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g_J-Factor of He^4 in the 2^3S_1 State*

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ABSTRACT

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

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

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 $g_J(He, 2^3S_1)/g_I(He^3)$, with the objective of deducing a more precise value for the metastable-helium, ground-state hydrogen g-factor ratio: $[g_J(He, 2^3S_1)/g_J(H, ^2S_{\frac{1}{2}})]$. 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 three and a half 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 Perl and Hughes. The calculation of Grotch demonstrates that the terms neglected by Perl and Hughes are an order of magnitude too small to account for the discrepancy observed by Leduc.

The value obtained by Leduc is also in mild disagreement with a direct atomic beam measurement carried out by Drake, Hughes, Lurio and White[5] fifteen years ago. In order to clarify the experimental situation, we undertook a series of atomic beam measurements of the ratios $g_J(He,2^3S_1)/g_J(Rb,^2S_{1/2})$ and $g_J(He,2^3S_1)/g_J(Cs,^2S_{1/2})$; combining our results with the high precision optical-pumping measurements of Robinson and his coworkers,[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 three times more precise. Our results, however, differ from those of Leduc, et al. by three times their assigned error or five 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 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 Figure 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 a 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 contains 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 reference 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 50Ω terminated hairpin identical to that described in reference 8; the second hairpin--a shorted vacuum-dielectric microstrip--yielded noticably 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 to 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 obtained 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 and our final results are given in Table I. A histogram of all of the data used in calculating our result is given in Fig.2. Taking all data into account, we find $g_J(\mathrm{He},2^3S_1)/g_J(\mathrm{H},1^2S_{1/2}) = 1 - 23.25(30)\times10^{-6}$ and $g_J(\mathrm{He},2^3S_1) = 2.002\ 237\ 35(60)$. 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, however, remains unexplained.

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

Trans.	Field Orientation	Hair-pin Orientation	Number of obs.	a(S.D.)	Ave. to corr. 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)		

From the Rubidium data and from Table II:

$g_J(He)/g_J(Rb) = 1 - 46.83(30) \times 10^{-6}$

$g_J(He)/g_J(H) = 1 - 23.25(30) \times 10^{-6}$

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

From the Cesium data and from Table II:

$g_J(He)/g_J(Cs) = 1 - 151.28(30) \times 10^{-6}$

$g_J(He)/g_J(H) = 1 - 23.24(30) \times 10^{-6}$

$g_J(He^4, 2^3S_1) = 2.002\ 237\ 36(60)$

Overall results:

$g_J(He^4, 2^3S_1)/g_J(H^1, 1^2S_{1/2}) = 1 - 23.25(30) \times 10^{-6}$

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

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

$g_J(Cs^{133})/g_J(Rb^{87})$	=	1.000 104 473 7(44)[a]
$g_J(Rb^{87})/g_J(Rb^{85})$	=	1.000 000 004 1(60)[b]
$g_J(Rb^{87})/g_J(H^1)$	=	1.000 023 585 5(6)[c]
$g_J(H^1)/g_e$	=	.999 982 31(10)[d]
g_e	=	2(1.001 159 656 7(35))[e]

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FIGURE CAPTIONS

Fig. 1. Geometry for simultaneous observation of a "flop-out" transition in metastable helium, and a "flop-in" transition in rubidium or cesium.

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 helium-hydrogen g-factor ratio. The values for the quantity "a" above are: Perl (1953), a = 23.3; Drake (1958), a = 23.3(8); Leduc (1972), a = 21.6(5); Hughes (1973), a = 23.29; Grotch (1973), a = 23.212; Aygün (1973), a = 23.25(30).

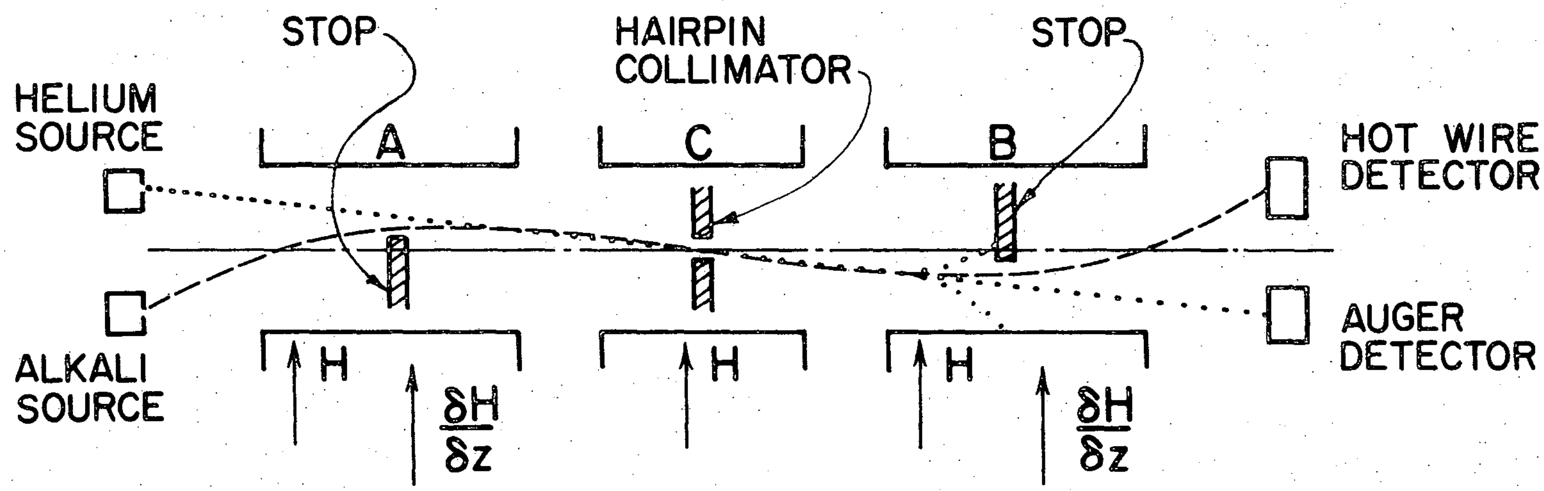

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Fig. 1

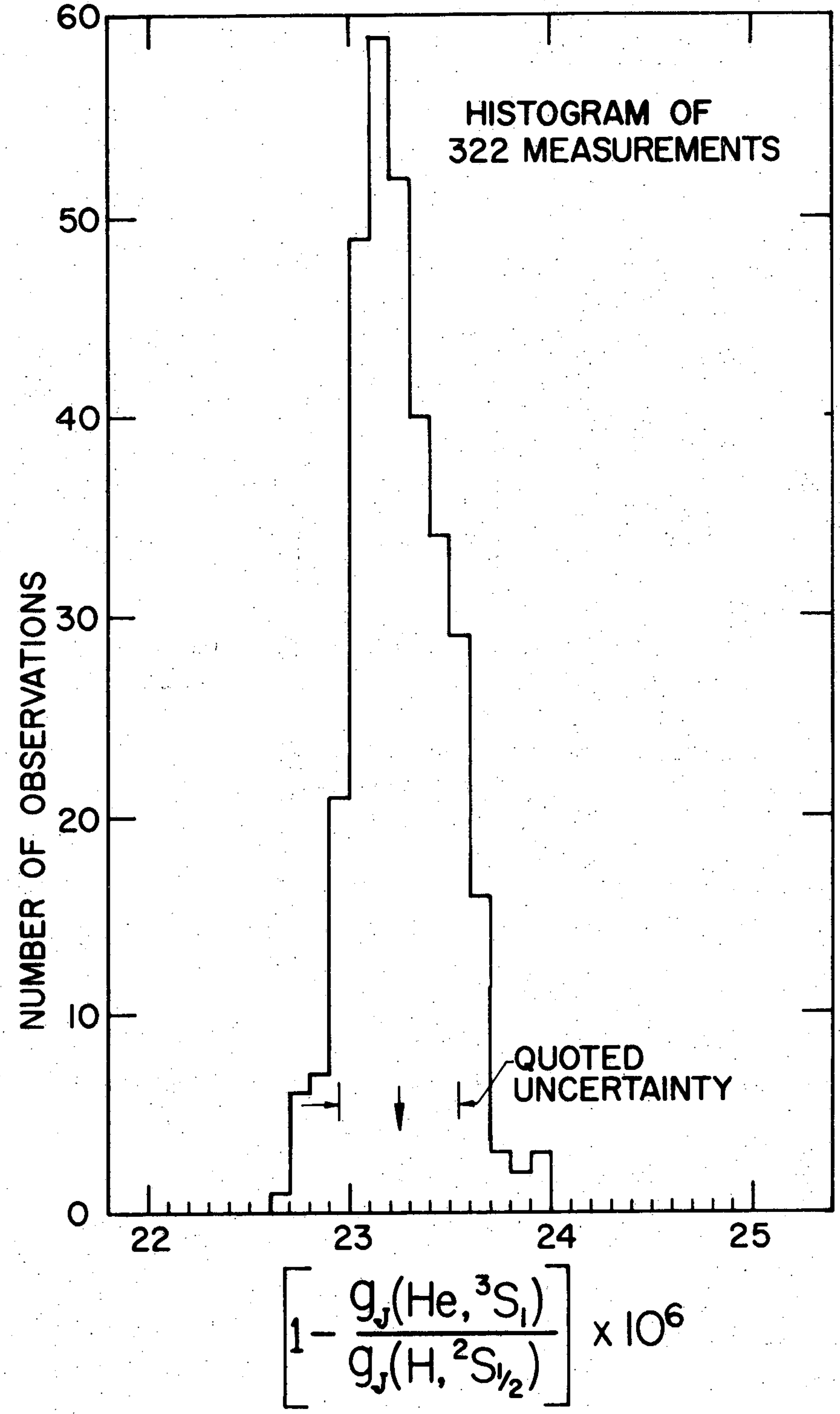

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Fig. 2

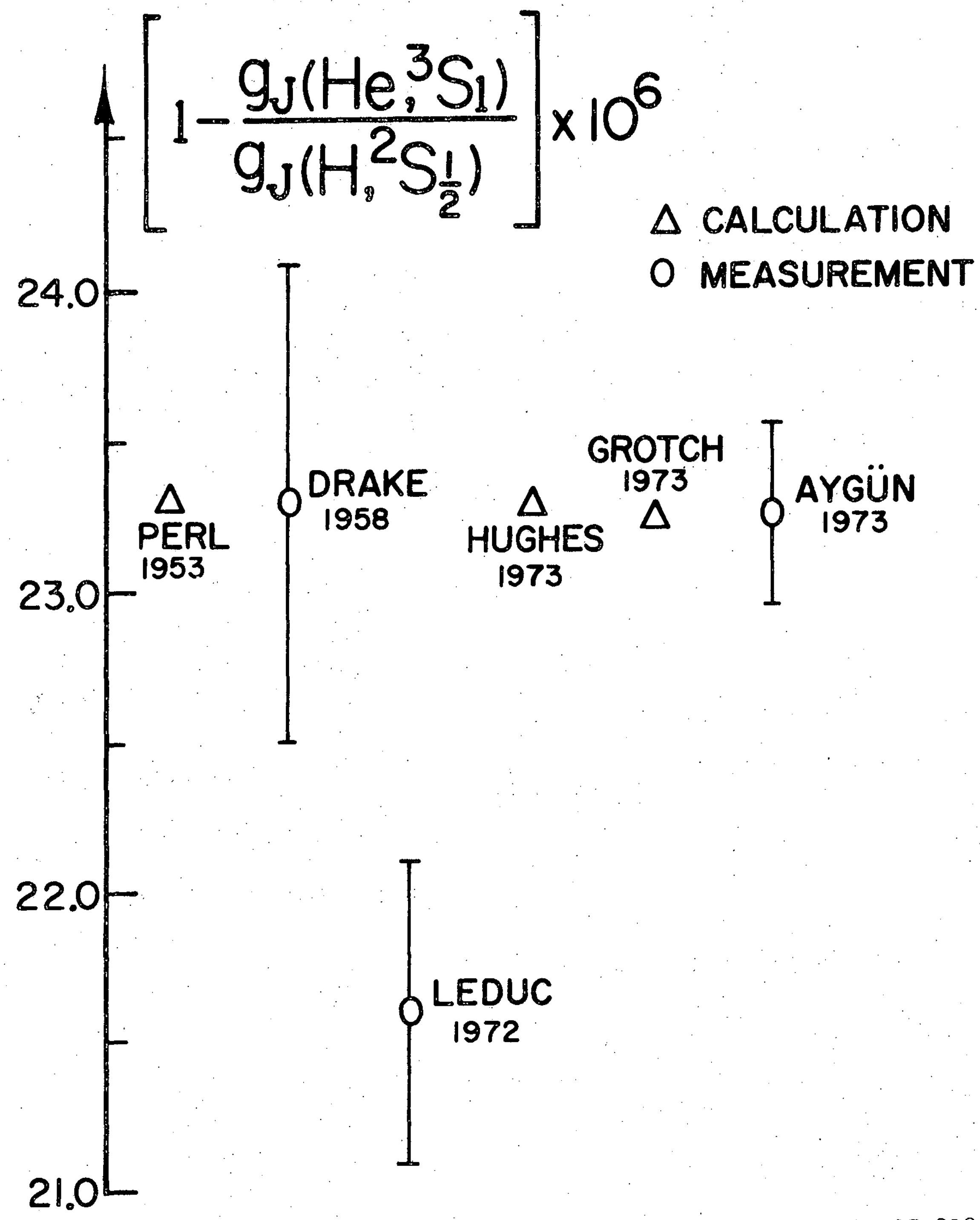

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Fig. 3

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