Hyperfine Splittings of Hydrogen and Tritium. II*†

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The spin-exchange optical polarization method was used to remeasure the zero-field hyperfine splittings of atomic hydrogen and atomic tritium. The transmission of circularly polarized rubidium resonance radiation through a flask containing rubidium, atomic hydrogen, or atomic tritium, and a buffer gas was monitored as a function of the frequency of an applied radio-frequency field. Measurements were made for hydrogen in helium, neon, molecular hydrogen, and argon buffer gases and for tritium in neon and argon buffer gases. The values of the hyperfine splittings obtained are $\Delta\nu(\mathrm{H}) = 1\,420\,405\,749.1 \pm 6.0$ cps; $\Delta\nu(\mathrm{T}) = 1\,516\,701\,476.8 \pm 6.0$ cps. The assigned limits of error represent the range of disagreement of the zero-pressure extrapolations in the different buffer gases. The fractional pressure shifts [pressure shift in cps/mm Hg divided by the hyperfine splitting in kMc/sec] for hydrogen in helium, neon, molecular hydrogen, and argon are 4.80 ± 0.09, 2.88 ± 0.05, -0.56 ± 0.10, and -4.77 ± 0.12, respectively. Those for tritium in neon and argon are 3.24 ± 0.09 and -5.05 ± 0.15, respectively.

INTRODUCTION

RECENTLY one of the authors (F. M. P.) was engaged in an experiment which used spin-exchange collisions with optically oriented rubidium to measure the zero-field hyperfine splittings of atomic hydrogen, deuterium, and tritium.[1] The measurements on hydrogen and tritium were somewhat unsatisfactory for several reasons. The observations of the hyperfine splitting made on the same absorption bulb on two successive evenings seemed to vary more than would be expected from statistical considerations; the fractional pressure shifts (pressure shift divided by the hyperfine splitting) for the same buffer gas varied from hydrogen isotope to hydrogen isotope in an unexpected manner; the values of the hyperfine splitting obtained by extrapolating to zero buffer-gas pressure varied considerably from buffer gas to buffer gas. It was suspected that most of the erratic behavior was due to the fact that the measurements were being made by averaging the frequency of two magnetic-field-dependent hyperfine transitions. In order to improve this situation, the present authors undertook a program to improve the measurements. A careful study of the spin-exchange detection problem was made in order to determine the basic limitations on the linewidth. These calculations indicated hydrogen hyperfine lines with a full width at half maximum of 50 cps and the signal power one million times the noise power in a one-cycle bandwidth should be physically realizable. This result was partially confirmed by the previous observations on deuterium where field-independent transitions were measured. In the first part of this paper the improvements of the apparatus are described; in the second part the new measurements of the zero-field hyperfine splittings of hydrogen and tritium are reported.

REFINEMENTS IN THE APPARATUS

Since the previous experiments on deuterium and the calculations indicated that the limiting linewidth for the hydrogen Zeeman transitions was much less than the 1400 cps (1 mG) full width at half-maximum achieved in the previous experiment, it was presumed that the increased width was principally due to a combination of inhomogeneities in the earth's magnetic field and 60-cycle magnetic fields. The component of the ac magnetic field along the axis of the apparatus was measured and found to have an 0.25-mG peak-to-peak amplitude. It did not have a pure 60-cycle waveform. A simple feedback system was built to reduce this ac magnetic field.[2] Two pickup coils, 6 in. in diameter, were wound with 7000 turns each of number 28 magnet wire. The coils were shielded electrostatically by winding them on brass forms which were slotted perpendicular to the winding direction so as not to form a shorted secondary winding. One such coil was mounted at the center of each of the 28-in. diam Helmholtz coils. The outputs of the two pickup coils were connected in series and fed into a battery-operated preamplifier with a gain of 100. The output of this preamplifier drove an audio amplifier, the output transformer of which was connected to the main Helmholtz coils. When it was desired to run dc current through the Helmholtz coils, a suitable low-impedance source was connected in series with the transformer output. The output of the preamplifier was monitored with an oscilloscope, and the gain of the feedback system was advanced to just below the point at which it began to oscillate. This circuit reduced the ac fields along the axis of the apparatus by a factor of 10 to 20.

This feedback system reduces only the component of the ac field along the axis of the apparatus. If the

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† A preliminary account of part of this work has been given: F. M. Pipkin and R. H. Lambert, Bull. Am. Phys. Soc. **5**, 412 (1960).
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[1] L. W. Anderson, F. M. Pipkin, and J. C. Baird, Jr., Phys. Rev. **120**, 1279 (1960); **121**, 1864 (1961); **121**, 1962 (1961).

[2] Since the completion of this experiment a similar system has been reported in the literature: L. A. Marzetta, Rev. Sci. Instr. **32**, 1192 (1961).

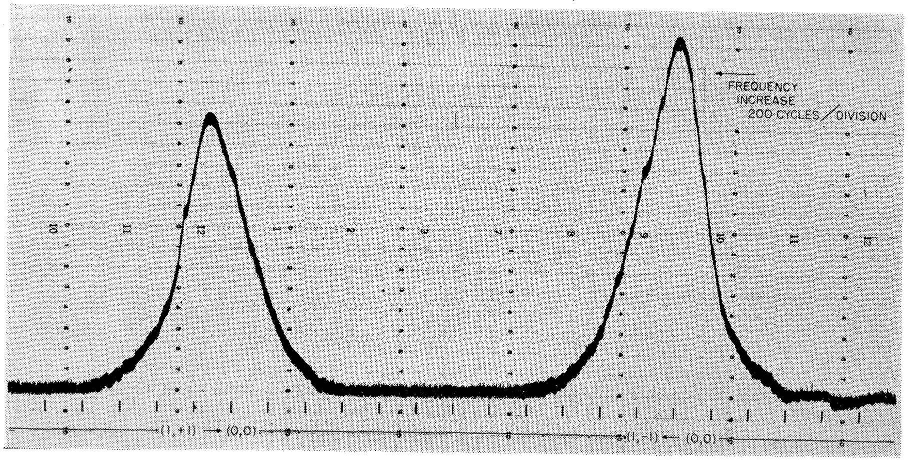

FIG. 1. Recorder tracing of the two tritium hyperfine transitions for a bulb with tritium in neon. For this recording the output time constant of the lock-in detector was 0.1 sec.

static magnetic field is not parallel to this axis, the transverse ac components become important. In order to minimize this effect, another set of Helmholtz coils was installed in addition to those already present for cancelling the vertical component of the earth's field.

To investigate the inhomogeneities in the static field, the oven was removed and the optical pumping system was set up with only an absorption bulb and rf coil between the two Helmholtz coils. The light entering the bulb was then masked, and the resonance frequencies of the Rb^{87} optical pumping signals obtained by illuminating various portions of the bulb were measured. These measurements showed that there was a vertical gradient of approximately 0.5 mG over a 10-cm length and a much smaller horizontal gradient. Further measurements with a magnetometer indicated a uniform decrease of the horizontal component of the earth's field as one went from floor to ceiling. Several unsuccessful attempts were made to use auxiliary coils to shim the field. It was finally decided to shim with small cylindrical bar magnets. Four such magnets were arranged around the apparatus by a system of successive approximations in which alternately the linewidth was measured and the position of the magnets changed. Each of the magnets was located 4 to 5 ft from the absorption bulb with its dipole axis parallel to the axis of the apparatus. In this fashion the linewidth of the Rb^{87} Zeeman transitions (700 cycles/mG) was reduced from 1000 to 125 cps. No simple combination of magnets which would reduce the linewidth further could be found.

In the previous experiment a pulsed discharge was employed to create the atomic hydrogen. This has the undesirable effect of producing a transient spike in the light output, of creating a hydrogen density which varies in time, and of making it difficult to measure the resonance frequencies on the oscilloscope. Consequently an effort was made to use a continuous rather than a pulsed discharge. The main problem with the continuous discharge is to make it weak enough so that it does not produce too much hydrogen but strong enough so it does not go out. It was found that individual coupling transformers could be devised for each bulb so as to achieve this result. This was especially easy in the case of tritium where the decay electrons furnished fuel for the discharge. The rest of the apparatus was the same as in the previously reported experiment.[1]

MEASUREMENT PROCEDURE

All measurements were made between the hours of 1:30 and 5:00 a.m. when the trolleys were not running and the magnetic activity in the neighborhood was a minimum. Each evening at the start of a run the Rb^{87} Zeeman resonances were observed with reduced light intensity and the shimming magnets were readjusted to minimize the Rb^{87} linewidth. The full width at half-maximum of the Rb^{87} lines varied from 125 to 150 cps. The best position of the shimming magnets did not change by more than a few inches from evening to evening. The radio-frequency discharge was turned on, and the linewidth of the hydrogen Zeeman transitions was observed. The smaller of the two $\Delta F=1$, $\Delta m=\pm 1$ hydrogen hyperfine transitions was located, and the amplitude of the radio-frequency signal driving the transition and the discharge intensity were adjusted so as to minimize the linewidth while maintaining a good signal-to-noise ratio. The full width at half-maximum of the hyperfine transition was recorded. The measurements were then started. First one of the hyperfine transitions was measured, then the other; then the sequence was repeated in reverse order. One set of measurements consisted of two observations on each hyperfine line. The measurements were made either by maximizing the signal on the lock-in detector output meter or by using the oscilloscope to find the point at which the modulation of the signal by the residual 60-cycle field ($10 \rightarrow 20$ cps) was minimized.

In the later phases of the experiment after ten sets of measurements were completed, the Helmholtz coils were connected to a dc source, and the coil current was adjusted so as to produce a net magnetic field equal in

TABLE I. A summary of all the run averages for the bulbs with atomic hydrogen in a neon buffer gas. The letter N or R after the run number indicate whether the run was made with the magnetic field in the normal direction (N) along the horizontal component of the earth's field or with the field reversed (R). Runs made on the same evening are designated with the same number. The linewidth is the full width at half maximum of one of the two hyperfine lines and the width measurement was made at the beginning of the run. The error for the run average is the expected standard deviation of the mean [Eq. (1)]. For computing the N mean and the R mean, only those runs where measurements in both the N and R configurations were made on the same evening were used. The bulb average was computed by weighting the various run averages with the number of measurements in the run, and the error was computed by treating each run average as a single measurement and using Eq. (1).

Pressure (mm of Hg)	Run	Number of measurements	Linewidth (cps)	$\Delta\nu - 1\,420\,405\,000$ (cps)	
9.91	1-N	10	310	793.5±1.8	
	1-R	10	348	798.3±3.2	
	2-N	10	328	785.3±2.7	
	3-N	8	354	788.7±1.8	
	4-N	12	340	775.2±1.5	
	5-N	5	360	785.0±3.2	
	6-N	10	413	781.5±2.7	
	7-N	14	360	781.8±1.9	
	8-N	12	340	783.2±4.7	
	8-R	14	350	808.7±5.1	
	9-R	6	360	784.6±4.1	
	9-R	5	308	782.0±5.8	
	9-N	7	308	770.9±5.8	
	Mean of N			783.0±9.3	
	Mean of R			794.1±3.8	
	Mean of all runs				787.1±2.6
19.50	1-N	10	365	822.5±2.8	
	1-R	10	392	826.3±2.2	
	2-N	14	304	833.0±1.8	
	3-N	10	360	826.6±3.1	
	4-N	12	314	822.2±3.3	
	4-R	10	360	841.3±5.3	
	4-N	11	380	828.4±4.0	
	5-N	10	300	825.8±4.1	
	5-R	10	410	837.5±1.6	
	5-N	12	410	832.7±2.5	
	Mean of N			826.3±4.4	
	Mean of R			835.0±7.8	
	Mean of all runs				829.7±2.0
26.31	1-N	10	320	842.6±2.2	
	2-N	10	350	857.2±2.9	
	3-N	12	360	850.9±3.3	
	Mean				850.3±4.9

Pressure (mm of Hg)	Run	Number of measurements	Linewidth (cps)	$\Delta\nu - 1\,420\,405\,000$ (cps)	
51.47	1-R	10	405	958.4±1.6	
	1-N	10	302	955.5±1.7	
	2-N	10	310	969.0±3.0	
	3-N	10	260	945.8±5.1	
	4-N	10	380	964.8±3.7	
	5-N	10	400	953.4±3.5	
	6-N	10	360	947.5±1.3	
	7-R	10	340	965.0±3.0	
	7-N	10	420	955.2±3.7	
	Mean of N			955.4±2.0	
	Mean of R			961.7±4.7	
	Mean of all runs				957.2±2.6
34.55	1-N	10	390	891.9±4.1	
	2-N	10	315	888.7±3.3	
	3-N	13	313	881.2±3.4	
	Mean				886.7±3.2
39.49	1-N	11	280	893.4±2.4	
	1-R	10	324	900.3±1.9	
	2-N	10	372	902.9±1.3	
	3-N	10	380	908.2±1.8	
	4-N	12	323	903.3±5.4	
	4-R	20	380	915.7±3.3	
	4-N	10	372	893.8±2.9	
	4-N	10	380	906.5±1.8	
	5-N	10	316	895.4±1.8	
	5-R	11	316	904.9±4.4	
	Mean of N			896.5±4.4	
	Mean of R			907.0±7.9	
	Mean of all runs				903.6±2.2
49.74	1-N	10	370	949.1±2.2	
	1-N	10	360	954.5±2.2	
	1-N	11	305	954.1±2.2	
	Mean				952.6±1.7

magnitude but opposite in direction to the horizontal component of the earth's field. The circular polarizer was left unchanged during this operation. This reversal of the field direction interchanged the amplitudes of the two hydrogen hyperfine signals and reversed the rubidium polarization. Ten more sets of measurements were made with the reversed field.

In most cases the bulbs used in this experiment were the same as those employed in the previous experiment. Several new bulbs were constructed as a check on the reliability of the old ones, and some bulbs were made with higher and lower pressures than those employed previously. Only one bulb (a neon bulb) was suspected of being in error and discarded.

Figure 1 is a recorder tracing of the two hyperfine lines in a neon-filled tritium bulb. The lines have an asymmetry which is believed to be produced by residual magnetic field inhomogeneities over the bulb. The full width at half maximum of these lines is 400 cps. Figure 2 shows in the form of a histogram the results of all the sets of measurements on the four hydrogen in helium bulbs.

REDUCTION OF DATA AND RESULTS

The data were reduced as follows. For each run (usually ten sets of observations) the mean and the standard deviation of the mean,

$$\sigma = \left[\sum_{i=1}^{N} (x_i - \bar{x})^2 / N(N-1)\right]^{\frac{1}{2}}, \tag{1}$$

were calculated. To obtain the value for a given bulb, the various run averages were weighted with the number of measurements in the run, and a bulb average was computed. The error for each bulb was calculated by treating each of the run averages as a single observation and using Eq. (1) to compute the standard deviation of the mean. It is felt that this procedure gives an

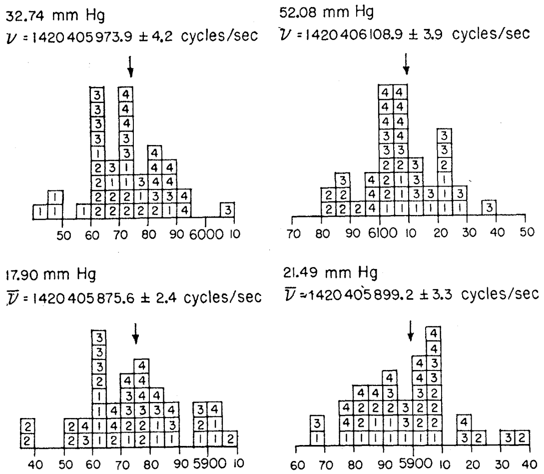

FIG. 2. A histogram of all the set averages for helium in neon. All the odd-numbered measurements were made with the magnetic field along the horizontal component of the earth's magnetic field and all the even ones with the field in the opposite direction. Measurements 1 and 2 were made on one evening and measurements 3 and 4 on another evening. The quoted averages are the expected standard deviations of the mean and were calculated by the procedure described in the text.

estimate of the error due to disturbances of unknown origin which cause the run averages from evening to evening to vary more than would be expected from sample statistical considerations. Separate bulb averages were calculated for the measurements made on the same evening with the field in the normal direction and the field reversed. Table I summarizes all the run averages for atomic hydrogen in a neon buffer gas. These data are typical in that they show how the linewidth and the run averages varied from evening to evening. Table II summarizes all the bulb averages for atomic hydrogen in molecular hydrogen, argon, and helium buffer gases; Table III summarizes all the bulb averages for atomic tritium in argon and neon buffer gases.

TABLE II. A summary of all the bulb averages for atomic hydrogen in molecular hydrogen, argon, and helium buffer gases. The notation is explained in the caption for Table I.

Buffer gas	Pressure (mm of Hg)	Number of runs	Number of measurements	$\Delta\nu - 1\,420\,405\,000$ (cps) *N*	*R*	All
H_2	12.39	6	68			738.4±2.6
	16.02	5	49			741.3±4.9
	27.50	5	54			730.3±1.8
	33.06	2	20			722.8±4.1
	36.81	4	41			717.9±7.2
	44.18	5	51			710.4±5.8
Ar	7.96	7	60	679.0±8.7	695.8±2.2	687.7±5.1
	17.12	5	54			620.4±7.5
	23.02	4	42			588.1±2.7
	32.71	4	40			516.1±5.3
	45.90	4	40			432.4±3.9
He	17.90	4	41	877.2±4.2	874.0±6.4	875.6±2.4
	21.49	4	40	898.5±7.6	900.1±3.1	899.3±3.3
	32.74	4	41	969.8±7.5	978.0±9.6	973.9±4.2
	52.08	4	42	1115.3±1.4	1102.4±3.5	1108.9±3.9

TABLE III. A summary of all the bulb averages for tritium in neon and argon buffer gases. The notation is described in the caption for Table I.

Buffer gas	Pressure (mm of Hg)	Number of runs	Number of measurements	$\Delta\nu - 1\,516\,701\,000$ (cps) *N*	*R*	All
Ne	16.58	8	75	563.7±1.3	552.6±3.1	558.1±1.9
	26.21	9	86	605.8±1.0	607.6±2.8	605.9±0.9
	38.17	9	87	669.4±1.8	674.9±4.2	664.1±2.1
Ar	16.74	5	50			347.5±4.4
	26.21	4	40			275.3±2.8
	36.93	4	40			192.5±2.6

A least-squares procedure was used to fit the bulb averages for a given buffer gas to a linear function of the buffer gas pressure. These calculations were made first weighting the various points inversely with the square of the standard deviation and then weighting the points with the number of measurements. The difference between the results of these two methods of analysis was taken as an indication of the sensitivity of the results to the mode of analysis. The standard least-squares procedure was used to compute the errors in the zero-pressure intercept and the pressure shift. The bulb averages for atomic hydrogen and the least-square straight lines are shown in Fig. 3; those for tritium in Fig. 4. The values of the zero-field hyperfine splitting of atomic hydrogen obtained by extrapolating to zero pressure in the various gases are summarized in Table IV; those for tritium in Table V. In order to further investigate the internal consistency of the data, the measurements made on the same evening with the opposite relative orientation of the static magnetic field and the direction of the light beam were analyzed separately. The results of this analysis are summarized in Table VI. This analysis suggests that there is a 5- to 10-cps difference in the values of the zero-field hyperfine splitting obtained by reversing the relative orientation of the magnetic field and the direction of the

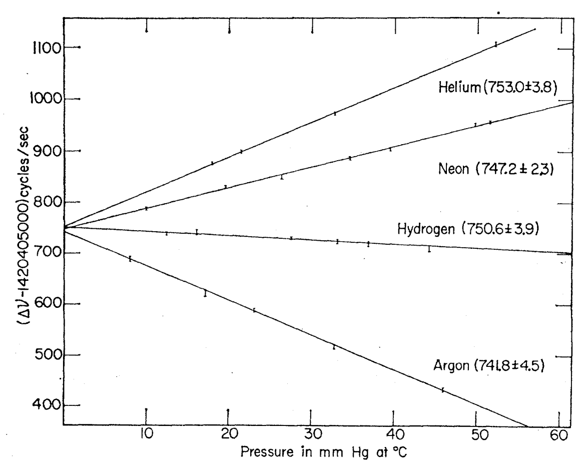

FIG. 3. A plot of $\Delta\nu_{obs}$ vs pressure for atomic hydrogen in neon, argon, helium, and molecular hydrogen buffer gases. The numbers beside the various curves give the extrapolated zero-pressure intercepts.

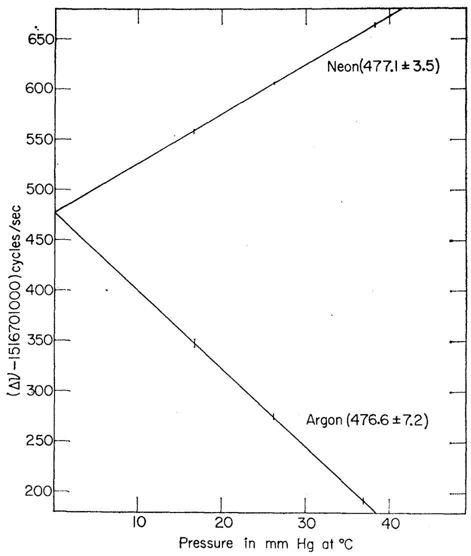

FIG. 4. A plot of $\Delta\nu_{obs}$ vs pressure for atomic tritium in neon and argon buffer gases. The numbers beside the various curves give the extrapolated zero-pressure intercepts.

light beam. Such a difference could be produced by a dependence of the average frequency of the $(1,1)\leftrightarrow(0,0)$ and the $(1,-1)\leftrightarrow(0,0)$ transitions upon the sign of the polarization of the rubidium and the hydrogen or by a change in the distribution of the magnetic field over the sample, the effect of which was not completely canceled out by averaging the observed frequencies of the two field-dependent transitions. During these measurements the orientation of the circular polarizer was such that when the magnetic field was in the direction of the horizontal component of the earth's magnetic field, the state $(1, -1)$ had a greater population than the state $(1, +1)$. A comparison of Tables IV and VI shows that for hydrogen in neon the zero-field hyperfine splitting obtained by averaging the results with the field normal and the field reversed does not differ from that obtained by simply averaging all the data even though most of the data were taken with the field in the normal direction. In view of the general

TABLE IV. The values of the hyperfine splitting of atomic hydrogen obtained by extrapolating to zero-pressure in helium, molecular hydrogen, neon, and argon buffer gases. The least-square calculations were made in the standard fashion using the mean of all the runs for a given bulb and weighting the various bulbs inversely with the square of their standard deviation. The value in parentheses after the χ^2 gives the probability of finding a χ^2 greater than the calculated one.

	Regular least squares			Weighting with number of measurements
Buffer gas	$\Delta\nu-1\,420\,405\,000$ (cps)	Degrees of freedom	χ^2	$\Delta\nu-1\,420\,405\,000$ (cps)
Helium	753.0±3.8	2	0.41 (52%)	752.3
Hydrogen	750.6±3.9	4	3.18 (53%)	753.1
Neon	747.2±2.3	5	10.04 (8%)	747.1
Argon	741.8±4.5	3	1.86 (61%)	739.4

TABLE V. The values of the hyperfine splitting of atomic tritium obtained by extrapolating to zero pressure in neon and argon buffer gases. The notation is explained in the caption to Table IV.

	Regular least squares			Weighting with number of measurements
Buffer gas	$\Delta\nu-1\,516\,701\,000$ (cps)	Degrees of freedom	χ^2	$\Delta\nu-1\,516\,701\,000$ (cps)
Neon	477.1±3.5	1	0.052 (83%)	477.0
Argon	476.6±7.2	1	0.019 (89%)	476.0

behavior of the data it is felt that the measurement is limited by systematic rather than statistical errors and that the range of variation of the zero-pressure intercepts for the various buffer gases gives a better estimate of the error than that determined by statistical considerations. This is borne out by a comparison of the results of this experiment and those of the previous one. In determining the final value for hydrogen, we have taken the mean of the values in Table IV and of the two means in Table VI. This procedure weights the hydrogen-in-helium and the hydrogen-in-neon data twice as much as the hydrogen-in-hydrogen and hydrogen-in-argon data. The final value for hydrogen is

$$\Delta\nu(\mathrm{H})=1\,420\,405\,749.1\pm6.0\mathrm{cps}.$$

A similar procedure gives for tritium

$$\Delta\nu(\mathrm{T})=1\,516\,701\,476.8\pm6.0\ \mathrm{cps}.$$

Both of these values assume the Cs^{133} frequency of the atomichron to be

$$\Delta\nu(\mathrm{Cs}^{133})=9\,192\,631\,840\ \mathrm{cps}.$$

This value for the hyperfine splitting of atomic hydrogen is not inconsistent with that obtained by Kleppner, Goldenberg, and Ramsey from studies of the hydrogen maser.[3] The published hydrogen maser result is

$$\Delta\nu(\mathrm{H})=1\,420\,405\,762\pm4\ \mathrm{cps}.$$

The results for the pressure shifts are summarized in Table VII. Also included in this table are the recalculated pressure shifts of deuterium based upon a better

TABLE VI. The values of the hydrogen hyperfine splitting obtained using only the data for which observations were made with the field in the normal direction (along the horizontal component of the earth's field) and the reversed direction during the same night's run. A least-squares fit was made for each of the two field directions.

Buffer gas	Field direction	$\Delta\nu-1\,420\,405\,000$ (cps)
Helium	Normal	749.8±6.0
Helium	Reversed	757.3±5.2
Mean		753.6±3.8
Neon	Normal	742.3±5.8
Neon	Reversed	754.5±4.6
Mean		748.4±3.9

TABLE VII. The pressure shifts for hydrogen, deuterium, and tritium in the various buffer gases. The shift is expressed in terms of the pressure at 0°C so that the density in the bulb is given by $N/V = p/T_0 k$, where T_0 is 273°K. The measurements were made at a temperature of 45±5°C.

Buffer gas	Hydrogen isotope	Pressure shift [(cps)/mm Hg]	(Pressure shift/$\Delta\nu$)$\times 10^9$ [(mm Hg)$^{-1}$]
He	H	6.81±0.13	4.80±0.09
Ne	H	4.09±0.07	2.88±0.05
	D	1.06±0.15	3.24±0.45
	T	4.90±0.13	3.24±0.09
H_2	H	−0.80±0.15	−0.56±0.10
Ar	H	−6.76±0.15	−4.77±0.12
	D	−1.48±0.13	−4.52±0.40
	T	−7.66±0.23	−5.05±0.15

determination of the density of the oil used in the manometer. The total errors in the bulb pressures are estimated to be less than 1% and they are probably mostly of a systematic nature. The pressure shifts have been expressed in terms of the pressure in the bulb at 0°C so that the density in the bulb is given by

$$N/V = p/kT_0, \quad (2)$$

where $T_0 = 273$°K. All the measurements were made at a temperature of 45±5°C. The quoted bulb pressures are mm of Hg at 0°C. The quoted errors are one standard deviation. These measurements suggest that the fractional pressure shifts are slightly greater for tritium than for hydrogen.

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Partial Atomic Stopping Power of Gaseous Hydrogen for Hydrogen Beams. I*

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The stopping power of H_2 gas for the atomic component of a hydrogen beam in charge equilibrium has been measured by placing the stopping cell in an intense transverse magnetic field. This allows only those particles to reach the exit which have entered as neutrals and have not experienced any collision, as a result of which they became electrically charged. These neutrals are partially converted to protons in a subsequent gas stripper cell, and their energy measured in an electrostatic deflector. As H_2 gas is admitted to the stripping cell, there is a rapid decay in beam intensity, since at each charge-changing collision the particle is extracted from the beam by the magnetic field. By counting individual exit particles, however, a beam diminution factor of 10^{-7} is acceptable and a well-defined energy group is detected which has experienced a loss of approximately 1% of its energy, and for which the stopping power ϵ_0 of H_2 gas, for instance at 50 keV, is only 0.42 of the conventional ϵ, measured with the field off. The values of ϵ reported agree with those of Reynolds, Dunbar, Wenzel, and Whaling. The results for ϵ_0 and ϵ_0/ϵ are:

Kinetic energy (keV)	ϵ_0 in eV cm^2/atom	ϵ_0/ϵ
20	$(3.3\pm0.5)\times10^{-15}$	0.64±0.10
50	2.8×10^{-15}	0.42
100	1.8×10^{-15}	0.31
150	$(1.4\pm0.35)\times10^{-15}$	0.30±0.08

Above 50 keV the experimental ϵ_0 values agree well with those theoretically calculated by Dalgarno and Griffing for atomic hydrogen gas; at lower energies the experimental values are somewhat higher.

INTRODUCTION

THE term "proton beam" is well known to be inadequate to describe the composition of a pencil of hydrogen projectiles of velocities comparable to $c/137$ (2.19×10^8 cm/sec) moving through matter. The processes of electron capture and loss take place with the result that the components H^0 and H^-, in addition to H^+, appear in the beam in certain characteristic fractions, F_0 and $F_{\bar{1}}$, dependent on the beam velocity, the atoms per cm of material traversed, and the target material itself. This assemblage of particles in essentially unidirectional motion we call a hydrogen beam. In the experiments to be described here, the beam contains no H^- before it begins to interact with the gaseous hydrogen target, and it is known[1] that after sufficient material has been traversed to establish the equilibrium fraction $F_{\bar{1}\infty}$, the maximum $F_{\bar{1}\infty}$ attainable in H_2 gas is 0.020, at about 15-keV kinetic energy. H^- plays no detectable role in the effects to be described and we will treat the hydrogen beam as a two-component system, containing H^0 and H^+. Our experimental definition

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

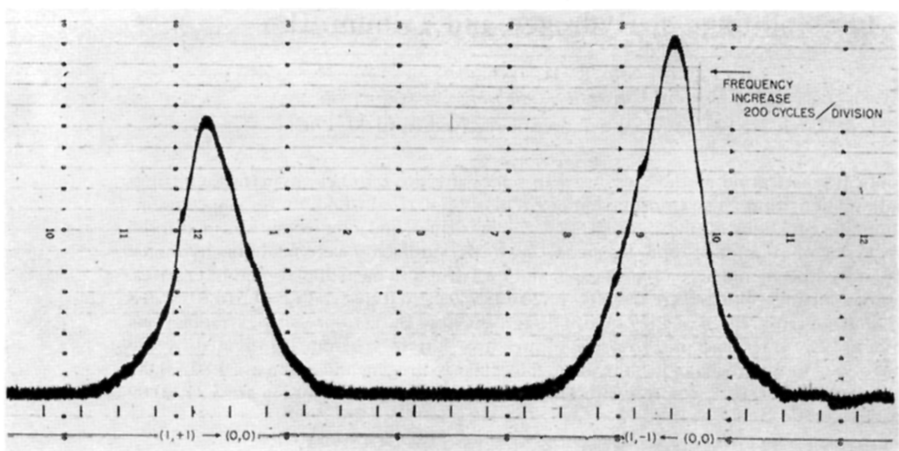

FIG. 1. Recorder tracing of the two tritium hyperfine transitions for a bulb with tritium in neon. For this recording the output time constant of the lock-in detector was 0.1 sec.