PHYSICAL REVIEW LETTERS

VOLUME 31 | 24 SEPTEMBER 1973 | NUMBER 13

g_J Factor of He^4 in the $2\,^3S_1$ State*

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(Received 6 August 1973)

We report precision atomic-beam measurements which yield a value for the helium-hydrogen g-factor ratio:

$$g_J(\mathrm{He}, 2\,^3S_1)/g_J(\mathrm{H}, 1\,^2S_{1/2}) = 1 - 23.25(30)\times 10^{-6}.$$

This value is in very good agreement with theory, and with an earlier, less precise atomic-beam measurement; it is in serious disagreement, however, with a recent optical-pumping determination which had seemed to cast doubt upon the adequacy of the theory.

For the past few decades, the properties of simple atomic systems have been a subject of enduring interest. One reason is that for such systems, quantum electrodynamics makes predictions which are sufficiently clear to allow definitive tests of the theory. In particular, atomic g factors of simple systems have been subjected to close scrutiny. Recently, Leduc, Laloë, and Brossel[1] carried out a very careful measurement of the ratio $g_J(\mathrm{He}, 2\,^3S_1)/g_I(\mathrm{He}^3)$, with the objective of deducing a more precise value for the metastable-helium, ground-state–hydrogen g-factor ratio $g_J(\mathrm{He}, 2\,^2S_1)/g_J(\mathrm{H}, ^2S_{1/2})$. Combining their results with those of other researchers, they found a value for the helium-hydrogen g-factor ratio which differs from the theoretical value by 3.5 standard deviations. Leduc and coworkers speculated that higher-order terms which had been neglected in the calculation by Perl and Hughes[2] could be responsible for this discrepancy. This speculation stimulated two new calculations; the calculation of Grotch and Hegstrom[3] and that of Hughes and Lewis[4] agree very well with each other, and with those of Perl and Hughes. The calculation of Grotch and Hegstrom demonstrates that the terms neglected by Perl and Hughes are an order of magnitude too small to account for the discrepancy observed by Leduc, Laloë, and Brossel.

The value obtained by Leduc, Laloë, and Brossel is also in mild disagreement with a direct atomic-beam measurement carried out by Drake *et al.*[5] fifteen years ago. In order to clarify the experimental situation, we undertook a series of atomic-beam measurements of the ratios $g_J(\mathrm{He}, 2\,^3S_1)/g_J(\mathrm{Rb}, ^2S_{1/2})$ and $g_J(\mathrm{He}, 2\,^3S_1)/g_J(\mathrm{Cs}, ^2S_{1/2})$; combining our results with the high-precision optical-pumping measurements of Robinson and his co-workers,[6] we obtain two independent values for the helium-hydrogen g-factor ratio. These values are in agreement with each other, and with all three calculations; they also agree with the earlier direct atomic-beam measurement, but are about 3 times more precise. Our results, however, differ from those of Leduc, Laloë, and Brossel by 3 times their assigned error or 5 times our assigned error.

The atomic-beam magnetic-resonance technique used in our measurements has been described in detail elsewhere.[7] Here it is sufficient

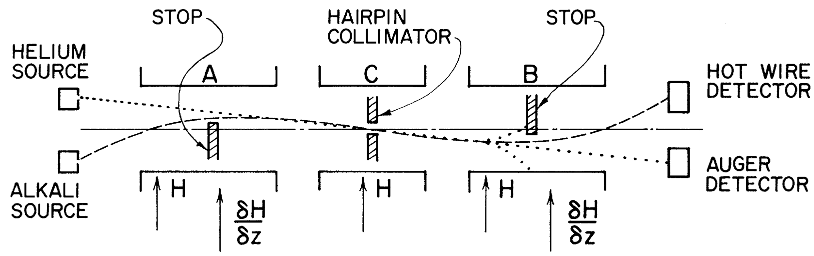

FIG. 1. Geometry for simultaneous observation of a "flop-out" transition in metastable helium, and a "flop-in" transition in Rb or Ce.

to mention the novel features of this experiment. In making g-factor ratio measurements, it is necessary to measure a transition frequency at the same value of the applied magnetic field in each of the two species under study. It is usual to make these measurements sequentially. Here, by appropriately choosing the geometry, the transitions, and the field strength, we observe both transitions simultaneously. The geometry is shown in Fig. 1. The electron gun which metastabilizes a small fraction of the helium beam is laterally displaced from the oven which provides the alkali beam. The two beams are simultaneously detected on Auger and hot-wire detectors, respectively. The positions of the sources, hairpin, stops, and detectors allow only "flop-out" transitions to be observed on the helium beam, and "flop-in" transitions to be observed on the alkali beams. In order to make it possible to induce both transitions with a single rf signal applied to the hairpin, the magnetic field strength has been chosen so that both transitions occur at essentially the same frequency. This arrangement eliminates uncertainties arising from possible differences in the spatial distribution of the rf power causing the two transitions, and guarantees that the transitions are observed under identical field conditions.

Another major improvement pertains to the homogeneity of the field applied to the transition region. In earlier measurements on the g_J factor of nitrogen, systematic shifts were observed that depended upon the history of the applied field.[8] It was speculated that history-dependent inhomogeneity was responsible for these shifts. To eliminate this source of error, shim coils were used to flatten the field over the hairpin to within 2 or 3 parts in 10^7. In order to carry out the field flattening, in addition to the shim coils, we constructed two NMR systems; one system was used to map the field to 1 part in 10^7, while the field remained locked by the other system. Our first measurements, made without flattening the field, contain systematic shifts of 2 or 3 parts in 10^6. Our final data also contain systematic shifts, but their relative size is reduced by an order of magnitude or more.

In all, over 600 pairs of helium and alkali resonances were recorded, using a computerized data-taking system similar to that described in Ref. 8; the majority of these resonances were taken in an extended search for possible sources of systematic error. With an appropriately flattened field, systematic shifts greater than our assigned error arose only from gross overpowering of the transitions.

In addition to the rf power, the relative position and orientation of the hairpin, the sources, the applied field, and the detectors were varied, yielding results within our assigned uncertainty. Data were also taken with two kinds of rf hairpins. The final result is based upon data taken with a 50-Ω terminated hairpin identical to that described in Ref. 8; the second hairpin—a shorted vacuum-dielectric microstrip—yielded noticeably distorted resonances. In spite of the distortion, the results obtained with that hairpin also fall within our assigned uncertainty. Resonances were recorded with both dome-shaped and dish-shaped magnetic fields; in both cases, the field deviation was held to 2 or 3 parts in 10^7 over the hairpin. Again, no shifts larger than our assigned error were observed. The helium and the alkali transition frequencies were derived from the data by fitting each resonance by a Lorentzian curve; the amplitude, width, center frequency, background, and background slope were allowed to vary. The results did not change when the background slope was held at zero.

The final results were calculated by averaging values obtained with a given relative orientation of the hairpin and applied field, with those ob-

TABLE I. Results with terminated hairpin, given in terms of $a=[1-g_J(\mathrm{He}^4, 2\,^3S_1)/g_J(\mathrm{H}^1, 1\,^2S_{1/2})]\times 10^6$.

Transition	Orientation Field	Orientation Hairpin	Number of obs.	a	Av. to correct for phase errors	Isotope average
Rb^{85}	$-$	$+$	140	23.16(20)	23.21	23.25
$(3,0)\leftrightarrow(2,-1)$	$+$	$-$	10	23.25(13)		
at 3161 G	$+$	$+$	25	23.24(14)	23.29	
	$-$	$-$	22	23.33(19)		
Cs^{133}	$-$	$+$	58	23.19(20)	23.24	23.24
$(4,-1)\leftrightarrow(3,-2)$	$+$	$-$	23	23.30(37)		
at 4306 G	$+$	$+$	22	23.34(33)	23.24	
	$-$	$-$	22	23.14(21)		

tained with both the hairpin and the field reversed. This procedure tends to cancel residual errors due to inhomogeneity in the static and rf fields.[9] Since there are four possible orientations of the hairpin and field, for each transition one finds two independent averages which can be cross checked. A summary of our data is given in Table I, and the constants used in the computation are listed in Table II. A histogram of all the data used in calculating our result is given in Fig. 2. From the rubidium data, we obtain

$$g_J(\mathrm{He})/g_J(\mathrm{Rb})=1-46.83(30)\times10^{-6},$$

$$g_J(\mathrm{He})/g_J(\mathrm{H})=1-23.25(30)\times10^{-6},$$

$$g_J(\mathrm{He}^4, 2\,^3S_1)=2.002\,237\,34(60);$$

TABLE II. Constants used to deduce absolute helium g factor and helium-hydrogen g-factor ratio.

$g_J(\mathrm{Cs}^{133})/g_J(\mathrm{Rb}^{67})=1.000\ 104\ 473\ 7(44)$ [a]
$g_J(\mathrm{Rb}^{87})/g_J(\mathrm{Rb}^{85})=1.000\ 000\ 004\ 1(60)$ [b]
$g_J(\mathrm{Rb}^{87})/g_J(\mathrm{H}^1)=1.000\ 023\ 585\ 5(6)$ [c]
$g_J(\mathrm{H}^1)/g_e=0.999\ 982\ 31(10)$ [d]
$g_e=2[1.001\ 159\ 656\ 7(35)]$ [e]

[a]C. W. White, W. M. Hughes, G. S. Hayne, and H. G. Robinson, Phys. Rev. A 7, 1178 (1973).

[b]C. W. White, W. M. Hughes, G. S. Hayne, and H. G. Robinson, Phys. Rev. 174, 23 (1968).

[c]W. M. Hughes and H. G. Robinson, Phys. Rev. Lett. 23, 1209 (1969).

[d]J. S. Tiedeman and H. G. Robinson, in *Atomic Physics 3, Proceedings of the Third International Conference on Atomic Physics*, edited by S. J. Smith and G. K. Walters (Plenum, New York, 1973).

[e]S. Granger and G. W. Ford, Phys. Rev. Lett. 28, 1479 (1972).

from the cesium data,

$$g_J(\mathrm{He})/g_J(\mathrm{Cs})=1-151.28(30)\times10^{-6},$$

$$g_J(\mathrm{He})/g_J(\mathrm{H})=1-23.24(30)\times10^{-6},$$

$$g_J(\mathrm{He}^4, 2\,^3S_1)=2.001\,237\,36(60).$$

Taking all data into account, we find

$$g_J(\mathrm{He}^4, 2\,^3S_1)/g_J(\mathrm{H}^1, 1\,^2S_{1/2})=1-23.25(30)\times10^{-6},$$

$$g_J(\mathrm{He}^4, 2\,^3S_1)=2.002\,237\,35(60).$$

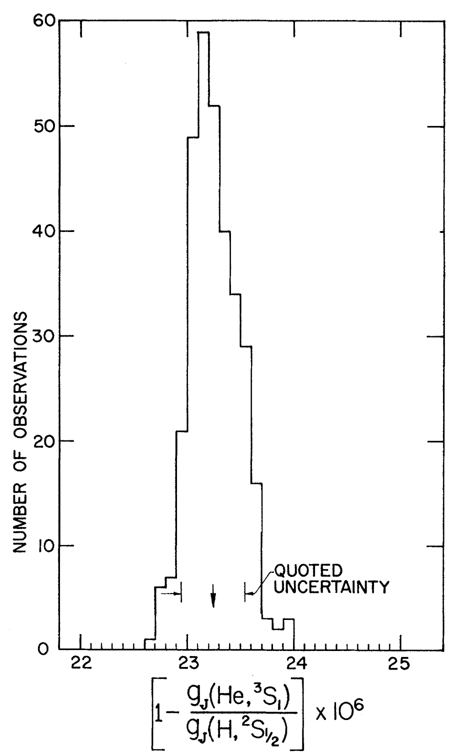

FIG. 2. Histogram showing the distribution of values obtained in the 322 measurements included in the calculation of our final result.

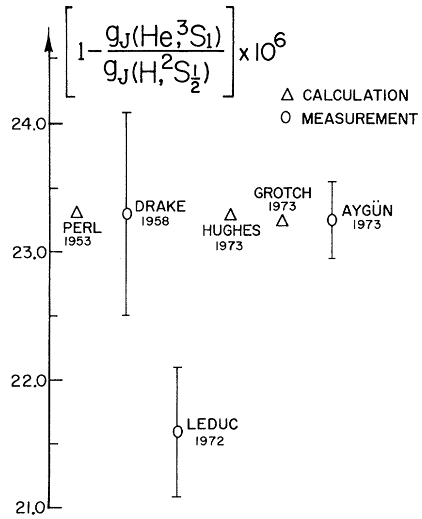

FIG. 3. Experimental and theoretical determinations of the He-H g-factor ratio. The values for the quantity a (Table I) are the following: from Ref. 2 (1953), $a=23.3$; Ref. 5 (1958), $a=23.3(8)$; Ref. 1 (1972), $a=21.6(5)$; Ref. 4 (1973), $a=23.29$; Ref. 3 (1973), $a=23.212$; this work (1973), $a=23.25(30)$.

The error we assign to our result reflects our estimate of the residual systematic error arising from all sources.

The present state of both experiment and theory for the helium-hydrogen g-factor ratio is shown in Fig. 3. As can be seen, the agreement between the theoretical results and all atomic-beam measurements is very good. The discrepancy between these results and the value obtained by Leduc, Laloë, and Brossel, however, remains unexplained.

We are indebted to C. E. Johnson for several valuable suggestions.

*Work supported by the U.S. Atomic Energy Commission and the Ford Foundation. To be submitted by E. Aygün to the Middle East Technical University, Ankara, Turkey in partial fulfillment of the requirements for the Doctor of Philosophy degree.

[1]M. Leduc, F. Laloë, and J. Brossel, J. Phys. (Paris) 33, 49 (1972).

[2]W. Perl and V. W. Hughes, Phys. Rev. 91, 842 (1953).

[3]H. Grotch and R. A. Hegstrom, Phys. Rev. A (to be published).

[4]V. W. Hughes and M. L. Lewis, Bull. Amer. Phys. Soc. 18, 120 (1973); M. L. Lewis and V. W. Hughes, Phys. Rev. A (to be published).

[5]C. W. Drake, V. W. Hughes, A. Lurio, and J. A. White, Phys. Rev. 112, 1627 (1958).

[6]W. M. Hughes and H. G. Robinson, Phys. Rev. Lett. 23, 1209 (1969); C. W. White, W. M. Hughes, G. S. Hayne, and H. G. Robinson, Phys. Rev. A 7, 1178 (1973).

[7]N. F. Ramsey, *Molecular Beams* (Oxford Univ. Press, Oxford, England, 1956).

[8]B. D. Zak and H. A. Shugart, Phys. Rev. A 6, 1715 (1972).

[9]K. D. Boklen, thesis, University of Bonn, West Germany, 1971 (unpublished); S. Penselin, private communication.

Microwave Emission from an Anisotropy Instability in a High-Current Relativistic Electron Beam

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A momentum anisotropy, created by injecting an electrostatically unneutralized annular electron beam through various foils, is shown experimentally to lead to high-power microwave emission. The radiation occurs at a frequency such that the phase velocities of cyclotron waves on the beam and the TE_{01} mode in the guide are equal.

Recent work on the application of high-current relativistic electron beams to microwave generation[1-3] has been centered on the injection of the beams through a rippled magnetic field. The results developed show that the most probable explanation of the microwave generation is associated with the interaction of a cyclotron wave and a wave-guide mode. The injection through the rippled field serves the purpose of tailoring the particle distribution function to provide transverse motion of the beam electrons. The present experiment was designed to investigate the role of anisotropy in the particle distribution function as a source of free energy to drive the instabil-