Excitation of 10-MeV H^0 Atoms in Neutral- and Charged-Particle Collisions*

KLAUS H. BERKNER, SELIG N. KAPLAN, GEORGE A. PAULIKAS, AND ROBERT V. PYLE
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received 19 November 1964)

Ten-MeV hydrogen atoms with a distribution of excited states were produced by collisional dissociation of 20-MeV H_2^+ ions. The populations of the higher excited levels were removed by Lorentz ionization, and the levels were then repopulated by collisional excitation of the atoms in molecular or weakly ionized hydrogen targets. The populations of the levels $n=6$ to 9 were determined by a second Lorentz ionization. For collisions with electrons and ions in hydrogen-plasma targets, cross sections for transitions from the levels $n=5$, 6 to $n'=6$, 7, 8, 9, and upper limits for the transitions $n=1$ or 4 to $n'=6$ or 7 have been obtained. These are compared with calculations in the first Born, Bethe, and impact-parameter approximations; good agreement is found for all transitions, although those with $\Delta n=2$ are somewhat larger than calculated. For molecular-hydrogen targets, transitions are observed from the sum of all levels with $n\leq 4$, 5, 6 to levels $n'=6$, 7, 8, and 9. Cross sections for the individual transitions from $n=5$, 6 to the levels $n'=6$, 7, 8, and 9 have been deduced from these results. These cross sections differ from those for charged-particle collisions in that they are smaller by about 3 orders of magnitude, and the ratios of cross sections with $\Delta n>1$ to those of $\Delta n=1$ are larger than in the charged-particle case.

I. INTRODUCTION

THE probability of exciting a neutral hydrogen atom from principal quantum level n to $n+1$ by a collision with a charged particle can be very large if n is large. For the case of hydrogen-electron collisions, Milford and co-workers[1] have calculated cross sections for n up to 10 using the first Born and Bethe approximations, and Saraph[2] has calculated up to $n=40$ using Seaton's impact-parameter method. The results of the two calculations are in good agreement in the high-energy region of interest in the present work. Bouthilette, Healey, and Milford[3] have calculated excitation cross sections for neutral hydrogen atom-atom collisions with $n\leqslant 4$, using the first Born approximation.

In the present experiment we have determined the cross sections for excitation from some of the lower lying states into states with $n=6$ to 9 when 10-MeV hydrogen atoms collide with a molecular hydrogen or with a proton-electron target. Populations of the levels $n=6$ to 9 were determined by Lorentz ionization. The high energy puts the experiment well into the region of validity of the Born approximation and allows us to obtain large electric fields with dc magnetic fields (43.7 kV/cm per kG). This makes possible measurements on the nonoverlapping levels of low-lying excited states. In addition, the thermal motion of electrons and the capture of electrons in the targets can be neglected. Preliminary results for the $n=6$ to 7 transition induced by collisions with H_2 have been reported previously.[4]

* Work done under the auspices of the U. S. Atomic Energy Commission.
[1] G. C. McCoyd and S. N. Milford, Phys. Rev. **130**, 206 (1963).
[2] H. E. Saraph, Proc. Phys. Soc. (London) **83**, 763 (1964).
[3] D. B. Bouthilette, J. A. Healey, and S. N. Milford, *Proceedings of the Third International Conference on the Physics of Electronic and Atomic Collisions*, edited by M. R. C. McDowell (North-Holland Publishing Company, Amsterdam, 1964), p. 1081.
[4] Klaus H. Berkner, John R. Hiskes, Selig N. Kaplan, George A. Paulikas, and Robert V. Pyle, *Proceedings of the Third International Conference on the Physics of Electronic and Atomic Collisions*, edited by M. R. C. McDowell (North-Holland Publishing Company, Amsterdam, 1964), p. 726.

II. THEORY SUMMARY

A. Excitation

1. Electron-Atom Collisions

The cross-section calculations of Milford and co-workers[1] were carried out for 0.2- to 10 000-eV electrons by means of the first Born approximation and the Bethe (dipole) approximation. The form of the latter is given by

$$\sigma(n,l\rightarrow n',l')=\pi a_0^2[C(n,l,n',l')/E]\ln D(n,l,n',l')E, \quad (1)$$

where E is the electron impact energy, D is a function of the cutoff momentum and the energy difference between the states, and C is a function of the orbital angular momentum and the dipole matrix element connecting the states. Calculations of the $n=3$ to $n=4$ transitions for all possible l showed that transitions with $\Delta l=\pm 1$ predominate. One also notes that the large-angular-momenta states are most easily excited, that the excitation cross sections increase very rapidly with n (approximately as n^4), and that transitions with $\Delta n=\pm 1$ dominate by about an order of magnitude. The calculations are estimated to be accurate to about 10%.

Cross sections of interest in the present experiment are given in Table I where we have evaluated the above formula at an electron energy of 5425 eV, which corresponds to 10-MeV hydrogen atoms colliding with a cold electron gas. As we are not able to distinguish individual l states experimentally, we statistically average them, i.e., weight them by $(2l+1)$, to find the total cross sections for transitions between principal quantum levels (see discussion in Sec. IV).

The calculations of Saraph,[2] who used Seaton's impact-parameter method, agree with the above results to within about 1%. Values for an electron energy of 5425 eV, together with extrapolations of other perti-

TABLE I. Cross sections, $\sigma_{n,n'}$, for collisions of 10-MeV hydrogen atoms with cold electrons (theoretical). All entries are in units of 10^{-18} cm^2.

$n \backslash n'$	1	2	3	4	5	6	7	8	9	10	11	12	Continuum
1		3.1[a] 3.6[b] 3.6[c]	0.52[a] 0.63[c]	0.22[c]	0.11[c]	0.058[c]	0.035[c]	0.023[c]	0.016[c]	0.012[c]			2.8[e] 3.3[f] 2.8[h]
2	0.9		32[a] 34[b] 53[d]	4.5[a] 6[d]	3[d]	1[d]	0.6[d]	0.4[d]	0.3[d]	0.2[d]			4.8[e] 29[g] 15[h]
3	0.06	15		130[a] 134[b]	17[a]								10[e]
4	0.014	1.1	74		374[a] 374[b]	43[a]							13[e]
5	0.004	0.5	7	240		846[a]	93[a]						18[c]
6	0.002	0.1		12	588		1650[a] 1650[b]	175[a]					22[e]
7	7×10^{-3}	0.05			47	1210		3070[a]	300[a]				26[e]
8	4×10^{-4}	0.03				98	2350		4990[a] 4960[b]	481[a]			30[e]
9	2×10^{-4}	0.01					181	3930		7870[a]	749[a]		34[e]
10	1×10^{-4}	0.01						308	6370		11 900[a] 11 900[b]	1080[a]	39[e]
11									501	9830			43[e]
12										750			46[e]

[a] Ref. 1.
[b] Ref. 2.
[c] Ref. 5.
[d] Statistical average over states of the results of Refs. 6 and 7.
[e] Ref. 8.
[f] Ref. 9.
[g] Ref. 10.
[h] Ref. 11.

nent excitation calculations by McCarroll,[5] McCrea and McKirgan,[6] and Boyd[7] are shown in Table I.[8–11]

2. Proton-Atom Collisions

At high energies the Born approximation gives identical results for collisions of electrons or protons of the same velocity with atoms.[12]

3. Atom-Atom Collisions

Collisions of excited hydrogen atoms with ground-state hydrogen atoms have been investigated in the first Born approximation by Bouthilette, Healey, and Milford (BHM).[3] These calculations are for $n \leqslant 4$ for collisions of the type

$$\mathrm{H}(n,l)+\mathrm{H}(1s) \rightarrow \mathrm{H}(n+1, l')+\mathrm{H}(2s \text{ or } 2p).$$

Although these are only part of the processes by which an atom can be excited from n to $n+1$, the BHM results illustrate two important differences between H-H and H-e collisions: The H-H collisions are smaller by at least two orders of magnitude and they have a very weak dependence on n. Their results were tabulated for energies up to about 4 MeV and indicated a $1/E$ dependence at high energies. Cross sections extrapolated to 10 MeV are given in Table II for the individual transitions and for the total of all transitions, $n \rightarrow n+1$, obtained by statistically weighting the l levels.

TABLE II. Cross sections in units of 10^{-18} cm^2 for hydrogen-hydrogen collisions in which one atom undergoes the indicated transition while the other atom is excited from $n=1$ to $n=2$. The theoretical results of Ref. 3 have been extrapolated to 10 MeV by the assumption of a $1/E$ dependence. The values in brackets are weighted averages over all l values.

Transition	Cross section	Transition	Cross section
$2s$–$3s$	0.028	$3s$–$4p$	0.039
$2s$–$3p$	0.043	$3p$–$4d$	0.068
$2s$–$3d$	0.111	$3d$–$4f$	0.206
$2p$–$3s$	0.006	⟨3–4⟩	0.141
$2p$–$3p$	0.036	$4s$–$5p$	0.037
$2p$–$3d$	0.150	$4f$–$5g$	0.234
⟨2–3⟩	0.190		

B. De-excitation

1. Collisional

At high energies the cross sections for transitions from n to $n+1$ and vice versa are related by the detailed-balance expression

$$\sigma_{n,n+1}=(n+1/n)^2\sigma_{n+1,n}. \qquad (2)$$

[5] R. McCarroll, Proc. Phys. Soc. (London) **A70**, 460 (1957).
[6] D. McCrea and T. V. M. McKirgan, Proc. Phys. Soc. (London) **75**, 235 (1960).
[7] T. J. M. Boyd, Proc. Phys. Soc. (London) **72**, 523 (1958).
[8] A. D. Stauffer and M. R. C. McDowell, in *Proceedings of the Sixth International Conference of Ionization Phenomena in Gases* (Paris, 1963), Vol. I, p. 9.
[9] Wade L. Fite, in *Atomic and Molecular Processes*, edited by D. R. Bates (Academic Press, Inc., New York, 1962), Chap. 12.
[10] P. Swan, Proc. Phys. Soc. (London) **A68**, 1157 (1955).
[11] F. Omidvar and E. Sullivan, in *Proceedings of the Sixth International Conference of Ionization Phenomena in Gases* (Paris, 1963), Vol. I, p. 15.
[12] D. R. Bates, in *Atomic and Molecular Processes*, edited by D. R. Bates (Academic Press, Inc., New York, 1962), p. 551.

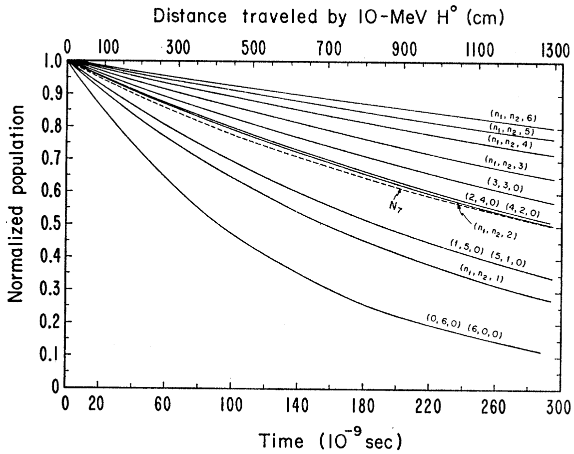

FIG. 1. Radiative decay of the populations of the individual states of the level $n=7$ for the Stark case. The dashed line is the statistically averaged decay rate for that level. The curves are labeled by the parabolic quantum numbers n_1, n_2, and m [Ref. 15(a)].

2. Radiative

The radiative decay of a quantum level n is determined by the radiative lifetimes and the populations of the various states of the level. The radiative lifetimes (electric-dipole radiation) for excited states of the hydrogen atom have recently been calculated by Hiskes, Tarter, and Moody[13] and Hiskes and Tarter[14] in both spherical (field-free case) and parabolic (Stark case) coordinates. Since the population of the states was not known, we assumed that initially all states $(n, l, \pm m)$ in the field-free case or $(n_1, n_2, \pm m)$ in the Stark case were equally populated. The time development of the number of particles in the level n is then given by

$$[N_n(t)/N_n(t=0)]=(1/n^2)\sum_{l=0}^{n-1}(2l+1)\times\exp[-t/\tau(n,l)], \quad (3)$$

for the field-free case, and by the following equation for the Stark case[15(a)]:

$$\frac{N_n(t)}{N_n(t=0)}=\frac{1}{n^2}\left\{\sum_{n_1=0}^{n-1}\exp\left[-\frac{t}{\tau(m=0,\,n_1)}\right]+\sum_{m=1}^{n-1}2(n-m)\exp\left[-\frac{t}{\tau(n,m)}\right]\right\}. \quad (4)$$

[13] John R. Hiskes, C. Bruce Tarter, and D. A. Moody, Phys. Rev. **133**, A424 (1964).

[14] John R. Hiskes and C. Bruce Tarter, Lawrence Radiation Laboratory Report UCRL-7088 and UCRL-7088 (Rev. 1), 1963 (unpublished).

[15] (a) The weak dependence of $\tau(n_1,n_2,m)$ on n_1 and n_2 for $m>0$ makes it permissible to use $\tau(n,m)$ for $m>0$. See the discussion in Ref. 13. (b) J. R. Hiskes, in *Proceedings of the Sixth International Conference of Ionization Phenomena in Gases* (Paris, 1963), Vol. I, p. 99.

Expressions (3) and (4) have been evaluated for $n=3$ to 10 from the results of Hiskes and Tarter. In the Stark case the levels decay somewhat more rapidly than in the field-free case, but for the conditions of the present experiment the populations that survive the longest flight path do not differ by more than a few percent for the two cases. Because of the stray magnetic fields in the experimental area, we believe that the Stark lifetimes are appropriate. The calculated decay of the states of the $n=7$ level are given in Fig. 1 and the statistically weighted decays of the various levels are shown in Fig. 2.

The theoretical cross sections shown in Table I were all calculated for the field-free case. It can be shown, however, from the results of Hiskes[15(b)] that at our energy the statistically averaged field-free and Stark cross sections differ at most by 5%.

C. Ionization

1. Collisional

For ionization of excited hydrogen atoms, Bethe approximation calculations for e-H collisions have been reported by Stauffer and McDowell.[8] The results obtained by extrapolation from 200- to 5425-eV electrons are given in Table I. For low-n values these calculations are smaller than first-Born-approximation results by as much as a factor of five. Although the magnitudes may be too small, these results indicate that the ionization cross section is approximately proportional to n. Excitation and ionization cross sections are comparable for the ground state, but the cross sections for excitation of the higher levels are much greater than those for ionization.

2. Lorentz

Theoretical calculations have been reported for the ionization of hydrogen atoms in strong electric fields, and Hiskes has shown that these results apply for Lorentz ionization in a magnetic field by the equivalent electric field $\mathbf{v}\times\mathbf{B}$.[16]

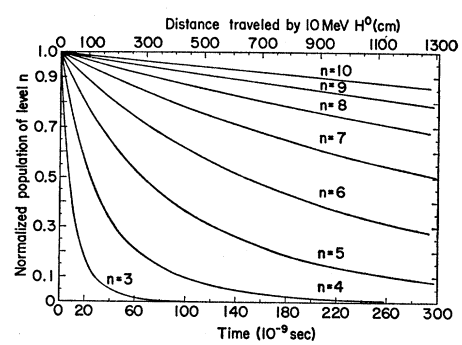

FIG. 2. Radiative decay (statistically averaged over states) of the population of the levels $n=3$ to 10 for the Stark case.

[16] J. R. Hiskes, Nucl. Fusion **2**, 38 (1962).

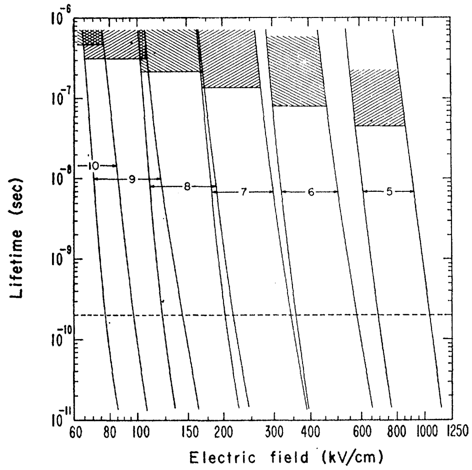

FIG. 3. Detachment lifetimes versus field strength for the extreme Stark components of the $n=5$ to 10 levels, using the Rice and Good model (from Ref. 17). The shaded region indicates the range of lifetimes for spontaneous radiative transitions to lower levels for the various Stark states of each level (Ref. 13). The dashed line is the mean lifetime in the field profile used in this experiment. To achieve this detachment lifetime for the $n=4$ level, 1300 to 1600 kV/cm would be required.

The results of Bailey, Hiskes, and Riviere[17] (who used the Rice and Good[18] model) for the extreme Stark components of the levels $n=5$ to 9 are shown in Fig. 3. Ionization of a particular level n will occur over the indicated field range due to a population distribution over all Stark states within a given level. Note that for $n\geqslant 7$ the threshold fields for states of neighboring levels begin to overlap. This becomes more pronounced for very large n, and the thresholds for states of as many as five different levels may overlap for $n=25$. Various states (n_1,n_2,m) of each level have different lifetimes for radiative decay to lower states, and the shaded regions indicate the range of spontaneous radiative transition lifetimes for the states of each level.[13]

III. EXPERIMENTAL APPARATUS AND PROCEDURE

A. Production of 10-MeV Excited Hydrogen Atoms

The over-all experimental arrangement is shown schematically in Fig. 4. The Berkeley heavy-ion linear accelerator (Hilac) produced a beam of 20-MeV H_2^+ ions. This beam was bent 15 deg to remove possible contaminants and was partially dissociated by collisions in the first gas cell. Of the two modes of collisional dissociation,

$$H_2^+ \rightarrow 2H^+ + e^-,$$

and

$$H_2^+ \rightarrow H^+ + H^0(n,l),$$

the second produces 10-MeV atoms with a distribution of excited levels. Since only the atoms were of interest, the charged particles H^+ and H_2^+ were swept out of the beam with magnet $LM1$. The first gas cell was filled with H_2 gas at a pressure of 2×10^{-2} Torr; this gave a good yield of neutral atoms and made it possible for the adjacent drift section to be maintained at less than 10^{-5} Torr.

The magnet $LM1$ not only swept out the ions but also Lorentz ionized the highly excited neutral atoms. The minimum field used to sweep out the ions was 2 kG($\mathbf{F}=\mathbf{v}\times\mathbf{B}=87.4$ kV/cm), which is sufficient to Lorentz ionize all levels above $n=10$. The field could be increased to a maximum of 22 kG(961 kV/cm), which is sufficient to Lorentz ionize most of the $n=5$ level. By choice of the appropriate field strength, it was thus possible to prepare a beam of hydrogen atoms in which only the excited levels $n=1$ to n^* were populated, where n^* could be varied from 4 to 10.

B. Targets

1. The Neutral Gas Target

The neutral beam passed through a 200-cm drift section and then entered the target section, where either a differentially pumped gas cell or a weakly ionized Philips ionization gauge (PIG) discharge could be used. The gas cell [Fig. 5(a)] consisted of a target chamber and an intermediate-pressure region backed by a 1500 liter/sec oil-diffusion pump. It was possible to maintain the pressure in the intermediate region a factor of 100 lower than the pressure in the target chamber. The pressure in the drift sections was again a factor of 100 less. For example, when the pressure in the target section was 5×10^{-2} Torr, the pressure in the drift sections was approximately 5×10^{-6} Torr.

A base pressure of 1×10^{-6} Torr could be achieved in the gas cell. During operation, hydrogen gas was continuously bled through the chamber. The gas was obtained from a cylinder of commercial high-purity gas and no further purification was attempted. Typical operating pressures ranged from 1×10^{-3} to 5×10^{-2} Torr.

A linear pressure drop in the connecting tubes was assumed, and the effective length of the target chamber was taken to be 24 ± 1 cm, the distance between the

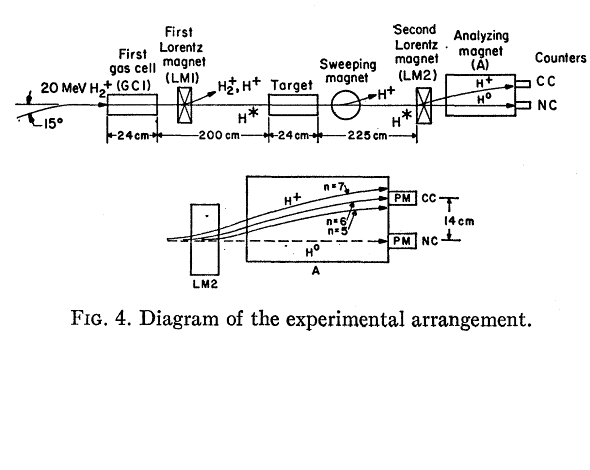

FIG. 4. Diagram of the experimental arrangement.

[17] D. S. Bailey, J. R. Hiskes, and A. C. Riviere, U. K. A. E. A. Culham Laboratory Report CLM-P 50, 1964 (unpublished).
[18] M. H. Rice and R. H. Good, Jr., J. Opt. Soc. Am. 52, 239 (1962).

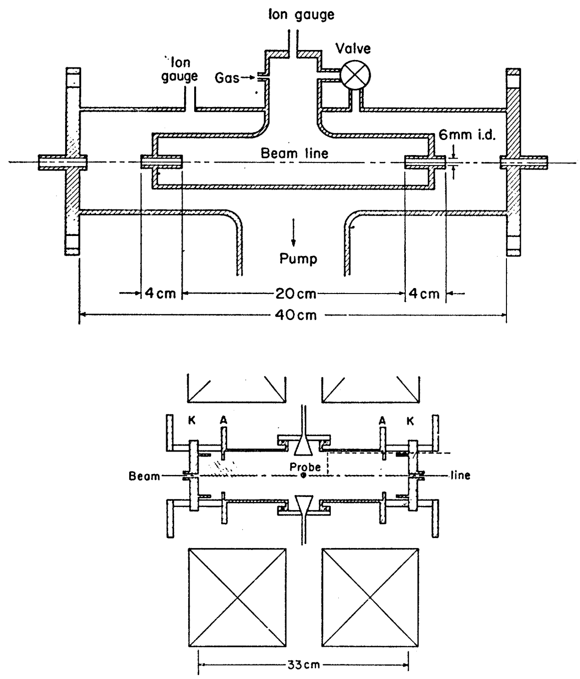

FIG. 5. (a) (Above.) Diagram of the gas target. (b) (Below.) Diagram of the PIG discharge-target chamber (drawn to scale). The dashed line indicates the shape of the right-angle probe used for longitudinal density measurements. The radial probe is indicated by ⊙ midway between the microwave horns.

midpoints of the connecting tubes. The pressure in the target chamber was monitored by a Westinghouse-Type 7676 high-pressure ionization gauge (Schulz-Phelps gauge). This was cross calibrated with three liquid-nitrogen or acetone—dry-ice—trapped McLeod gauges. At best, the McLeod gauge readings agreed within 5%. This uncertainty of the absolute accuracy of the McLeod gauges and fluctuations in the calibration from day to day indicate an uncertainty of $\pm 10\%$ in the target-cell-pressure measurement.

2. *The Weakly Ionized Target*

For the study of collisions with charged particles, the gas target was replaced by a PIG discharge. A diagram of the discharge chamber is shown in Fig. 5(b). The field coils provided an axial magnetic field of the order of 200 G. A brass central chamber, maintained at ground potential, served as the anode. Two oxidized aluminum disks, insulated from the anode by 5-cm glass sections, served as cold emission cathodes.

The beam pulses from the Berkeley Hilac are 3 msec long, with a 12 to 20 per sec repetition rate. The discharge was operated on a pulsed basis; a negative potential, typically 500 V with respect to the anode, was applied 1 msec before the beam pulse arrived and was maintained for 5 msec. The discharge current during this time was approximately 1 A. The PIG operated in hydrogen over a pressure range from 2×10^{-3} to 2×10^{-2} Torr, and the gas was continuously bled through the chamber. Both the applied voltage and the pressure were varied to achieve a range of electron densities. A maximum of 1% ionization could be attained.

During data runs the plasma density was monitored by a radial Langmuir probe, 1.25 cm from the beam axis, and by phase-shift analysis of radially propagated 8-mm microwaves. Integrated results of a complete radial density profile were typically 30% lower than the microwave values, so the two values were averaged. The results were multiplied by 2 to give the total charged-particle density (electrons and ions). The total number of particles along the axis of the target chamber was determined from the above measurements and from measurements with an axially movable Langmuir probe with a 90-deg bend 3.5 cm from the tip so that the probe shaft would not perturb the discharge [Fig. 5(b)]. The net uncertainty in the number of charged particles "seen" by the beam is estimated to be $\pm 25\%$.

C. Measurement of the Population of the Excited Levels

A 225-cm drift section, maintained at a pressure of 10^{-5} Torr or less, connected the target with the analyzing section. In this region, a sweeping magnet (1.4 kG) removed the protons produced by ionizing collisions in the target. Magnets $LM2$ and A, together with the detectors NC and CC, were used to measure the populations of the excited levels of the 5-mm-diam beam of neutral atoms. Magnet $LM2$, which has tapered pole faces, produced a nonuniform field profile so that the Lorentz ionization of successively lower levels occurred sequentially in space as the beam passed through this nonuniform field. Consequently, the protons resulting from Lorentz ionization of levels of high n underwent larger deflections in the field of $LM2$ than those from lower levels. This process is illustrated in the inset at the bottom of Fig. 4. The maximum field strength of $LM2$ is 18 kG, equivalent to an electric field of 787 kV/cm in the rest frame of the 10-MeV H^0. This field is sufficient to Lorentz ionize some of the states of the $n=5$ level and all states of the levels with $n>5$ in the time that the beam spends in the field region. While the unstripped neutrals were monitored by the neutral counter NC, the protons were steered to the charged-particle counter CC by the analyzing magnet A. The particles left the vacuum region through 125 μ thick Al windows and struck the detectors, each of which was a 5-cm-diam plastic scintillator connected by a 28-cm Lucite light pipe to an RCA-type-6810A photomultiplier tube. The outputs of the photomultipliers were recorded on scalers. A profile of the spatial distributions of the protons resulting from Lorentz ionization of various levels in $LM2$ was obtained by varying the field of A.

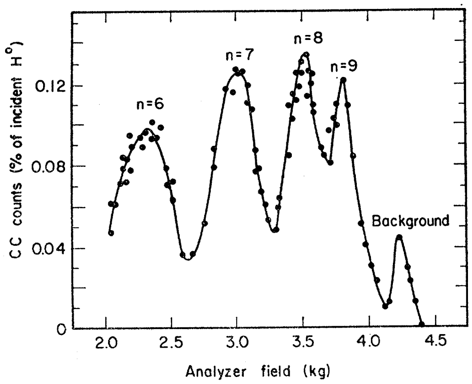

FIG. 6. Lorentz-ionization profile, measured with counter *CC*, for the excited levels $n=6$ to 9. The peak labeled "Background" is due to ionization by collisions with the background gas in the drift section between the sweeping magnet and *LM*2. The pressure in the first gas cell was 24×10^{-3} Torr (1.9×10^{16} H_2 molecules per cm^2), and in the second gas cell $<10^{-6}$ Torr. The magnetic fields were *LM*1, 0; *LM*2, 13.85 kG (607 kV/cm); sweeping magnet, 1.6 kG (70 kV/cm), sufficient to Lorentz ionize levels with $n\geq10$.

Good resolution in these profiles was obtained by using a 3-mm-wide by 40-mm-high collimating slit in front of the detector *CC*. An example is shown in Fig. 6.

To permit integration of the counts in each peak, the resolution of the system was measured by stripping the neutral beam with a 6-μ-thick Al foil placed in various positions in the field of *LM*2 and sweeping the resultant proton beam with magnet *A* across two 3-mm-wide collimator slits, 22 mm apart, in front of *CC*. The dispersion, approximately 45 mm/kG, varied by 15% over the range of magnetic field used in *LM*2. From a comparison of these trajectories with measured Lorentz profiles, it was estimated that the levels undergoing Lorentz ionization had an average lifetime in the field of approximately 2×10^{-10} sec. The data-collection rate was limited by the response time of the *NC* scaler to the very large neutral-beam intensity. To reduce the counting time, a 0.27-mm-thick perforated nickel plate was placed in front of the neutral-atom detector *NC* to attenuate the neutral-beam counts. This plate allowed 1 out of 63 incident atoms to reach the detector, thus allowing the beam level to be raised by this factor.

A pulse-height analysis of the photomultiplier signals was also made. This showed a clean signal at 10 MeV, with some very low-energy noise. Discriminators were adjusted to remove this noise. With no perforated nickel plate, it was found that $<0.2\%$ of the pulses in the neutral detector corresponded to an energy transfer of 20 MeV; this sets an upper limit of 0.2% on the $2H^0$ or $H_2{}^0$ contamination of the H^0 beam.

Since the PIG target was weakly ionized, it was necessary to separate out the effects of collisions with neutrals. This was accomplished by pulsing the PIG on only during every second beam pulse. Two sets of scalers were used with each detector, and these were electronically gated so that one set recorded the data for the beam pulse when the PIG was on, the other when the PIG was off. The difference in these two readings was then due to collisions with electrons and protons.

An alternate method for determining the Lorentz-ionization profile for the neutral gas target was to use a nuclear emulsion instead of the counter *CC*. For a fixed field in magnet *A*, the protons were recorded on an Ilford K-2 nuclear emulsion placed in the vacuum system. During the exposures the neutral beam was monitored with *NC*.

When the target was evacuated, positive identification of the level *n* corresponding to each peak was obtained by observing the disappearance of individual peaks caused by Lorentz ionization as the magnetic field in *LM*1 was increased from zero. The disappearance of a particular peak was correlated with the theoretical predictions for strong field ionization (Fig. 3) to determine the corresponding level.

To determine changes in the population of the excited levels due to collisional excitation, *LM*1 was set to remove all incident atoms in excited levels above a predetermined value n^*. The repopulation of these levels was then observed as a function of the target thickness. Figure 7 is an example obtained with a nuclear emulsion for the case for which all levels with $n>5$ had been removed by Lorentz ionization, and then repopulated by collisions with H_2 molecules.

Population measurements for the levels $n=6$, 7 were reproducible within 15% when measured with counters and within 20% when measured with nuclear emulsions. However, the emulsion results averaged about 30% lower than the counter measurements, presumably because of a systematic error in the spatial resolution of the charged-particle counter, and/or the scanning efficiency of the nuclear emulsions.

Further experimental details can be found in Ref. 19.

IV. ANALYSIS AND RESULTS

In the analysis the measured populations were corrected for radiative decay with the lifetimes calculated by Hiskes, Tarter, and Moody (Fig. 2). To make cor-

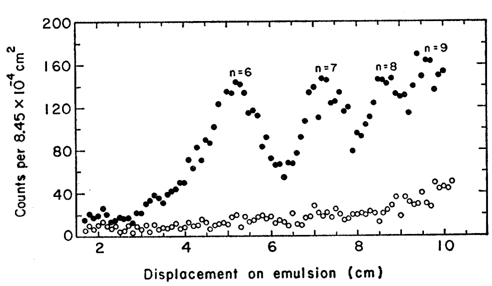

FIG. 7. Change in population of the levels $n=6$ to 9 due to collisions with H_2. All levels above $n=5$ of the incident beam were depopulated by Lorentz ionization of *LM*1. ○, evacuated target; ●, 49×10^{-3} Torr (5.7×10^{16} molecules/cm^2).

rections for radiative decay we assume that there is a statistical-population distribution among the states of a given level, but it must be emphasized that we do not in fact know the population distribution. Although, in the initial process of formation, the neutral atoms are primarily in low-angular-momentum states,[20] a redistribution toward higher angular-momentum states with the same principal quantum number will be caused by further collisions in the gas cell.[21] Decay measurements by Riviere on low-energy atoms in the $n=11$ level indicated rates intermediate between those for $l=1$ and a statistical distribution.[22] Similar decay measurements on the $n=6$ and 7 levels during the present experiment, although not very accurate, are consistent with a statistical distribution.

The total neutral beam incident on the target cell was obtained by correcting the observed neutral counts for ionization in the targets. For the neutral targets, the previously measured ionization-cross-section value of $\sigma_C=2.2\times10^{-18}$ cm² per H_2 molecule was used,[23] and for the ionized targets we extrapolated the experimental values of Fite and Brackmann[9] and obtained $\sigma_C=3.3\times10^{-18}$ cm² per electron or proton.

The collision-induced change in the population of the level n is described by the equation

$$\frac{dN_n}{d\pi}=-N_n(\pi)[\sigma_{n,C}+\textstyle\sum_{n'\neq n}\sigma_{n,n'}]+\textstyle\sum_{n'\neq n}N_{n'}(\pi)\sigma_{n',n}\,, \qquad (5)$$

where π is the number of electrons per cm² traversed by the beam (distance times target density), and $N_n(\pi)$ is the number of atoms in the level n after passing through an element of target thickness π. The first term on the right-hand side describes the losses from the level n due to ionization, de-excitation, and excitation of that level. The second term describes gains resulting from excitation and de-excitation of the neighboring levels.

A. Lorentz Ionization

Attenuation curves for the levels 5 through 9 have been investigated previously[4] and found to be in good agreement with the model of Rice and Good.

B. The Populations of Excited Levels of H^0 Atoms from Collisional Dissociation of H_2^+

Neutrals produced by dissociation of H_2^+ ions are expected to be excited in the proportion A/n^3, where A can range from 2 to 8 depending on the populations of the H_2^+ vibrational levels.[24] Our results, corrected for radiative decay, are consistent with $A\approx2$.

C. H^0–Charged-Particle Collisions

The experimental results for excitation by charged particles in a proton-electron gas, analyzed in the thin-target approximation to Eq. (5), are given in Table III. The observed population of $n=6$ was consistent with $2/n^3$ to within 10%. The populations of levels with $n<6$ could not be determined experimentally, and we assumed that the $2/n^3$ distribution holds for $n=4$ and 5 and corrected them for radiative decay. The $n=2$ and 3 levels were almost completely depopulated by radiative decay in the 2-m drift section. However, the $n=4$ level did not decay completely and could not be removed by $LM1$. Therefore, only upper limits could be derived for excitation from $n=1$ and $n=4$. In the case of excitation from $n=5$ it was not possible to separate the $n=8$ and 9 populations, which have therefore been lumped together in the table.

Table III. Cross sections $\sigma_{n,,n'}$ for excitation of 10-MeV H atoms by collisions with charged particles in a hydrogen plasma, in units of 10^{-18} cm²/charged particle. The theoretical values are from Table I. The estimated relative uncertainties in the experimental values are ±25% and the absolute uncertainties are ±40%.

<table>
<tr><th></th><th colspan="4">Experimental</th><th colspan="4">Theoretical</th></tr>
<tr><th>$n \backslash n'=$</th><th>6</th><th>7</th><th>8</th><th>9</th><th>6</th><th>7</th><th>8</th><th>9</th></tr>
<tr><td>1</td><td><1.3</td><td><0.5</td><td></td><td></td><td>0.058</td><td>0.035</td><td>0.023</td><td>0.016</td></tr>
<tr><td>4</td><td><148</td><td><57</td><td></td><td></td><td>43</td><td></td><td></td><td></td></tr>
<tr><td>5</td><td>945</td><td>210</td><td colspan="2">135</td><td>846</td><td>93</td><td></td><td></td></tr>
<tr><td>6</td><td></td><td>1700</td><td>510</td><td>190</td><td></td><td>1650</td><td>175</td><td></td></tr>
</table>

Theoretically, the ionization cross sections are predicted to be at least an order of magnitude smaller than the excitation cross sections (Table I). We were not able to measure the ionization cross sections but we do observe that the amount of depletion of a quantum level can be accounted for by increased populations of the other levels. This observation is consistent with the ionization's being small.

D. H^0-H_2 Collisions

In this case contributions from $\Delta n>1$ transitions are comparable to those of $\Delta n=1$, as can be seen from Fig. 7. (From 0 to 50-mTorr, the approximately linear growth with pressure of the populations of $n=6$ to 9 confirms that these are thin-target measurements.) Consequently, the determination of cross sections for transitions between two levels is difficult. The difficulty is compounded by the fact that the ionization cross sections for highly excited atoms cannot be ignored. At this energy the ground-state ionization cross section has been measured[23] to be 2.2×10^{-18} cm²/molecule.

[19] Klaus H. Berkner, Lawrence Radiation Laboratory Report UCRL-11249, 1964 (unpublished).
[20] Reference 12, p. 575.
[21] This is commonly believed, but we know of no theoretical calculation for these collisions.
[22] A. C. Riviere and H. Wind, U. K. A. E. A. Culham Laboratory Report CLM-PR 7, 1964, p. 48 (unpublished).
[23] Klaus H. Berkner, Selig N. Kaplan, and Robert V. Pyle, Phys. Rev. **134**, A1461 (1964).
[24] John R. Hiskes, Bull. Am. Phys. Soc. **7**, 486 (1962).

TABLE IV. The probability of excitation to levels $n=6$ to 9 from the sum of all levels $n \leq n^*$, in units of 10^{-20} cm²/molecule. The stated errors represent the estimated uncertainties in the unfolding of the emulsion data into the various n levels.

n^* \ n	6	7	8	9
4	1.03±0.09	0.77±0.05	0.72±0.08	0.53±0.05
5	1.46±0.09	1.00±0.04	0.77±0.06	0.55±0.04
6		1.44±0.05	1.00±0.06	0.66±0.04

TABLE V. Cross sections $\sigma_{n,n'}$ for excitation by collisions with with H_2 in units of 10^{-18} cm²/molecule. The errors reflect only the experimental uncertainties of Table IV.

n \ n'	6	7	8	9
1	<0.014	<0.009	<0.008	<0.006
4	<1.9	<1.3	<1.1	<0.8
5	0.67±0.24	0.32±0.10	0.065±0.15	0.025±0.08
6		0.81±0.13	0.40 ±0.20	0.16 ±0.16

From the variation with pressure of data of the kind shown in Table IV we conclude that ionization cross sections for $n=6$ to 9 are comparable to, but perhaps as much as a factor of two larger than, that for the ground state.[25–27]

Table IV gives values directly deducible from experimental data, namely the observed probability per target H_2 molecule that collisions of neutrals having quantum numbers less than or equal to a specified value n^* will populate a level with principal quantum number n. These results were obtained with a pressure of 50 mTorr in the second gas cell.

Table V shows cross sections for specific transitions obtained from the data of Table IV and based on the following assumptions: Levels are initially populated as $2/n^3$; states of a given level are statistically populated and decay with Stark lifetimes; and the ionization cross sections of excited levels are the same as for the ground state (2.2×10^{-18} cm²/molecule). Ionization cross sections twice this size would increase the tabulated values by about 13%.

[25] A similarly weak n-dependence of the ionization cross section can be deduced for 100-keV H^0 atoms by comparing the $n=14$ measurements of Riviere and Swetman (Ref. 26) with the measurements of Stier and Barnett (Ref. 27).

[26] A. C. Riviere and D. R. Sweetman, *Proceedings of the Third International Conference on the Physics of Electronic and Atomic Collisions*, edited by M. R. C. McDowell (North-Holland Pubishing Company, Amsterdam, 1964) p. 734.

[27] P. M. Stier and C. F. Barnett, Phys. Rev. **103**, 896 (1956).

V. DISCUSSION

The observed threshold fields for Lorentz ionization of the levels $n=5$ to 9 are in good agreement with theoretical calculations for electric-field ionization. For collisions with electrons and protons in a hydrogen plasma, the observed $\Delta n=\pm1$ cross sections are in good agreement with the results of calculations in which the first Born, Bethe, and impact-parameter approximations are used. For transitions with $\Delta n=\pm2$, the experimental results appear to be somewhat larger than those theoretically predicted.

Cross sections for excitation by collisions with neutral hydrogen molecules are smaller than those for collisions with charged particles by about three orders of magnitude, and the ratios of cross sections with $\Delta n>1$ to those with $\Delta n=1$ are larger than in the charged-particle case.

ACKNOWLEDGMENTS

We are grateful to Dr. C. M. Van Atta for supporting and encouraging this research. One of us (SNK) thanks Dr. Burton J. Moyer for the support and interest that enabled him to participate. We also thank Dr. John R. Hiskes for many helpful discussions. The help of J. Warren Stearns and Vincent J. Honey is greatly appreciated. Mrs. Aneta E. Wharry did much of the emulsion scanning.