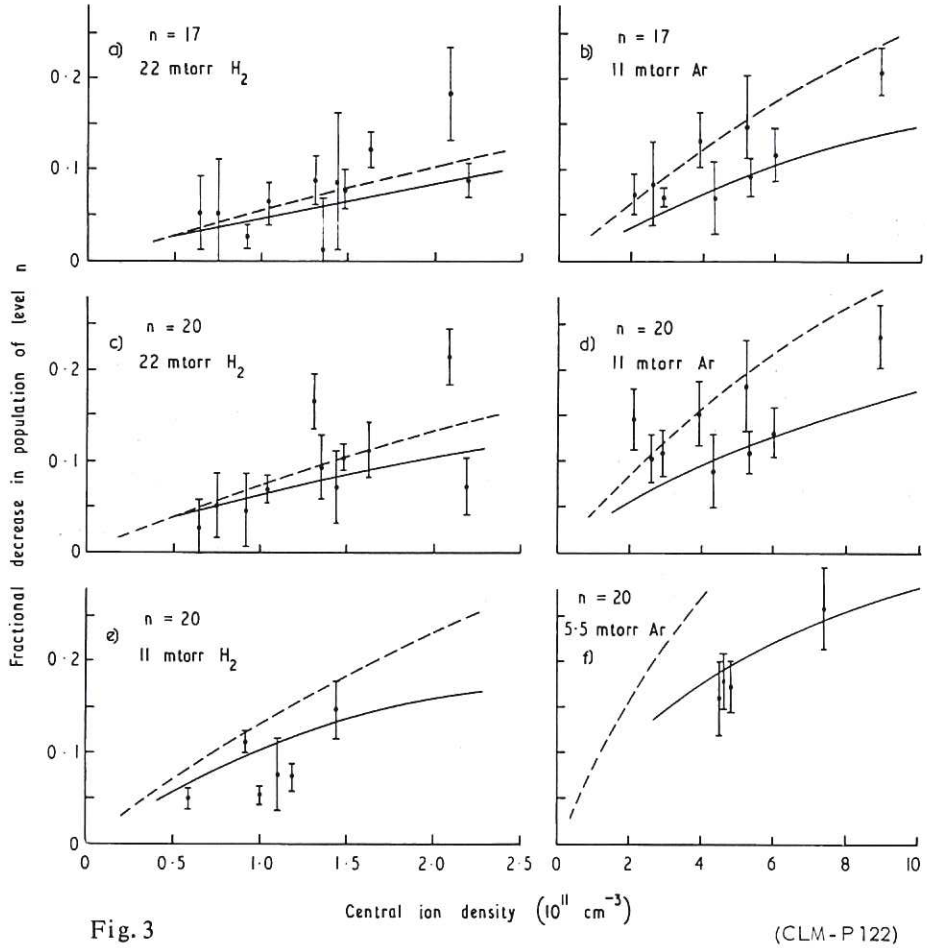

Fig. 3 (CLM-P122)

Fractional population decrease of a level n due to partial ionization of gas in the cell vs, central ion density. The points are the experimental results (the uncertainty in ion density, which is not indicated, is ± 30 per cent). The solid line is the numerical solution to equations (1); the dashed line is the solution to the flow approximation eqn. (6).

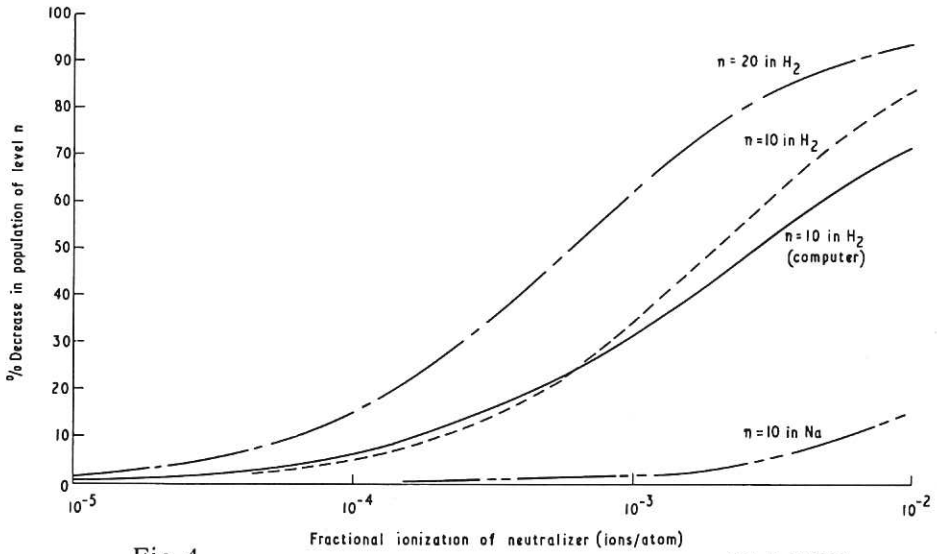

Fig. 4 (CLM-P122)

Expected fractional decrease in the population of the level n plotted against fractional ionization for a 25 keV H^+ beam passing through a 10 cm long charge exchange cell

——— n = 10 in H_2, numerical solution to equations (1) ($n^0 = 1 \times 10^{15}$ molecules/cm^2)

– – – – n = 10 in H_2, flow approximation (equation (6))

—— – —— n = 20 in H_2, flow approximation (equation (6))

—— – – —— n = 10 in Na, flow approximation (equation (6))