ory and data call attention to the need for further investigation on the more exact inclusion of the Coulomb interaction. Until such calculations are performed, it appears that further conclusions will be limited, particularly those concerning nuclear charge-symmetry breaking in the three-nucleon system.

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Measurement of Excited-State Charge-Exchange Cross Sections

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A new fast-beam microwave optical detection technique which uses a specially designed interaction region to observe resonances with both polarizations of the microwave field and both polarizations of the emitted light has been developed to study charge-exchange collisions in greater detail. The first measurements of the partial cross sections for capture into each of the L and M_L states in the $n = 3$ manifold for protons incident on a nitrogen target are reported.

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The charge-exchange reaction in which protons capture an electron and form hydrogen atoms is a fundamental reaction which has great relevance in both pure and applied physics.[1-4] There are many theoretical calculations based on a wide variety of methods which disagree in detail with one another. Most of the comparisons of theory and experiment are confined to measurements of the total cross sections. There are, in particular, no measurements of the L and M_L dependence for the cross sections for capture into a manifold with a given principal quantum number. This paper reports the development of a new fast-beam microwave resonance optical detection technique for the study of charge-exchange collisions which uses a specially designed microwave interaction region to observe resonances with both polarizations of the microwave field and both polarizations of the emitted light. This technique has been used to measure for the first time the partial cross sections for capture into each of the L and M_L states of the $n = 3$ manifold. Measurements for 49-keV protons incident on a nitrogen target are reported.

The microwave optical detection (MROD) technique has been successfully used on charge-exchange–produced fast atomic beams to measure the fine structure and the Lamb shift in hydrogen and other simple atoms.[5] The magnitude of the observed signals has also been used to study charge-exchange collisions.[6-8] In the simplest approximation the amplitudes of the MROD signals are proportional to the differences of the populations of the excited-state atoms. The major difficulties in the study of charge-exchange collisions are understanding how the experimental signals depend on the charge-exchange–produced populations, making enough independent measurements to determine all the populations, and determining the cross sections from the signals.

Figure 1 shows the energy levels for the $n=3$ manifold of hydrogen and the electric dipole rf transitions that can be observed. The P states decay dominantly through the emission of Lyman-β radiation to the ground state; the S and D states decay to the $2P$ state with the emission of Balmer-α radiation.

A schematic diagram of the apparatus is shown in Fig. 2. The fast protons ($E=49$ keV) enter the 1-cm target cell where some of the protons undergo electron-capture collisions to form hydrogen atoms in excited states. After a short (1 cm) field-free region, the excited atoms enter the microwave interaction region. This interaction region is a precision TEM transmission line which produces an rf electric field whose polarization can be selected to be either parallel or perpendicular to the beam axis. The electric field drives electric dipole transitions between the levels and thereby rearranges the excited-state populations. The effect of these transitions is observed with a detector consisting of a photomultiplier, interference filter, and polarizer which monitors the Balmer-α photons emitted from the $n=3$ manifold. The target pressure is measured with an Alpha-tron gauge and the beam current is measured with a Faraday cup.

By observing the fractional decrease in the light when the microwave power is switched on and off, a line scan such as the ones shown in Fig. 3 is obtained. This line scan shows the expected electric dipole resonances along with a few transitions in higher manifolds observed through cascades. One of the advantages of the MROD technique over that in which the exponential decay is observed[9,10] is that the signal at one frequency depends only on the populations of a few states in the manifold. This greatly simplifies the analysis. The use of two rf polarizations and the observation of both polarizations of the emitted light provide enough independent measurements to determine the L, M_L populations.

One of the major problems in any experiment concerning excited-state charge exchange is cascade pollution of the signals. Cascades can affect the MROD signal via two paths. First, the populations of the higher manifolds can decay into the $n=3$ manifold and thus increase the apparent cross sections. Since any cascades after the interaction region will not affect the signal, this effect has been reduced to a negligible correction by keeping the distance from target to interaction region short. Cascades can also affect the signal if the microwave field is resonant with a transition in a higher manifold and is detected in subsequent decay through the $n=3$ manifold. Only

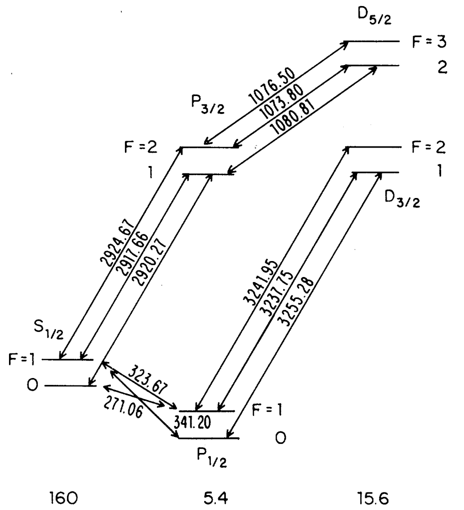

FIG. 1. Energy-level diagram for the $n=3$ manifold of hydrogen showing the frequencies in megahertz of the allowed electric dipole transitions. The numbers at the bottom are the lifetimes of the states in nanoseconds.

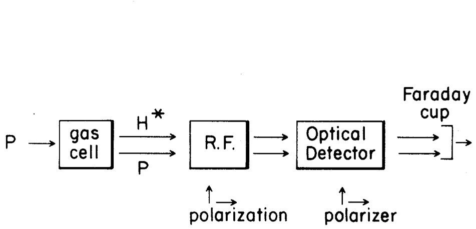

FIG. 2. Schematic diagram of the apparatus.

the $n=4$ $J=\frac{1}{2} \longleftarrow J=\frac{3}{2}$ resonances will distort the three higher-frequency $n=3$ transitions. Since these cascades (see Fig. 3) do not overlap much with the 1080-MHz transition, the residual overlap can be subtracted. The ${}^2S_{1/2}$-${}^2P_{1/2}$ Lamb shift resonance can be strongly affected by overlapping resonances and thus cannot be used in the analysis. The complete set of $\sigma(n=3, L, M_L)$ cross sections are determined with use of only the three high-frequency resonances.

In order to extract the cross sections, it is necessary to understand how the observed signals depend on the charge-exchange collisions. The signal, which is defined as the fractional change in the emitted light when the rf field is switched on, can be expressed as follows:

$$S(\omega, \vec{E}, \delta) = \sum_{L,M_L} A(L, M_L, \omega, \vec{E}, \delta) Q(n, L, |M_L|).$$

The function $A(L, M_L, \omega, \vec{E}, \delta)$ gives the probability that atoms initially formed with quantum numbers, n, L, M_L will be affected by the microwave field $\vec{E}$ with frequency ω and then subsequently detected when the polarizer is aligned at an angle δ with respect to the beam. For the calculation it is assumed that the collision does not depend on the electron or nuclear spins and that there is rotational and reflection symmetry with respect to the beam axis as z axis so that the full 36×36 density matrix matrix describing the $n=3$ manifold depends only on six population parameters, $Q(n, L, |M_L|)$, and four coherence parameters representing possible $L \neq L'$ coherences. The evolution of the density matrix through the apparatus is calculated using standard techniques. Because of the field-free detection and the random entry into the microwave field, the experiment is not sensitive to the four coherence terms. Thus the theoretical expression for the signal only contains as free parameters the six population parameters.

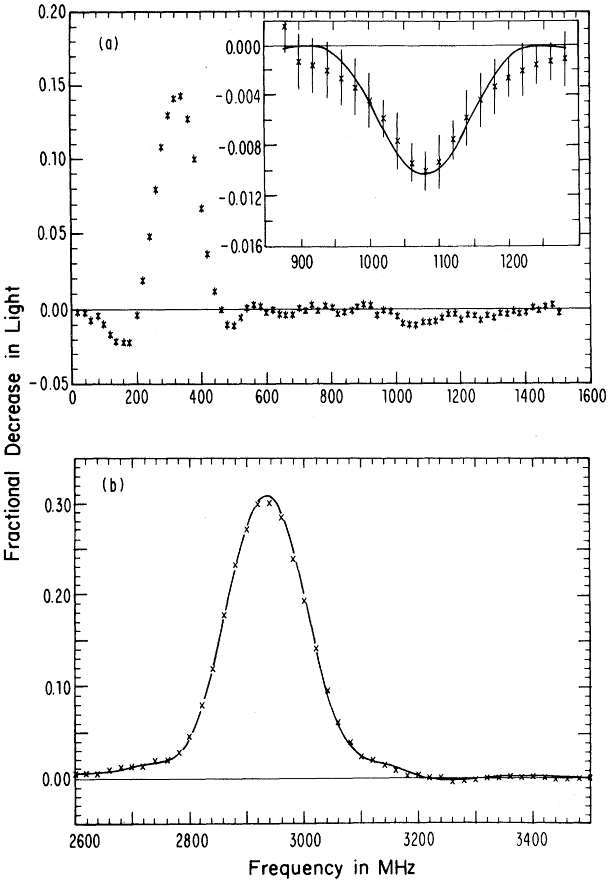

FIG. 3. Typical line scans observed with the microwave electric field and the transmission axis of the polarizer perpendicular to the beam axis. The scan in the main part of (a) is an uncorrected raw scan. The solid lines are the least-squares fits to the corrected data used to determine the charge-exchange cross sections.

Figure 3 shows the least-squares fit to one of the line scans obtained when both the rf electric field and the transmission axis of the polarizer are perpendicular to the beam axis. The fitted data have been corrected to constant microwave power and for the small $n=4$ $J=\frac{1}{2} \longleftarrow \frac{3}{2}$ cascade resonances. From fits to the four independent scans the relative cross sections summarized in

TABLE I. Summary of the relative partial cross sections for charge capture into the $n=3$, L, M_L states for 49-keV protons incident on molecular nitrogen. $\sigma(3,0)$ is the absolute cross section for capture into the S state in units of 10^{-18} cm^2.

State		This experiment	Hughes *et al.*[a]	Ford *et al.*[b]
L	$\lvert M_L \rvert$			
0	0	1	1	1
1	0	0.48(9)		
	1	0.05(8)		
	All	0.58(14)	0.48(12)	0.57(18)
2	0	0.03(4)		
	1	0.03(3)		
	2	−0.02(1)		
	All	0.07(6)	0.09(2)	0.09(3)
$\sigma(3,0)$		6.5 ± 3.4	6.6 ± 0.7	7.0 ± 1.8

[a] Ref. 9. [b] Ref. 10.

Table I were obtained. The absolute cross section for production of atoms in the $3S$ state was determined from the target pressure, the detection efficiencies, and the $3S$ population parameter found in the least-squares fits. Table I also summarizes the results from other experiments.[9,10]

The measurements show that electron capture into the $3S$ state dominates and that the cross sections decrease with increasing L. The cross sections for capture into the different M_L states decrease with increasing $|M_L|$. The partial cross sections for production of atoms in the P and D states agree satisfactorily with the measurements of Hughes *et al.*[9] and the extrapolated measurements of Ford and Thomas.[10] There are no theoretical predictions for the partial cross sections for electron capture from a nitrogen target. The reported calculations for electron capture from an atomic hydrogen target vary by more than a factor of 2 from one calculation to another.

In summary this paper reports the first complete determinations of the partial cross sections for capture into each of the L, M_L states for the $n=3$ manifold. With some modifications in the design of the apparatus the precision of the measurements can be improved. In particular the measurement of the absolute cross section can be increased by an order of magnitude. We plan to use this method with an atomic hydrogen target to measure the cross sections for protons incident on hydrogen atoms and thus make an unambiguous test of the theoretical calculations.

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Failure of Cross-Section Additivity for Electron Capture from Hydrocarbon Gases to Bound States of Hydrogen Ions

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The measured total electron-capture cross sections per number of carbon atoms in $\mathrm{C}_m\mathrm{H}_n$ ($m=1,2,3,4$), σ_c/m, decrease with increasing m. This decrease is largest at the lowest velocities of 0.8–3 MeV $^1_1\mathrm{H}^+$ ions, and diminishes in the limit of high velocities where the strict additivity of atomic cross sections in a molecular target is approached. The breakdown of the additivity rule in the present data is primarily attributed to, and accounted for in terms of, intramolecular electron loss processes.

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According to the additivity rule the value of a quantity of interest for a molecular target is equal to the sum of the values of these quantities for the constituent atoms in the molecule. The uncontested utility of this rule is marred by questions as to the range of its validity. As an example, the stopping power of a compound is often determined as the sum of stopping powers for its elements (Bragg rule).[1] The validity of this additivity rule outside the high-velocity limit becomes, however, questionable.[2] Significant deviations from the additivity rule were seen in