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THE IONIZATION OF EXCITED HYDROGEN ATOMS BY STRONG ELECTRIC FIELDS

by

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ABSTRACT

Ionization of excited hydrogen atoms by electric fields of up to 1.2×10^5 volt/cm was observed. The differential rate of ionization as a function of field was obtained by a modulated field technique and the results show the individual levels of the atom with quantum numbers in the range $n = 9$ to $n = 22$. The identification and position of each level as a function of electric field is discussed and compared with quantum theory predictions. The Lorentz force $e\underline{v} \times \underline{B}$ was found to be equivalent to a pure electric field for the ionization of 50 keV hydrogen atoms.

The formation of excited atoms by electron capture was studied for 100 keV deuterons in H_2, He, Ne, A, Kr and Xe. The results for the sum of the populations of the levels with $n = 8, 9, 10$ and 11 are presented.

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1. INTRODUCTION

The ionization of excited hydrogen atoms by the $e\underline{v} \times \underline{B}$ Lorentz force is an important means for trapping energetic protons in magnetic mirror machines(1,2). The present work was undertaken to gain further knowledge of this ionization process by using a pure electric field(3). A comparison between the effects of Lorentz ionization and electric field ionization, which is described later, shows that they are equivalent for hydrogen atoms with a kinetic energy of 50 keV as expected.

The probability of ionization in an electric field was first calculated by Oppenheimer(4) for an atom in the ground state. The electric field strengths required to quench the Balmer lines arising from the levels with n = 5, 6, 7 and 8 were later calculated by Lanczos(5). Further calculations have been made recently by Rice and Good(6) for the ionization probability as a function of the applied field for levels with n = 5, 6 and 7. A general discussion on the behaviour of hydrogen atoms in electric fields has been given for example by Bethe and Salpeter(7). We have used the formula for the ionization probability given by Bethe and Salpeter to obtain the ionization probability for all levels from n = 7 to n = 20. In these calculations we used the results of second order perturbation theory(7) to obtain the level energies as a function of the electric field. This method breaks down near the limit of the potential barrier and the more recent calculations of Rice and Good should be more accurate in this region. Since results for higher n values using the Rice and Good theory were not available the present data are compared with the simpler calculations referred to above.

2. EXPERIMENTAL METHOD

A small accelerator with a radio frequency ion source supplied a beam of protons with energies up to a maximum of 100 keV. The spread in energy due to the source excitation conditions was not more than ± 250 eV and the high voltage supply was stabilised to one part in 10^3. Ions of the correct mass were selected by a 90^o deflection magnet. This was energised by permanent magnets but could be adjusted to field strength by a motor driven shunt. Between the 90^o magnet and the experimental equipment there were two adjustable beam defining slits and an electrostatic quadrupole focusing lens. These enabled the beam intensity and direction to be adjusted and defined.

A schematic drawing of the experimental equipment is shown in Fig. 1. The beam selection magnet separated a pure proton beam from any neutral atoms which may have formed by collisions with background gas in the focussing section. The beam then entered a gas cell through a 0.25 mm diameter aperture. All later apertures between this point and the counters were at least 2 mm in diameter except for that in the high field electrode system which was 0.25 mm in diameter. The apertures were optically aligned on assembly.

Following the gas cell charged components were deflected out of the line of the beam by a magnetic field. Fast neutral atoms remaining then passed through an electrode system where they were subjected to electric fields of up to 1.2×10^5 volt/cm. The field vector was parallel to and in the direction of motion of the particles. Details of the electrode configuration and the electric field distribution are shown in Fig.2. The field distribution for the particular electrode shapes used was determined by an iterative relaxation process with the aid of a digital computer. The error in this calculation was less than 1 per cent. The dimensions which determined the shape of the electrodes and size of the holes were measured with a microscope to an accuracy of ± 0.05 mm. The gap between the electrodes was measured on assembly with a micrometer depth gauge and found to be 0.74 ± 0.01 mm. The 0.25 mm diameter aperture in the first electrode defined the region of the field through which the beam would pass. Atoms which passed through at a radius of 0.125 mm from the axis experienced a field value 1 per cent higher than that on the axis. The absolute value of the voltage applied to the high field electrodes and of the voltage applied to the accelerator were calibrated by a precision wire wound resistance of 503.7 megohms to an accuracy of better than 1 per cent. The overall error in the electric field strength was ± 3 per cent.

The probability that an excited atom will lose its excitation between the gas cell and the high field electrodes is determined by the radiative lifetimes for the state. This in turn depends on the principal quantum number n and the substate of interest. In the present experiment individual substates were not resolved and the population of the substates not known. The effective lifetime for a level of given n was therefore not known. The substate with the shortest lifetime is known, however, and in the field free case this will be the p state. Here we are dealing with fast atoms moving in a stray magnetic field at least as strong as the earth's field and the Lorentz force $e\underline{v} \times \underline{B}$ is such that lifetimes calculated in the linear Stark approximation must be used. These have been calculated by Moody(8). The shortest possible lifetime for a level of given n varies from 0.32 μsec to 5.4 μsec for $n = 9$ to $n = 20$ respectively. The mean distance from the gas cell to the electrode system was 38 cms and the lowest proton energy used here was 50 keV. The time taken to transverse this distance was about 0.12 μsec so that some loss could be expected for the lower values of n considered here. A further experiment is planned to determine the effective lifetimes of these states.

Following the high field region the final analysing magnet directed protons onto one CsI(Tℓ) scintillation counter and neutral atoms passed onto a second similar counter. In the present measurements a modulated beam technique was used to observe the ionization of the excited atoms in the beam as a function of the applied electric field. The high voltage supply to the electrode system was modulated at 800 c/s and the 800 c/s component of the signal in the proton counter was recorded by a frequency and phase sensitive detector(9). This gives a result which is a measure of the rate of change of ionization as a function of the applied field.

3. IONIZATION OF EXCITED HYDROGEN ATOMS

Ionization of excited hydrogen atoms by a strong electric field was first observed by Traubenberg et al(10). In the present experiment protons with an energy of 50 keV were used to obtain a beam of fast neutral atoms by charge exchange in hydrogen. The gas target density seen by the proton beam was 2×10^{16} atoms/cm^2. It was observed that a small fraction of the atom beam was ionized when a voltage was applied to the electrode system. The rate of change of the fraction ionized was measured by means of the 800 c/s modulation technique and the result is plotted in Fig.3 as a function of the electric field strength. The amplitude of the 800 c/s modulation used within a given range of electric field strength is indicated in the diagram. The maxima in this differential curve were interpreted as being due to the successive ionization of the principal quantum levels of the hydrogen atom.

The positions of the maxima were compared directly with theory in the following way. The electric field strength is plotted in Fig.2 as a function of the position of an atom moving along the axis of the electrode system. Since the velocity corresponded to that of a proton with an energy of 50 keV the variation of electric field with time followed immediately. By combining this with the theoretical probability of ionization as a function of field strength a spectrum line shape was obtained in the limit of zero modulation amplitude. The result is shown in Fig.4 for the particular Stark component ($n_1 = 0$, $n_2 = 12$, $m = 0$) of the level with $n = 13$. The maximum of the line lies at a field strength of 1.99×10^4 volt/cm and this corresponds to an ionization probability of 2×10^{10} sec^{-1}. This probability was taken as a characteristic value of the present electrode geometry and proton energy. The electric fields required to cause this probability of ionization are shown in Fig.5 as a function of n for the extreme red, central and extreme blue components of all the levels from $n = 9$ to $n = 20$. Each vertical line indicates the range of electric field strengths for all the components of a level with a given value of n.

The electric field values corresponding to the positions of the observed maxima in the differential curve are also shown in Fig.5 as dashed horizontal lines. The n values which were taken as the best fit to the data are indicated by the solid diagonal line.

The shapes of the maxima in the differential curve were also compared with theory. The Stark effect splits each level of the hydrogen atom into $\frac{n}{2}(n + 1)$ components. Thus each of the levels observed here, with n values ranging from 9 to 22, consisted of a large number of components. The spectrum line shape was broad and consequently if all components were excited there was no possibility of resolving a single line. A portion of the differential curve around $n = 10$ was synthesised by adding together the contribution from each component in the form of a rectangular line of equivalent proportions to the calculated line shape. Allowance was made for the dependence of the ionization probability on electric field strength for each component. All components of a level of given n value were assumed equally populated and the population as a function of n was taken to vary as $1/n^3$. The result is shown as the solid curve in Fig.6 together with the corresponding experimental points of Fig.3. The artificial curve was normalised in amplitude to the central maximum but no adjustment was made of the horizontal axis.

The time spent by an atom in the electric field was changed by altering the energy of the protons. A portion of a differential curve near $n = 11$ which was recorded at a proton energy of 100 keV is shown in Fig.7 together with the corresponding portion of the results taken at a proton energy of 50 keV. There was no measurable shift in the position of the maximum with respect to field strength within the experimental error. However the expected shift is indicated on the diagram and it can be seen that the results do not disagree with this. A much greater change in velocity is required for a useful comparison to be made.

The low field strength part of the differential curve shows a threshold below which no ionization was observed. A detail of the threshold region is shown in Fig.8. The effect was caused by the $e\underline{v} \times \underline{B}$ field in the ion deflection magnet. Excited atoms which were ionized by this field were deflected out of the line of the beam and were not available for ionization in the electrode system. The strength of the field in this magnet was measured with a rotating coil gaussmeter and found to be 417 ± 10 gauss. This meter was calibrated by a proton resonance method. The energy of the atoms was known to be 50.0 ± 0.25 keV, hence the electric field strength equivalent to the $e\underline{v} \times \underline{B}$ field was 1.29×10^3 volt/cm. This value is indicated by the vertical dashed line in Fig.8. The results show that within the experimental error the Lorentz force and pure electric field ionization are equivalent as expected(2).

4. FORMATION OF EXCITED ATOMS BY ELECTRON CAPTURE

The electric field ionization technique was used to measure the formation of excited atoms by electron capture in H_2, He, Ne, A, Kr and Xe. The measurements were made in an earlier experiment in which the distance from the centre of the gas cell to the high field region was 87 cm. Deuterons at an energy of 100 keV were used. It was found that the excited state populations reached equilibrium values when the gas target densities were raised to approx. 10^{16} to 10^{17} atoms/cm^2. The populations of the sum of the four levels with n = 8, 9, 10 and 11 with respect to the total atom intensity was measured under the equilibrium conditions and the results are presented in Table I. In the data for the rare gases Ne, A, Kr and Xe the result for Krypton appears to break a sequence of increasing population with decreasing ionization potential. The ionization potential of Krypton is 14.0 eV and is close to that of atomic hydrogen at 13.6 eV. This may result in an appreciable loss of excited atoms by direct excitation transfer although the cross section for such a process would be expected to be small at this high impact energy. Further results which have been obtained on the formation of excited hydrogen atoms are to presented at the Third International Conference on the Physics of Electronic and Atomic Collisions to be held shortly in London.

TABLE I

GAS	Thick target population of the sum of the levels with n = 8, 9, 10 and 11.
H_2	0.0045 ± 0.0004
He	0.0034 ± 0.0003
Ne	0.0033 ± 0.0003
A	0.0042 ± 0.0004
Kr	0.0037 ± 0.0004
Xe	0.0051 ± 0.0005

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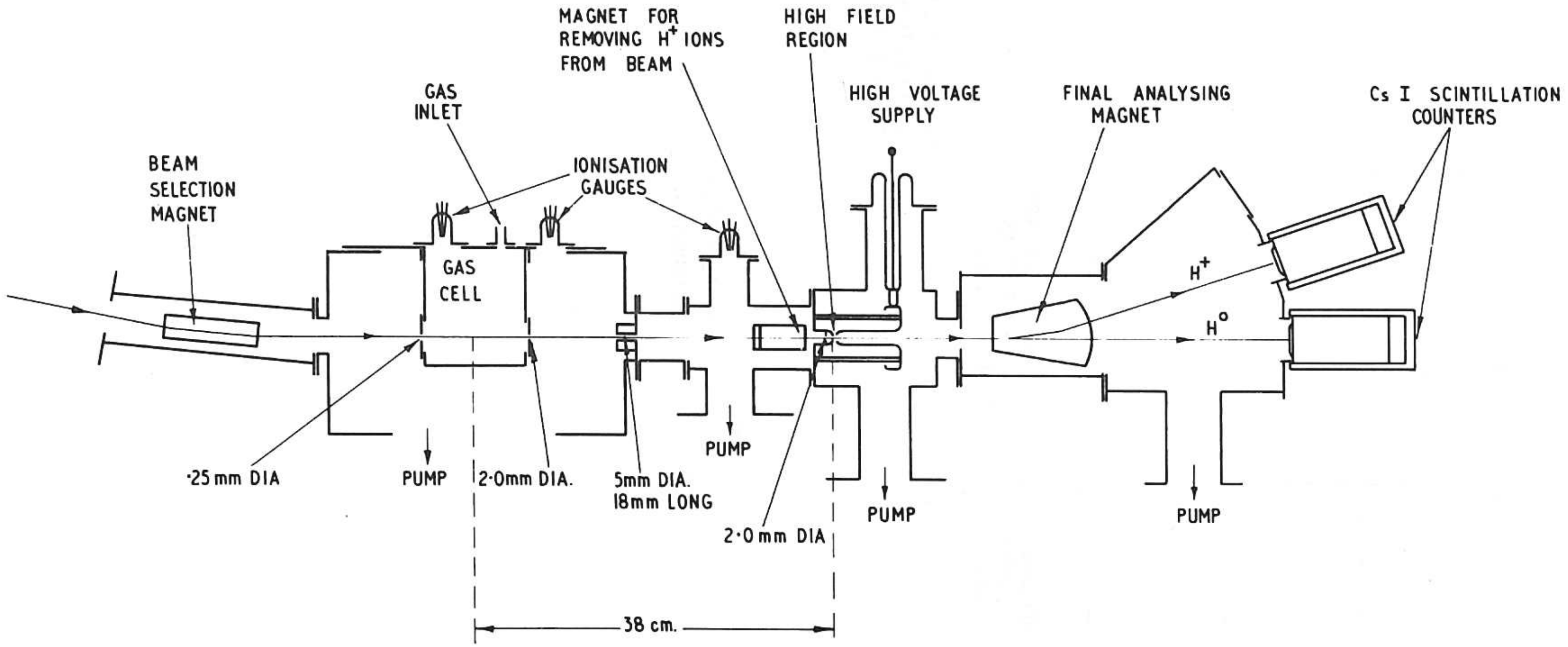
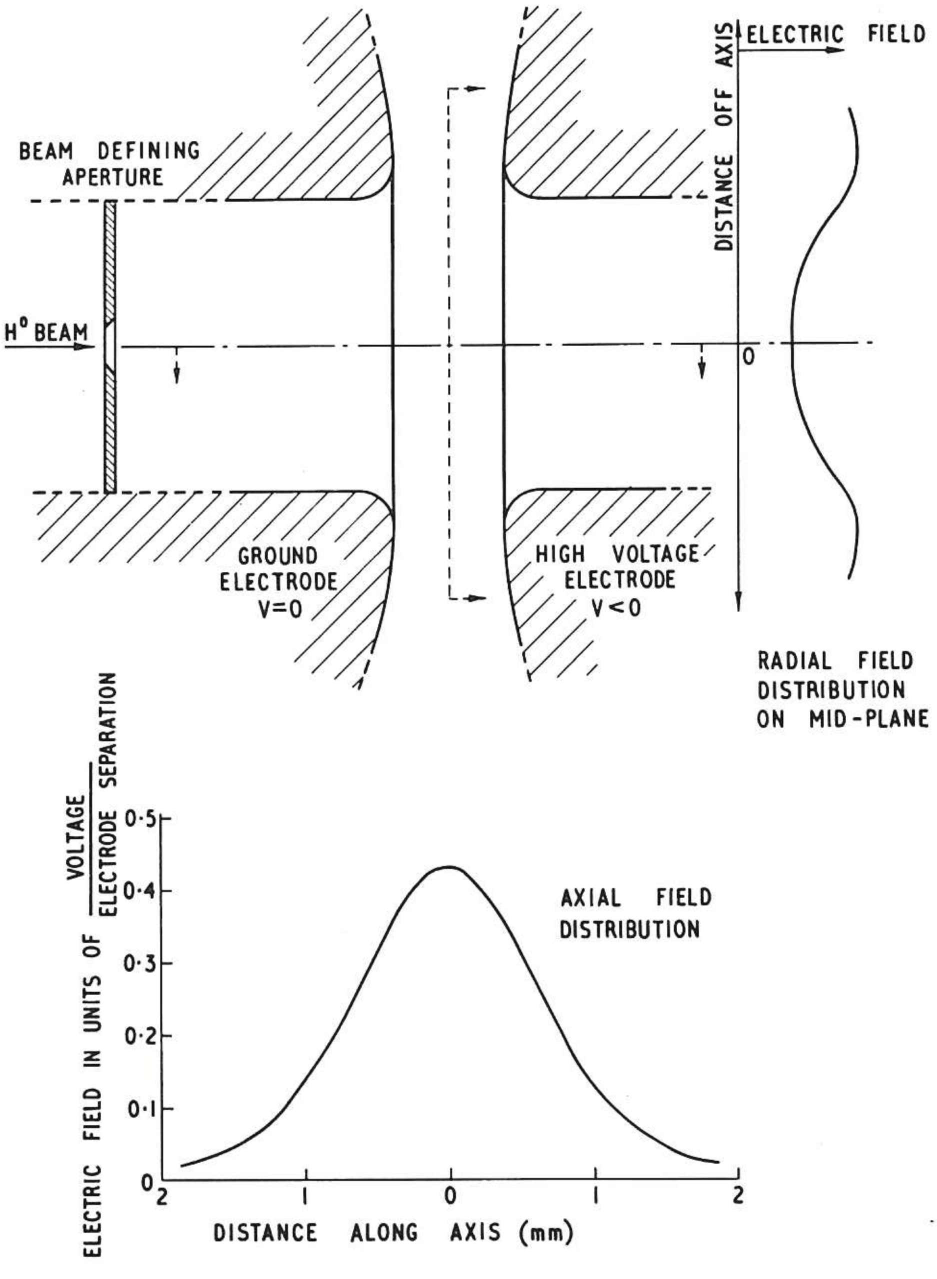
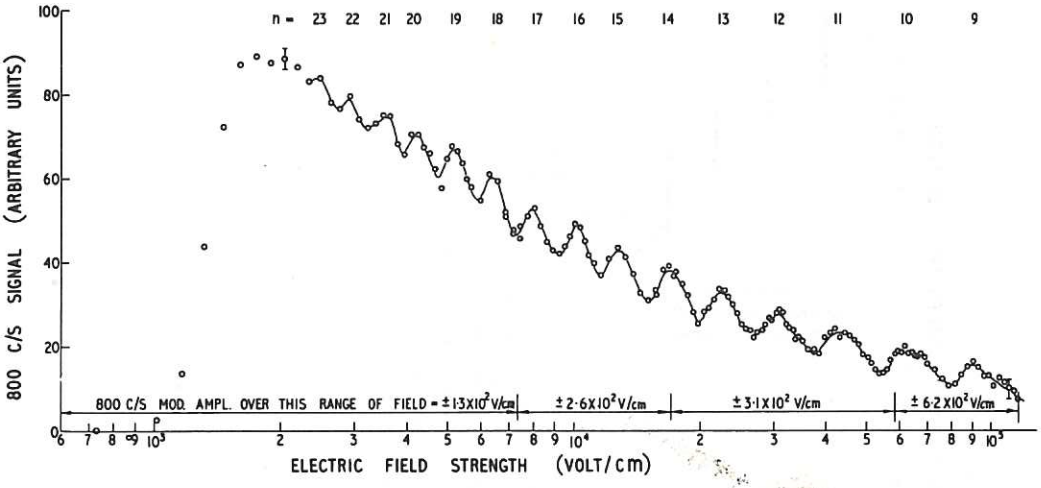


CLM-P 53 . Fig. 1
The experimental system used for electric field ionization of excited hydrogen atoms

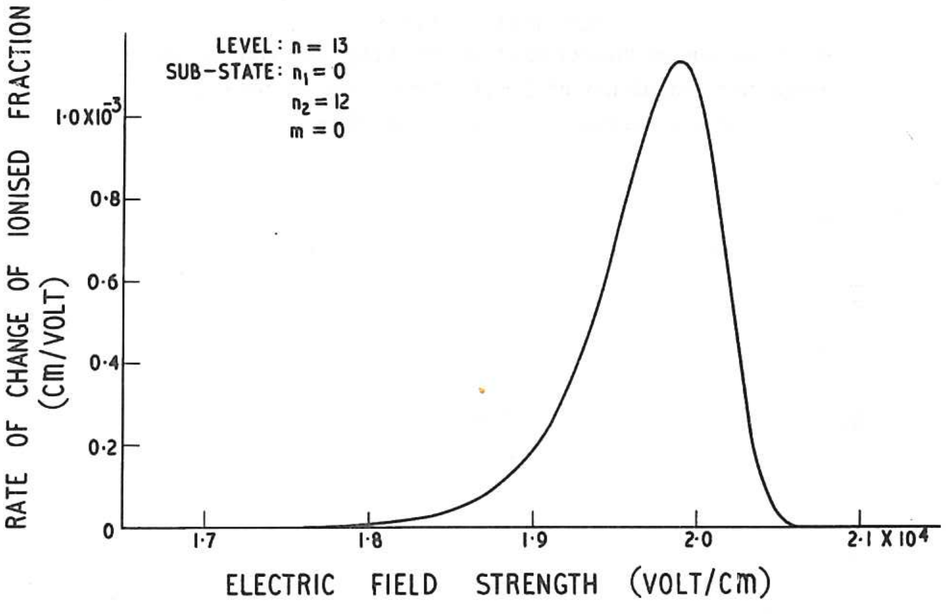


CLM-P 53 Fig. 2

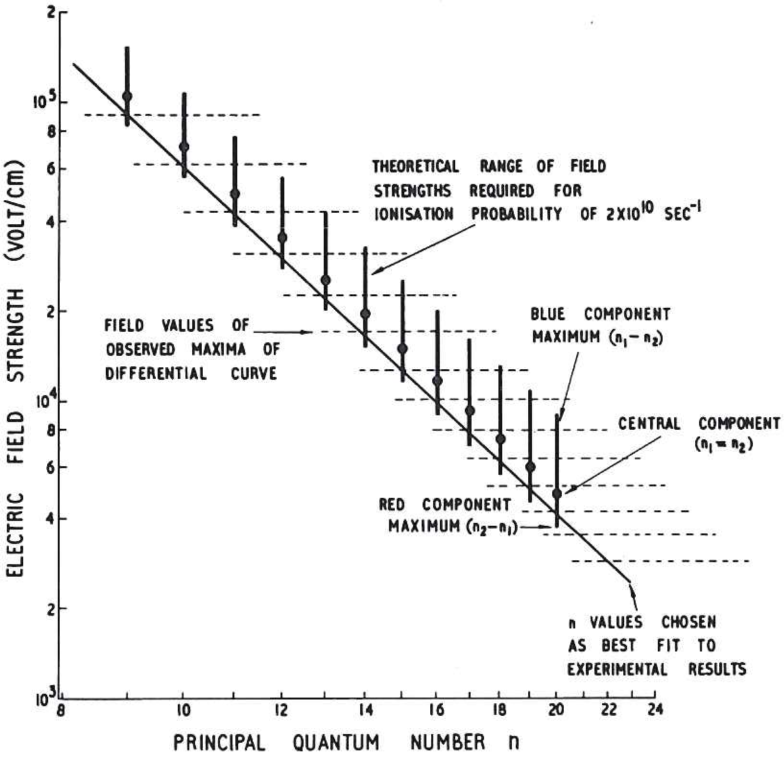
Details of the high field region and the electric field distribution



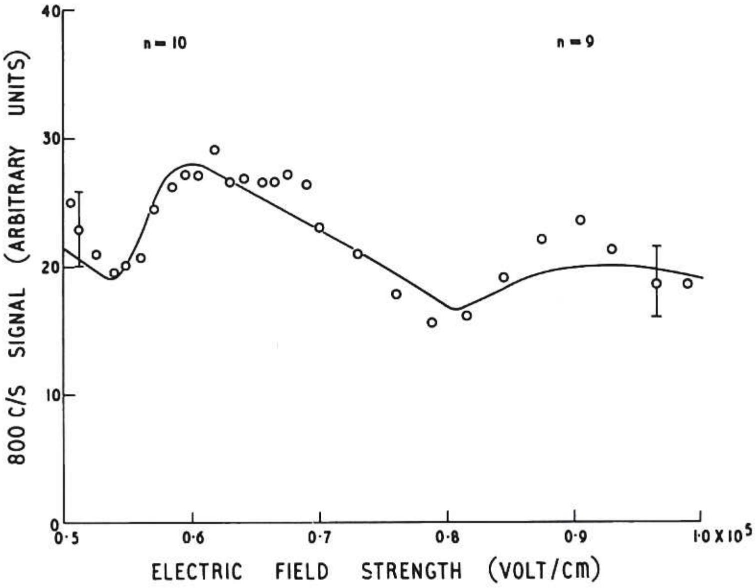
CLM-P 53 Fig. 3
The differential rate of ionization as a function of electric field strength obtained by the 800 c/s modulation technique



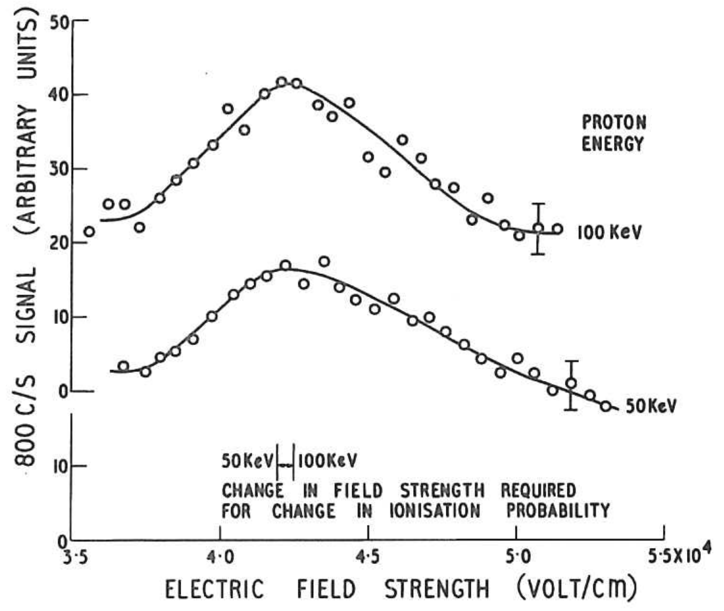
CLM-P 53 Fig. 4
The spectrum line shape for the ($n_1 = 0$, $n_2 = 12$, $m = 0$) component of the level with n = 13 in the limit of zero 800 c/s modulation amplitude



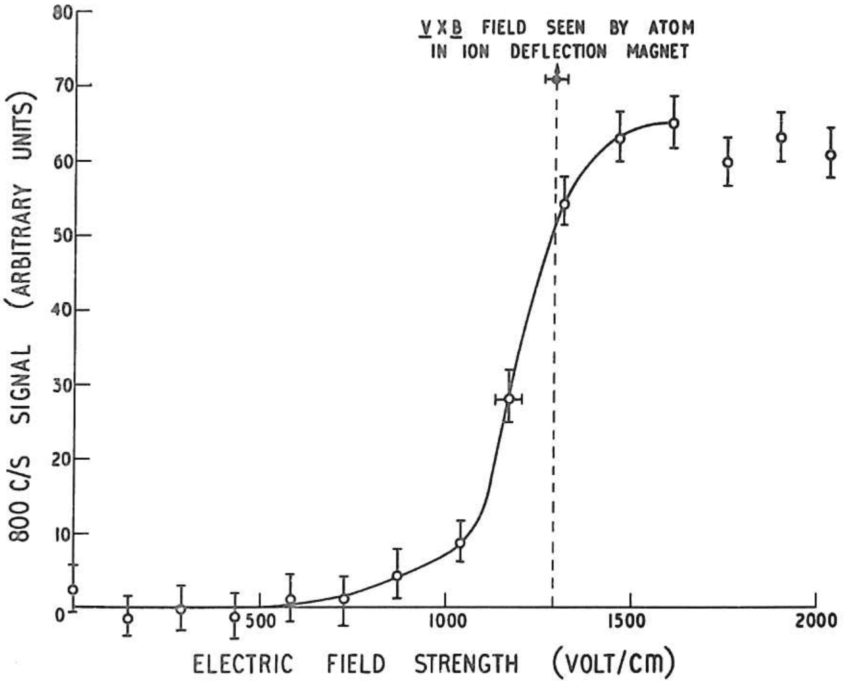
CLM-P 53 Fig. 5
A comparison of theoretical field strengths required for an ionization probability of 2×10^{10} sec^{-1} and the position of the maxima in the experimental results



CLM-P 53 Fig. 6
A comparison of the experimental differential curve with a synthesised curve assuming that all components were equally populated



CLM-P 53 Fig. 7
The differential curves which were taken at proton energies of 50 and 100 keV and which therefore correspond to different times spent in the electric field



CLM-P 53 Fig. 8
A detail of the differential curve near the threshold region showing a comparison with the Lorentz force $\underline{v} \times \underline{B}$ in the ion deflection magnet