Determination of g_J (^1H, $1^2S_{1/2}$)/g_S (e): Test of Mass-Independent Corrections

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A determination of the ratio of g factors of the electron bound in the hydrogen atom to that of the free electron has been made. For the first time mass-independent terms in the theory are confirmed through the α^3 radiative correction. Our result is $g_J(^1H,1^2S_{1/2})/g_S(e) = 1 - 17.709(13)\times 10^{-6}$.

Both experiment and theory have made advances in recent years in the precision attained for values of the magnetic moment of the electron bound in hydrogenlike systems. The most exacting experimental determination has been that of $g_J(D)/g_J(H)$ by Walther, Phillips, and Kleppner[1] where a precision of 3 parts in 10^{11} was attained, confirming the theoretical calculation.[2] Such determinations interact with theory only via the mass-dependent terms. The motivation for performing an experiment to determine $g_J(^1H, 1^2S_{1/2})/g_S(e)$, i.e., the ratio of the g factor of the electron bound in the electronic ground state of hydrogen to that of the free electron, is to check the mass-independent terms of the theory. Previously, technical difficulties involving observation of the Zeeman resonance of the free electron under high resolution have made interaction with theory difficult. However, for the first time we have been successful in confirming the α^3 radiative correction term.

The method used is that of spin-exchange optical pumping. An inert buffer gas of helium slows the diffusion of optically pumped Rb to the walls of a 30-cm^3 right-circular Pyrex cylinder. The decay of tritium, also contained in the cell, produces secondary ions, thereby generating the desired density of free electrons. This was the technique used by Balling and Pipkin,[3] whose determination of $g_J(H)/g_S(e)$ had a precision of 1 part in 10^6. Electron-spin-exchange collisions between the optically polarized Rb atoms and the free electrons allow observation of the electron-spin resonance through the effect on the Rb polarization. Thus the g-factor ratio directly determined is $R \equiv g_J(^{87}\text{Rb}, {}^2S_{1/2})/g_S(e)$.

In the applied magnetic field of 50 G, a typical Rb linewidth was 20 Hz in the absence of tritium. When a cell was moved ± 1 cm along the z axis, the shift in R was typically ≤ 4 parts in 10^9 with the line-shape asymmetry remaining ≤ 7 parts in 10^9. The hyperfine separation for Rb was directly determined for each cell by observing one $\Delta F = 1$ transition and one $\Delta F = 0$ transition. The shift in the hyperfine separation provided a convenient check on the pressure in each cell. The Rb Zeeman resonance and electron-spin resonance were each examined at eleven discrete frequencies covering at least 2 linewidths. The long-term stability of the applied magnetic field was sufficient to suppress error due to field drift. After fitting modified Lorentzians to the data, we used the Breit-Rabi formula to extract R for a given run.

Figure 1 shows an extrapolation of the average of R obtained with the two circular polarizations of light versus light intensity. Although Rb exhibits a small light-induced shift, the major shift is due to a spin-exchange frequency shift of the free-electron resonance.[4] As a function of light intensity, no significant slope was found for the average of R at opposite light polarizations. An extrapolation of R versus rf power applied to the free-electron resonance gave no significant slope on the average R thereby showing no significant electron heating effect due to rf power.

Table I shows the characteristics of the six

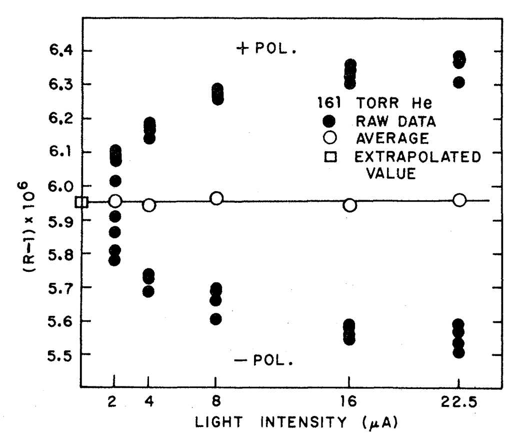

FIG. 1. Extrapolation of the average of R obtained with the two circular polarizations of light vs light intensity. The least-squares fit to a straight line is shown along with the extrapolated value.

TABLE I. Cell parameters at 15°C.

Cell	Amount of tritium (C)	He buffer pressure (Torr)	Electron density (10^7 cm^{-3})
a	0.1	22.4	1.1
b	0.1	43.7	4.3
c	0.1	43.7	4.3
d	0.01	43.7	0.43
e	0.05	79.7	8.7
f	0.025	161.6	18.0

cells used. The tritium pressure was set by using the equilibrium vapor pressure over heated UH_3. The average electron density, $\langle n_e \rangle$, was calculated by solving an approximation to the rate equation for electron density. The source term due to ionization by the β decay of tritium is uniform over the volume of the cell resulting in a more favorable spatial distribution of electrons than would occur with a localized discharge. Good agreement was obtained between the $\langle n_e \rangle$ found using the above method and that calculated by using the increase in Rb linewidth upon introduction of the tritium.

After extrapolation of the values of R against rf power and light intensity, the results were corrected for the known pressure shift of g_J(Rb) due to the helium buffer gas.[5] A least-squares fit to these corrected data resulted in a zero-pressure intercept of $\bar{R} = 1 + 5.949(9) \times 10^{-6}$. The fitted slope of the pressure-corrected data was zero, as might be expected. Figure 2 shows a summary of the pressure-corrected extrapolated data. The unweighted overall value is shown at the bottom with its associated rms error. This represents the primary experimental result at 15°C, which must be corrected by a factor of $(1 - \langle E_K \rangle / m_0 c^2)$ for the relativistic shift in $g_S(e)$ due to thermal velocity and motion in a magnetic field.[6] Thus a value is obtained for $\bar{R}$ at 0°K:

$$\left.\frac{g_J(^{87}\mathrm{Rb})}{g_S(e)}\right|_{0\,^\circ\mathrm{K}} = \left.\frac{g_J(^{87}\mathrm{Rb})}{g_S(e)}\right|_{288\,^\circ\mathrm{K}} \times (1 - 0.073 \times 10^{-6})$$
$$= 1 + 5.876(13) \times 10^{-6}.$$

By use of the previously determined ratio[7] $g_J(H)/g_J(\mathrm{Rb})$, comparison with theory is made through the following chain:

$$\left.\frac{g_J(\mathrm{H})}{g_S(e)}\right|_{0\,^\circ\mathrm{K}} = \frac{g_J(\mathrm{H})}{g_J(\mathrm{Rb})} \left.\frac{g_J(\mathrm{Rb})}{g_S(e)}\right|_{0\,^\circ\mathrm{K}}$$
$$= 1 - 17.709(13) \times 10^{-6}.$$

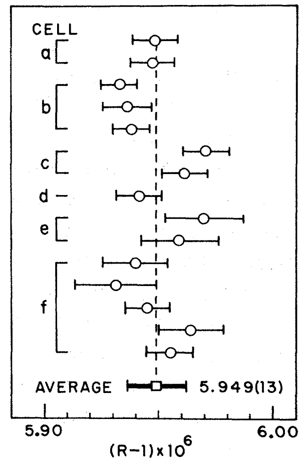

FIG. 2. Summary of pressure-corrected extrapolated data for $R \equiv g_J(^{87}\mathrm{Rb})/g_S(e)$ at 15°C. The rms error is shown associated with the average.

The error in this expression is due entirely to the error in $g_J(\mathrm{Rb})/g_S(e)$. Expansion of the theoretical expression[2] as a sum of the most significant terms gives

$$\frac{g_J(H)}{g_S(e)} = 1 - \alpha^2/3 + \alpha^3/4\pi + \alpha^2(m/2M) + \dots$$
$$= 1 - 17.7505 \times 10^{-6} + 0.0309 \times 10^{-6} + 0.0145 \times 10^{-6}$$
$$= 1 - 17.7051 \times 10^{-6}.$$

Higher order terms contribute less than 1 part in 10^{10}. The degree of experimental precision attained, 1.3 parts in 10^8, interacts with both the radiative correction, $\alpha^3/4\pi$, and the mass-dependent correction, $\alpha^2(m/2M)$.

The ultimate level of precision of this experiment appears to be determined by the small residual magnetic field gradients remaining after shimming. Scatter in data taken in a particular field is small compared to that between data acquired in similar runs with fields of different shimming histories. Since frequent reshimming was done, the data are expected to be randomly distributed with respect to field inhomogeneities. Other potential sources of error considered are those involving the Rb hyperfine separation and nuclear g factor. Neither contributes significantly to the error in the quoted result.

Preliminary results[8] on the determination of R used cells in which electrons were produced by a discharge rather than by tritium decay. Although both He and Ne buffer gases were used in taking data, only Ne-cell data were admitted in this early work since the He-cell data showed large systematic shifts, then attributed to the relativistic shift in $g_S(e)$ due to heating of the electrons. After the subsequent work[9] on $g_J(^4\text{He}, 2^3S_1)/g_J(^1H, 1^2S_{1/2})$ and that by Deloche *et al.*[10] on He afterglow, we believe this heating interpretation to be correct. No such effect was observed in the cells using tritium for the source of electrons. Furthermore, by the admitting of H_2 gas to one of the He discharge cells, the systematic shift in R was removed. This preliminary work is now in agreement with the result reported in this Letter, although none of the previous data are included in the present determination of R.

In conclusion, a new level of experimental precision has been attained for the ratio $g_J(\text{H})/g_S(e)$. Agreement with theory is obtained which, for the first time, confirms mass-independent corrections to order α^3 as well as the leading Breit term.

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Collisional Line Broadening Using Laser Excitation and Ionization

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A laser excitation and ionization process is used to measure Cs-Ar interaction forces at long range. With energy densities of 1 J/cm^2, nonlinear excitation persists as far out as 70 Å at one atmosphere of Ar. This method provides extreme sensitivity (even single absorption events can be measured) which allows absolute measurements on the very far wing where absorption or fluorescence becomes vanishingly small.

We report on a photoionization method which allows absolute measurements of line broadening on the very far wing where absorption and fluorescence become extremely small.[1] The method involves the conversion of essentially every absorption event of a colliding system to an ion pair in a two-photon ionization process. Thus, we avoid measurements of small numbers of absorbed or emitted photons in favor of the much more sensitive detection of free electrons. Previously we used this scheme, "resonance ionization spectroscopy" (RIS), in measuring absolute populations and lifetimes of excited states[2,3] following charged-particle excitation of He gas. Moreover, we recently used the RIS method in achieving detection and identification of single atoms[4,5] by utilizing the two-photon ionization process in a proportional counter.

Previously, line broadening by foreign gases was studied by absorption[6] and fluorescence.[7] In these studies, high-temperature absorption tubes are required in order to induce appreciable absorption of fluorescence. Dense samples introduce not only self-broadening but also dimer absorption. Moreover, high-pressure buffer gases can make three-body collisions wash out the satellite structure otherwise observable in the two-body collisions. The extra sensitivity achieved in the ionization method, however, will allow measurements at the very far wing of optically thin samples where the higher density problems are eliminated, and this promises excellent resolution of the satellites.

The present studies are also of particular inter-