

phys. J. **138**, 408 (1963); there is some indirect evidence that about 80% of the interstellar hydrogen is molecular.

⁹A. G. W. Cameron, *Astrophys. J.* **129**, 676 (1959).

¹⁰M. Schmidt, *Bull. Astron. Inst. Neth.* **13**, 247 (1957).

¹¹Note that, since nearly all the absorbing gas is concentrated within 100 parsecs (pc) of the galactic plane,

a location within a few hundred pc of Earth for Sco X-1 would be quite compatible with the observed absorption. The distance 2000 pc suggested by the Livermore group is, therefore, not implied by their data.

¹²Cf. J. E. Felten and P. Morrison, to be published. These authors summarize recent data on the diffuse radiation and discuss its sources.

ABSOLUTE VALUE OF THE PROTON g FACTOR*

Than Myint, Daniel Kleppner,† Norman F. Ramsey, and Hugh G. Robinson‡

Department of Physics, Harvard University, Cambridge, Massachusetts

(Received 6 July 1966)

The proton g factor is of fundamental importance in physics and chemistry because of the proton's role in nuclear and atomic interactions as well as its use as an nmr reference standard. However, in the past all precision determinations of g_p have been made by observing protons in molecules for which appreciable diamagnetic shielding corrections, typically 26 ppm, must be made.¹⁻⁴ Since the shielding correction had to be made with an experimentally untested theory due to Ramsey,⁵ lack of any method for directly measuring these corrections has resulted in uncertainty as to the exact value of the proton g factor. Furthermore, the g factor of the proton is required to evaluate the fine-structure constant α from hyperfine measurements of atomic hydrogen. Consequently, disagreement⁶ in the values of α inferred from fine- and hyperfine-structure measurements has sometimes been attributed to an incorrect g factor of the proton. This Letter reports a determination of the proton moment in atomic hydrogen for which the diamagnetic correction is known to high precision, thus allowing an absolute determination of g_p .

The quantity measured in this experiment is $g_j(\text{H})/g_p(\text{H})$, the ratio of the electron and proton g factors in atomic hydrogen. It can easily be corrected to yield the ratio of the free-space g factors, g_s/g_p , and since g_s is known to high precision, the result in turn leads to a value for g_p . By comparing this result with previous determinations of $g_j(\text{H})/g_p(\text{H}_2\text{O})$, where $g_p(\text{H}_2\text{O})$ is the uncorrected proton g factor as measured in water, the experimental value of the magnetic shielding constant, or chemical shift, for the proton in water is obtained, thus providing for the first time an absolute calibration for nmr spectroscopy. Since

the ratio of the magnetic shielding in H_2O to that in H_2 has been previously measured experimentally, the magnetic shielding of H_2 can be obtained from our result. This result is particularly significant since H_2 is the only molecule for which the entire shielding can be calculated to high precision. The result is thus a sensitive test of Ramsey's theory of magnetic shielding.⁵

The determination was made by operating a hydrogen maser⁷ in an applied magnetic field of 3500 G. The energy levels are shown in Fig. 1. The electron spin-flip transition, marked a , was observed by amplification, and the transition b , corresponding to proton spin flip, was simultaneously observed by double resonance. A schematic diagram of the apparatus

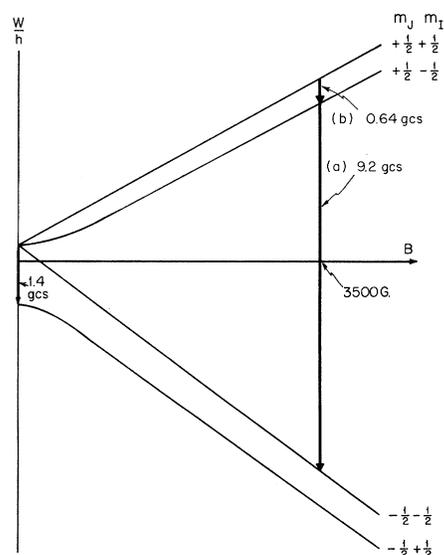


FIG. 1. Energy diagram of atomic hydrogen in the ground state.

is shown in Fig. 2. The source and state selector are of conventional design. The Teflon-lined storage bulb, 2 cm in diam, is centered in an X-band cavity in the field of a permanent magnet. The observed electron radiation lifetime is 2.5 msec, although the geometrical lifetime is 10 msec. The additional damping is due to magnetic-field inhomogeneities. These are to a large extent averaged by the motion of the atoms. Nevertheless, the requirements on field homogeneity are stringent; the fractional rms field deviation over the bulb is calculated to be 2×10^{-7} on the basis of the observed decay rate. Since the fractional width of the electron line is small, typically 1.4×10^{-8} , the magnet must also satisfy stringent stability requirements. The observed drift rate is under 10^{-8} /min.

The quantity $g_p(H)$ has not heretofore been measured because the interaction of the proton with the electron is considerably larger than its interaction with the externally applied magnetic fields. Consequently, even at a field of 3500 G the proton transition frequency must be determined roughly 40 times more precisely than the final value of g_j/g_p . This would

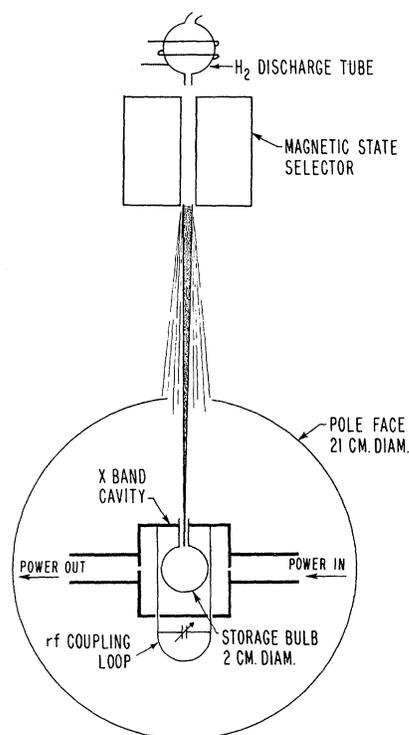


FIG. 2. Schematic diagram of the hydrogen maser used for determining $g_j(H)/g_p(H)$.

be prohibitive without the narrow resonance lines produced by the hydrogen maser, typically 60 cps for the proton transition and 130 cps for the electron transition, as contrasted to 20 000 cps for the electron transition by epr methods.

In this determination, the electron transition was pulsed and the free precession observed on an oscilloscope using a 3-kc/sec bandwidth. An applied signal at the proton transition frequency was then adjusted to quench the tail of the decay curve. In spite of the relatively crude detection method adopted for this initial determination, the experiment was sufficiently sensitive to yield a value of $g_j(H)/g_p(H)$ with a fractional uncertainty of 3×10^{-7} . This uncertainty represents the standard deviation of a single determination. The result is

$$g_j(H)/g_p(H) = 658.21049(20),$$

where the number in parentheses is the uncertainty in the last place.

Both $g_j(H)$ and $g_p(H)$ must be corrected to obtain their free-space values. The bound-electron g factor differs from g_s by the relativistic correction, $g_j = g_s(1 - \alpha^2/3)$. The proton g factor can be corrected for diamagnetic shielding by the Lamb theory⁸ giving $g_p(H) = g_p(1 - \alpha^2/3)$. Thus we have

$$g_s/g_p = g_j(H)/g_p(H) = 658.21049(20).$$

Using Wilkinson and Crane's⁹ value, $g_s/2 = 1.00115962(3)$, we obtain for the ratio of the proton magnetic moment to twice the Bohr magneton

$$g_p = 0.0030420652(9).$$

By comparing the present result with Lambe's value⁴

$$g_j(H)/g_p(H_2O) = 658.21591(4),$$

the following difference between the shielding constants for water and atomic hydrogen is obtained:

$$\sigma(H_2O) - \sigma(H) = 8.23(30) \times 10^{-6}.$$

Since $\sigma(H) = \frac{1}{3}\alpha^2 = 17.75 \times 10^{-6}$, this yields

$$\sigma(H_2O) = 25.98(30) \times 10^{-6}.$$

By utilizing the known difference of proton shielding in water and H_2 ,^{10,11} $\Delta\sigma = 0.45(50) \times 10^{-6}$,

we obtain

$$\sigma(\text{H}_2) = 26.43(60) \times 10^{-6}.$$

This is in good agreement with the theoretical value of Ramsey^{5,12} for H₂,

$$\sigma(\text{H}_2)_{\text{theor}} = 26.2(4) \times 10^{-6}.$$

Our determination thus corroborates the presently accepted values of the shielding constant for protons in H₂ gas and water. We anticipate that the precision of the experiment will be substantially improved and thus serve to check details of shielding calculations to which no experiment has so far been sensitive. Even at the present level of accuracy, however, the result eliminates the possibility of an error in the proton moment as an explanation for the discrepancy in the fine-structure constant as obtained from fine- and hyperfine-structure measurements.

We wish to thank R. V. Pound and R. E. Richards for guidance in selection of the magnet used, which was designed and constructed by the Mullard Co., England, and D. A. Gray for

assistance in construction of the apparatus.

*Work supported by the National Science Foundation and the U. S. Office of Naval Research.

†Alfred P. Sloan Foundation Fellow.

‡Present address: Department of Physics, Duke University, Durham, North Carolina.

¹S. H. Koenig, A. G. Prodel, and P. Kusch, *Phys. Rev.* **88**, 191 (1952).

²R. Beringer and M. A. Heald, *Phys. Rev.* **95**, 1474 (1954).

³J. S. Geiger, V. W. Hughes, and H. E. Radford, *Phys. Rev.* **105**, 183 (1957).

⁴E. B. D. Lambe, thesis, Princeton University, 1959 (unpublished).

⁵N. F. Ramsey, *Phys. Rev.* **78**, 699 (1950).

⁶E. R. Cohen and J. W. M. DuMond, *Rev. Mod. Phys.* **37**, 537 (1965).

⁷D. Kleppner, H. M. Goldenberg, and N. F. Ramsey, *Phys. Rev.* **126**, 603 (1962).

⁸W. E. Lamb, *Phys. Rev.* **60**, 817 (1941).

⁹D. T. Wilkinson and H. R. Crane, *Phys. Rev.* **130**, 852 (1963).

¹⁰H. A. Thomas, *Phys. Rev.* **80**, 901 (1950).

¹¹H. Gutowsky and R. E. McClure, *Phys. Rev.* **81**, 276 (1951).

¹²N. J. Harrick, R. G. Barnes, P. J. Bray, and N. F. Ramsey, *Phys. Rev.* **90**, 260 (1953).

SCATTERING OF POSITRONS AND ELECTRONS FROM PROTONS*

R. L. Anderson,[†] B. Borgia,[‡] G. L. Cassiday, J. W. DeWire, A. S. Ito, and E. C. Loh

Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

(Received 12 July 1966)

We wish to report some results from an experiment which compares the scattering of 1200-Mev positrons and electrons from protons. The beams of positrons and electrons were obtained from the electron pairs produced by the photon beam from the Cornell synchrotron operating at 1400 MeV. A five-magnet system served to analyze the electrons or positrons into a beam whose spread in momentum was ten percent and to transport the particles to a location suitable for performing the scattering experiment. The electron intensity was measured by a Quantameter¹ and was approximately 10^6 sec^{-1} , about one-tenth the maximum beam.

A schematic plan of the experiment is shown in Fig. 1. The electrons passed through a cylindrical liquid-hydrogen target, 45 cm long and and 3.2 cm diam. The target had double walls of 0.25-mm stainless steel and double entrance and exit windows of 0.025-mm stainless steel.

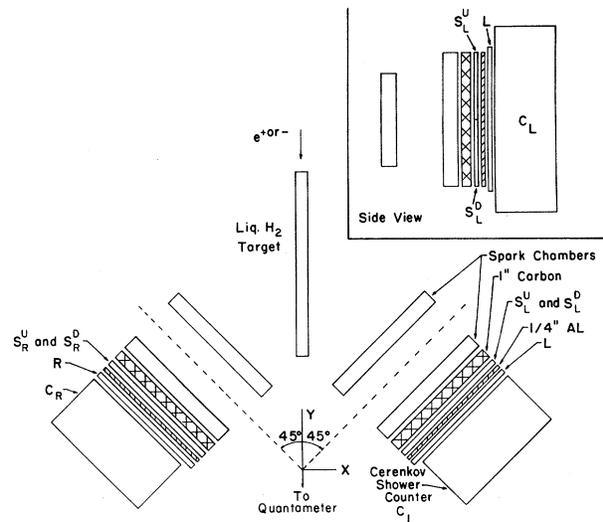


FIG. 1. Schematic plan of the detection equipment. The spark chambers are triggered on any one of the coincidences $LS_L^U C_L RS_R^D$, $LS_L^D C_L RS_R^U$, $RS_R^U C_R LS_L^D$, and $RS_R^D C_R LS_L^U$.