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PRECISION g_J MEASUREMENTS ON LIGHT ATOMS: $g_J(He^4, 2^3S_1)/g_J(H, {}^2S_{1/2})$[†]

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ABSTRACT

A concise review is presented of the experimental and theoretical determinations of three quantities: $g_J(H)/g_J(D)$; $g_J(H)/g_e$; and $g_J(He, 2^3S_1)/g_J(H)$. These quantities serve as tests of our understanding of the Zeeman effect in simple bound systems. We also critically examine the discrepancy between the helium-hydrogen g-factor ratio as determined by the present authors using an atomic beam technique: $g_J(He, 2^3S_1)/g_J(H) = 1-23.25(30)x10^{-6}$, and that obtained by Leduc, Laloë, and Brossel using optical pumping: $g_J(He, 2^3S_1)/g_J(H) = 1-21.60(32)x10^{-6}$. The uncertainty quoted for this determination is that given by a recalculation presented here. Our result is in excellent agreement with theory as well as with a previous measurement, while that of Leduc, Laloë, and Brossel now differs from theory by five standard deviations.

The purpose of this paper is to give a concise review of precision atomic g-factor measurements in hydrogen and helium, to describe briefly our own measurement of $g_J(\mathrm{He}, 2^3S_1)$, and to examine the discrepancy into which this measurement enters.

The first topic to receive attention in the current series of precision g-factor measurements on light atoms was the isotope shift in the g-factor of ground state hydrogen. Roger Hegstrom[1] and Howard Grotch[2] have extended the theory of the Zeeman effect in hydrogenic atoms to include terms of order α^3 and $\alpha^2 m/M$, where m is the electron mass, and M the nuclear mass. The nuclear mass dependent terms enter as reduced mass corrections to the spin-orbit, spin-other orbit, and relativistic mass increase terms. Since then, the theory has been developed and elaborated by several authors[3-5] using a number of different theoretical approaches.

The first published measurement of the hydrogen-deuterium g-factor ratio sensitive to these mass dependent terms was published by Hughes and Robinson.[6] They used spin-exchange with optically pumped rubidium to observe the hydrogen and deuterium Zeeman resonances. Their result, given in Table I, is in agreement with theory. Next, Larson, Valberg, and Ramsey[7] used a low-field hydrogen maser to measure this ratio; their value also agrees with theory. Finally, Walther, Phillips, and Kleppner[8] measured this quantity to three parts in 10^{11} using a pulsed double-mode hydrogen maser operated at 3500 G. This experiment yields agreement with theory to better than one part in 10^{11}. This very nicely confirms the value of the mass dependent terms to order $\alpha^2 m/M$. Higher precision yet would be required to test the next higher order mass dependent terms, each of which contributes about 1 part in 10^{11} to the hydrogen-deuterium g-factor ratio.

While the measurements mentioned above do adequately test certain terms in the Hamiltonian, they leave others unchecked. The most interesting test for the theory of hydrogenic atoms in external magnetic fields is the measurement of the magnetic moment of the bound electron relative to that of the free electron. Grotch and Hegstrom have derived the result, good to order α^3 and $\alpha^3 m^2/M^2$:

$$g_J(1S) = g_e \left[1 - \frac{(Z\alpha)^2}{3} \left(1 - \frac{3}{2}\frac{m}{M} + \frac{3}{2}\{1+Z\}\frac{m^2}{M^2}\right) + \frac{\alpha}{4\pi}(Z\alpha)^2 \left(1 - \frac{5}{3}\frac{m}{M} + \frac{6+Z}{3}\frac{m^2}{M^2}\right) \right]$$

With this expression, one obtains $g_J(H)/g_e = 1 - 17.7051\text{x}10^{-6}$. The first measurement of this ratio was made by Balling and Pipkin[9] with the spin-exchange optical pumping technique. They obtained agreement with the best theoretical value available at that time, that of Perl[10]. Since their value contains an uncertainty of 1 ppm, it only crudely confirmed the leading correction term due to the Breit interaction. Now, however, there is an experiment in progress which will ultimately do very much better. Tiedeman and Robinson, using the same technique as Balling and Pipkin, but with a more sophisticated apparatus, give $g_J(H)/g_e = 1 - 17.69(10)\text{x}10^{-6}$ as a preliminary result.[11] This value nicely confirms the mass independent terms to order α^2. The measurement may eventually be able to test the α^3 terms adequately as well, but almost certainly not the mass dependent terms.

Now we shift our attention from ground state hydrogen to the 2^3S_1 metastable state of helium. The quantity of interest here is the ratio $g_J(\mathrm{He},2^3S_1)/g_J(\mathrm{H})$, where, of course, the hydrogen is in the ground state. The succession of experimental and theoretical determinations of this ratio is shown in Table III.

Perl and Hughes[12] carried out the first calculation of this quantity to order α^2, starting from the Breit equation. Their value was first crudely, and then more precisely confirmed by atomic beam measurements -- in 1953 by Hughes, Tucker, Rhoderick, and Weinreich,[13] and in 1958 by Drake, Hughes, Lurio, and White.[14] That is where matters stood until Leduc, Lalöe, and Brossel[15] published the results of their optical pumping determination in 1972. This result differed from the calculated value of Perl and Hughes by 1.6 ppm, or three standard deviations. Leduc et al suggested that the discrepancy might be due to uncalculated higher order terms -- perhaps to the non-additivity of the anomalous moments of the electrons. The existence of this discrepancy inspired a burst of research activity.

Lewis and Hughes[16] calculated the helium-hydrogen g-factor ratio to order α^2 and m/M using up to 165 term Hylleraas wave functions. Grotch and Hegstrom [17] extended their earlier work to helium, taking account of terms of order α^3 and α^2m/M. Both calculations agree very well with the previous experimental and theoretical determinations, but not with the value of Leduc, Laloë, and Brossel. Furthermore, Gotch and Hegstrom found that the higher order terms contributed only -0.151 ppm to their value, much too small a contribution to account for the observed discrepancy.

Meanwhile, the present authors had begun a new atomic beam precision determination of the helium-hydrogen g-factor ratio; a brief description of the first phase of this experiment has already been published.[18] We have made independent measurements of the ratios $g_J(\mathrm{He},2^3S_1)/g_J(\mathrm{Rb})$ and $g_J(\mathrm{He},\ 2^3S_1)/g_J(\mathrm{Cs})$, where the rubidium and cesium are in their ground states. Using the results of others, we obtain two independent values for the helium-hydrogen g-factor ratio.

The experimental arrangement is shown in Fig. 1. This arrangement permits us to observe the helium and alkali resonances simultaneously, thereby minimizing the effect of magnetic field drift, and other sources of instability. As shown in Fig. 2, we have chosen the magnetic field at which to work so that the helium and the alkali resonances occur at the same frequency. The resonances are observed on separate detectors, and do not interfere with each other. Under these circumstances, the same R. F. field causes both transitions, guaranteeing that the spatial distribution of R. F. power is identical for both transitions. Finally, great care was taken in electrically shimming the magnetic field; all measurements were made with the field over the transition region flat to $\pm$ 2 parts in 10^7 or better.[19]

Our results are shown in Table IV. It is seen that our independent determinations using cesium and rubidium agree to a part in 10^8 with each other, and to within three parts in 10^8 with the theoretical value of Grotch and Hegstrom. A histogram of the 322 measurements upon which our reported value is based is given in Fig. 3. The uncertainty we assign to our result, 3 parts in 10^7, includes a generous estimate of systematic error arising primarily from residual field inhomogeneity. Our final value differs from that of Leduc by five times our assigned error.

In considering this discrepancy, it is important to note that our determination, as well as the determination of Leduc and his coworkers are both indirect. The intermediate values measured by others which we use to obtain the helium-hydrogen g-factor ratio from our measurements are given in Table V. (First three lines.) These quantities were measured by H. G. Robinson and his collaborators using the spin exchange optical pumping technique. They have characteristic uncertainties of 4 to 6 parts in 10^9 -- that is, about 1/60 of our assigned error. Consequently, if our determination is in serious error, it is likely that our own measurement is responsible, rather than these intermediate values.

The quantity that Leduc and her coworkers measured was the ratio of the atomic g-factor of metastable He^4 to the nuclear g-factor of ground state He^3. They quote an uncertainty for this measurement itself of 7 parts in 10^8. In Table VI, we give a re-calculation of the helium-hydrogen ratio from the data of Leduc, but using a somewhat more precise value for one of the intermediate quantities than was available to her. This change does not affect the final value of the g-factor ratio at all, but does substantially reduce the uncertainty. With this reduced error, the discrepancy between the value of Leduc and both the theoretical and our experimental value is five standard deviations, as shown in Fig. 4.

If one accepts the assumption that our determination is correct, then one is left with the question as to where the error arises in the determination by Leduc and her coworkers. As one notes from Table VI, there are three possibilities: the quantity z, the quantity y, or the measurement of Leduc itself.

It is the quantity z for which we have used a more precise value in the recalculation given in Table VI. It is derived from a high field hydrogen maser measurement of $g_J(H)/g_p(H)$ with an uncertainty of one part in 10^8 made by Winkler, Kleppner, Myint, and Walther,[20] and from the shielding factors for the proton in atomic and in molecular hydrogen. We follow Winkler in using the theoretical value for the atomic hydrogen shielding factor, and we use the value he determines for the molecular hydrogen shielding factor which is in good agreement with theory. The uncertainty on the value of z derived in this way is 3 parts in 10^7. One can derive the value of z from a number of other sets of measurements, but the result does not change significantly. Since this value is well buttressed with experiment and theory, it seems unlikely that it could be a major source of error.

On the other hand, the quantity y can look to neither experiment nor theory for adequate support. The value of y used here is due to Williams and Hughes.[21] It agrees with the earlier measurement of Anderson[22] to 3 parts in 10^7, but Anderson's assigned error is

1.6 ppm. It should be noted, though, that the error quoted by Anderson is four times his statistical error, and covers 70% of his measurements. Possible sources of systematic error which Anderson discusses appear to be smaller than his statistical error. This generous assignment of error in the final result appears to allow for possible unknown sources of systematic error. In fact, the measurement of Williams and Hughes agrees with that of Anderson to within the latter's statistical error.

To the knowledge of the experimenters, the measurement of Leduc, Lalöe, and Brossel has never been made before. The measurement was certainly very carefully done, including as it does a large number of tests for various sources of systematic error. In the final configuration of the experiment, all such tests give negative results to within statistical error. The paper by Leduc contains a thorough discussion of these tests and a number of other possible sources of error. Here we can only mention one possible source which was not adequately discussed. The quoted uncertainty of the measurement represents a precision of greater than a thousandth of the line-width of the He^4 metastable resonance observed by Leduc. The lines were determined to be symmetrical by a geometrical procedure which, it seems, may not have been sensitive to an asymmetry of a part in 10^3. A shift in the determined peak frequency of 1/60th the line width could account for the observed discrepancy.

Before closing, we are obliged to acknowledge that there are many recent experimental and theoretical studies of the Zeeman effect in hydrogen and helium which we have not mentioned. In particular, there is a body of work concerned with the Zeeman effect in the P states of these atoms; it has grown up, stimulated by the need to understand the Zeeman effect in order to make Lamb shift, fine, and hyperfine structure measurements. References contained in our own references 5 and 16 provide an entrance to that literature. Here we have concentrated upon the more stringent tests of the theory of the Zeeman effect in hydrogen and helium.

Looking back over our review, we may draw some conclusions. If indeed our atomic beam determination of the hydrogen-helium g-factor ratio is accepted as correct, then, in each of the three cases considered, there is very good agreement between experiment and theory. Yet it must also be recognized that the theory has not yet been pushed very hard by experiment. The agreement to parts in 10^{11} for the isotope shift in hydrogen is not quite so impressive as it sounds. After all, by these measurements one is testing mass dependent correction terms to parent terms which are of order α^2. The sensitivity of the implied test for the parent terms is diminished by the ratio m/M. So the test to parts in 10^{11} in the isotope shift is, in some sense, equivalent to a test to about 6 parts in 10^8 in the hydrogen-electron g-factor ratio experiment -- which is comparable to its present accuracy. The situation for the helium g-factor measurements is somewhat poorer. In all three cases, the α^2 terms are confirmed to about a part in 10^2, but the α^3 terms which are far more interesting are little more than detected.

So it is that the next round of experimental results should be of considerable importance. In both the hydrogen-free electron, and the helium-hydrogen experiments, the prospects are good for substantial improvements in the accuracy of the results. In both cases, plans are being implemented to realize those prospects.

Table I. EXPERIMENTAL AND THEORETICAL DETERMINATIONS OF THE RATIO $g_J(H)/g_J(D)$.

Author	Experiment	Theory
R. Hegstrom[a]		$1 + 9.7 \times 10^{-9}$
Hughes and Robinson[b]	$1+(7.2\pm1.2)\times10^{-9}$	
Larson, Valberg, and Ramsey[c]	$1+(9.4\pm1.4)\times10^{-9}$	
H. Grotch[d]		$1 + 9.7 \times 10^{-9}$
R. Faustov[e]		$1 + 7.3 \times 10^{-9}$
Close and Osborn[f]		$1 + 7.25 \times 10^{-9}$
Grotch and Hegstrom[g]		$1 + 7.22 \times 10^{-9}$
Walther, Phillips, and Kleppner[h]	$1+(7.22\pm.03)\times10^{-9}$	

[a] R. A. Hegstrom, Phys. Rev. 184, 17 (1969).

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

[c] D. J. Larson, P. A. Valberg, and N. F. Ramsey, Phys. Rev. Letters 23, 1369 (1969).

[d] H. Gotch, Phys. Rev. Letters 24, 39 (1970).

[e] R. Faustov, Phys. Letters 33B, 422 (1970).

[f] F. E. Close and H. Osborn, Phys. Letters 34B, 400 (1971).

[g] H. Grotch and R. A. Hegstrom, Phys. Rev. A 4, 59 (1971).

[h] F. G. Walther, W. D. Phillips, and D. Kleppner, Phys. Rev. Letters 28, 1159 (1972).

Table II. EXPERIMENTAL AND THEORETICAL DETERMINATIONS OF THE RATIO $g_J(H)/g_e$

Author	Experiment	Theory
W. Perl[a]		$1-17.7 \times 10^{-6}$
Balling and Pipkin[b]	$1-(17.4\pm1.0)\times10^{-6}$	
Grotch and Hegstrom[c]		$1-17.7051 \times 10^{-6}$
Tiedeman and Robinson[d]	$1-(17.69\pm0.10)\times10^{-6}$	

[a] W. Perl, Phys. Rev. 91, 852 (1953).

[b] L. C. Balling and F. M. Pipkin, Phys. Rev. 139, A19 (1965).

[c] H. Grotch and R. A. Hegstrom, Phys. Rev. A 4, 59 (1971).

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TABLE III. Experimental and Theoretical Determinations of the Ratio $g_J(\mathrm{He}, 2^3S_1)/g_J(\mathrm{H}, ^2S_{1/2})$

Author	Experiment	Theory
Perl and Hughes[a]		$1 - (23.3 \pm 1) \times 10^{-6}$
Hughes, Tucker, Rhoderick, and Weinreich[b]	$1 - (11 \pm 16) \times 10^{-6}$	
Drake, Hughes Lurio, and White[c]	$1 - (23.3 \pm 0.8) \times 10^{-6}$	
Leduc, Lalöe, and Brossel[d]	$1 - (21.6 \pm 0.5) \times 10^{-6}$	
Lewis and Hughes[e]		$1 - 23.287 \times 10^{-6}$
Grotch and Hegstrom[f]		$1 - 23.212(3) \times 10^{-6}$
Aygün, Zak, and Shugart	$1 - 23.25(30) \times 10^{-6}$	

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

[b] V. Hughes, G. Tucker, E. Rhoderick, and G. Weinreich, Phys. Rev. 91, 828 (1953).

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

[d] M. Leduc, F. Lalöe, and J. Brossel, J. Phys. (Paris) 33, 49 (1972); J. Brossel, in Atomic Physics 3, edited by S. J. Smith and G. K. Walters (Plenum, New York, 1973).

[e] M. L. Lewis and V. W. Hughes, Phys. Rev. A 8, 2845 (1973).

[f] H. Grotch and R. A. Hegstrom, Phys. Rev. A 8, 1166 (1973).

[g] E. Aygün, B. D. Zak, and H. A. Shugart, Phys. Rev. Letters 31, 803, (1973).

TABLE IV. 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	Hair-pin	Number of obs.	a(S.D.)	Ave. to corr. for phase errors	Isotope Average
	Orientation					
Rb^{85}	-	+	140	23.16(20)	23.21	23.25
(3,0) (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) (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 V:

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

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

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

From the Cesium data and from Table V:

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

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

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

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

$g_J(\mathrm{Cs}^{133})/g_J(\mathrm{Rb}^{87}) = 1.000\ 104\ 473\ 7(44)$[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]

$g_J(\mathrm{H}^{1})/g_e = .999\ 982\ 31(10)$[d]

$g_e = 2[1.001\ 159\ 656\ 7(35)]$[e]

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[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).

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TABLE VI. Values Used to Obtain the Helium/Hydrogen g-Factor Ratio from the Measurement of Leduc, Lalöe, and Brossel.

$a = g_J(\mathrm{He}^4,\ 2^3S_1)/g_I(\mathrm{He}^3) = 864.023\ 92(6)$[a]

$y = g_I(\mathrm{He}^3)/g_p(\mathrm{H}_2) = .761\ 786\ 85(8)$[b]

$z = g_J(\mathrm{H},\ ^2S_{1/2})/g_p(\mathrm{H}_2) = 658.216\ 28(20)$

Quantities used to evaluate z:

$g_J(\mathrm{H},\ ^2S_{1/2})/g_p(\mathrm{H}) = 658.210\ 706(6)$[c]

$\sigma(\mathrm{H}) = 17.733 \times 10^{-6}$[c]

$\sigma(\mathrm{H}_2) = 26.2(3) \times 10^{-6}$[c]

Final Result:

$g_J(\mathrm{He})/g_J(\mathrm{H}) = x = a(y/z) = 1-21.60(32)\times 10^{-6}$

Result Quoted by Leduc et al: $1-21.6(5)\times 10^{-6}$

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[a] M. Leduc, F. Lalöe, and J. Brossel, J. Phys. (Paris) 33, 49 (1972); J. Brossel, in Atomic Physics 3, edited by S. J. Smith and G. K. Walters (Plenum, New York, 1973).

[b] W. L. Williams and V. W. Hughes, Phys. Rev. 185, 1251 (1969).

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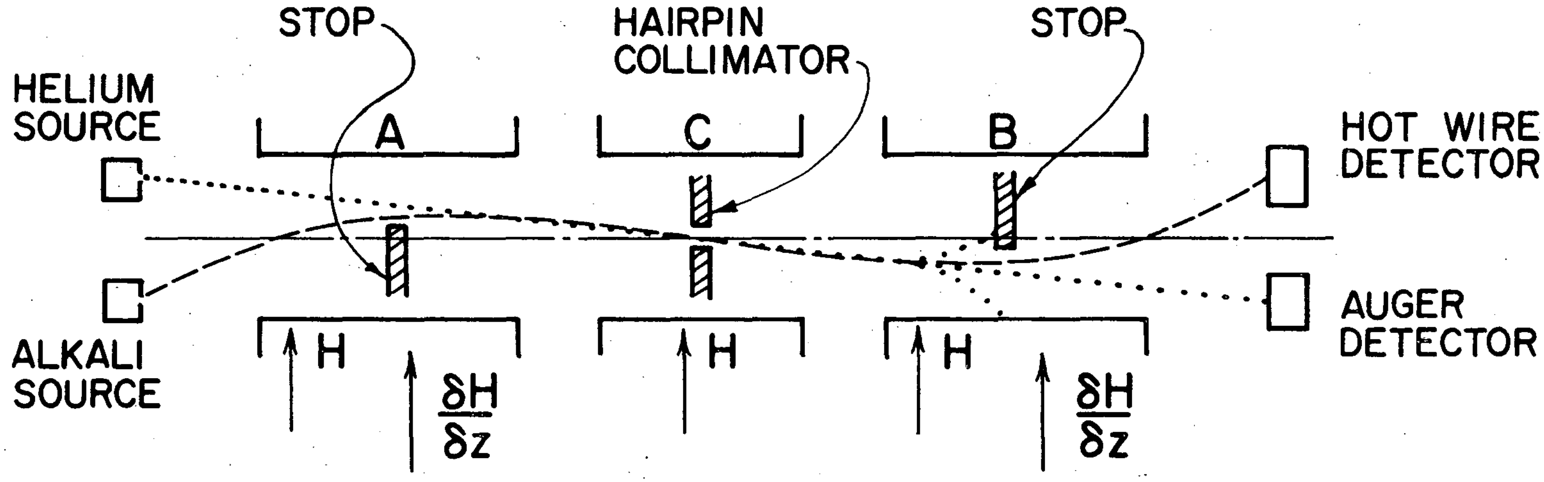
FIGURE CAPTIONS

Fig. 1. Apparatus geometry which permits the simultaneous observation of a flop-in alkali resonance and a flop-out metastable He^4 resonance.

Fig. 2. Coincidence between the $\Delta F = 0$, $\Delta m = \pm 1$ transition frequency in 2^3S_1 He^4 and the $(4,-1) \leftrightarrow (3,-2)$ transition frequency in $^2S_{1/2}$ Cs^{133}.

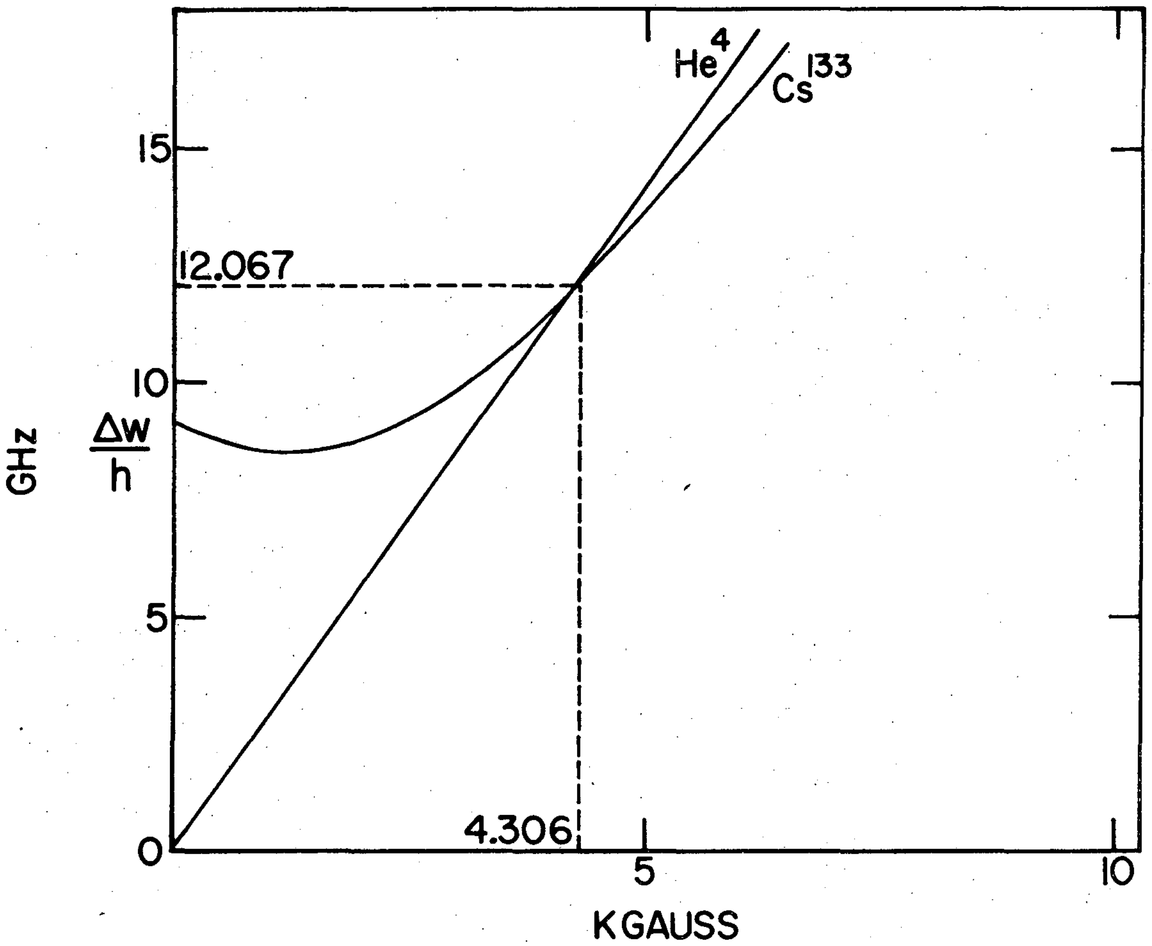
Fig. 3. Histogram of measurements showing the final value and the quoted uncertainty.

Fig. 4. Experimental and theoretical determinations of the helium-hydrogen g-factor ratio.



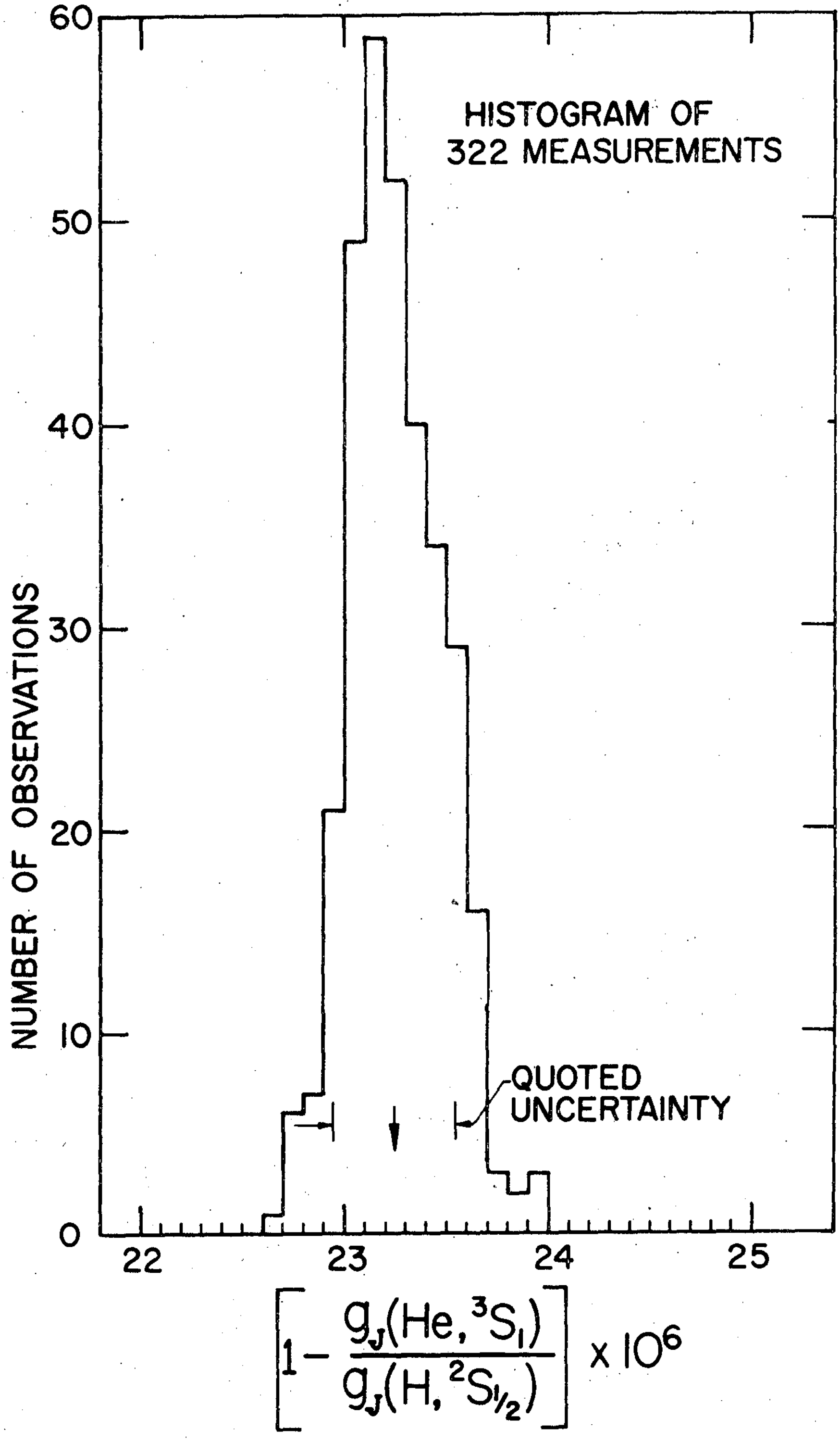
XBL 737-930

Fig. 1.



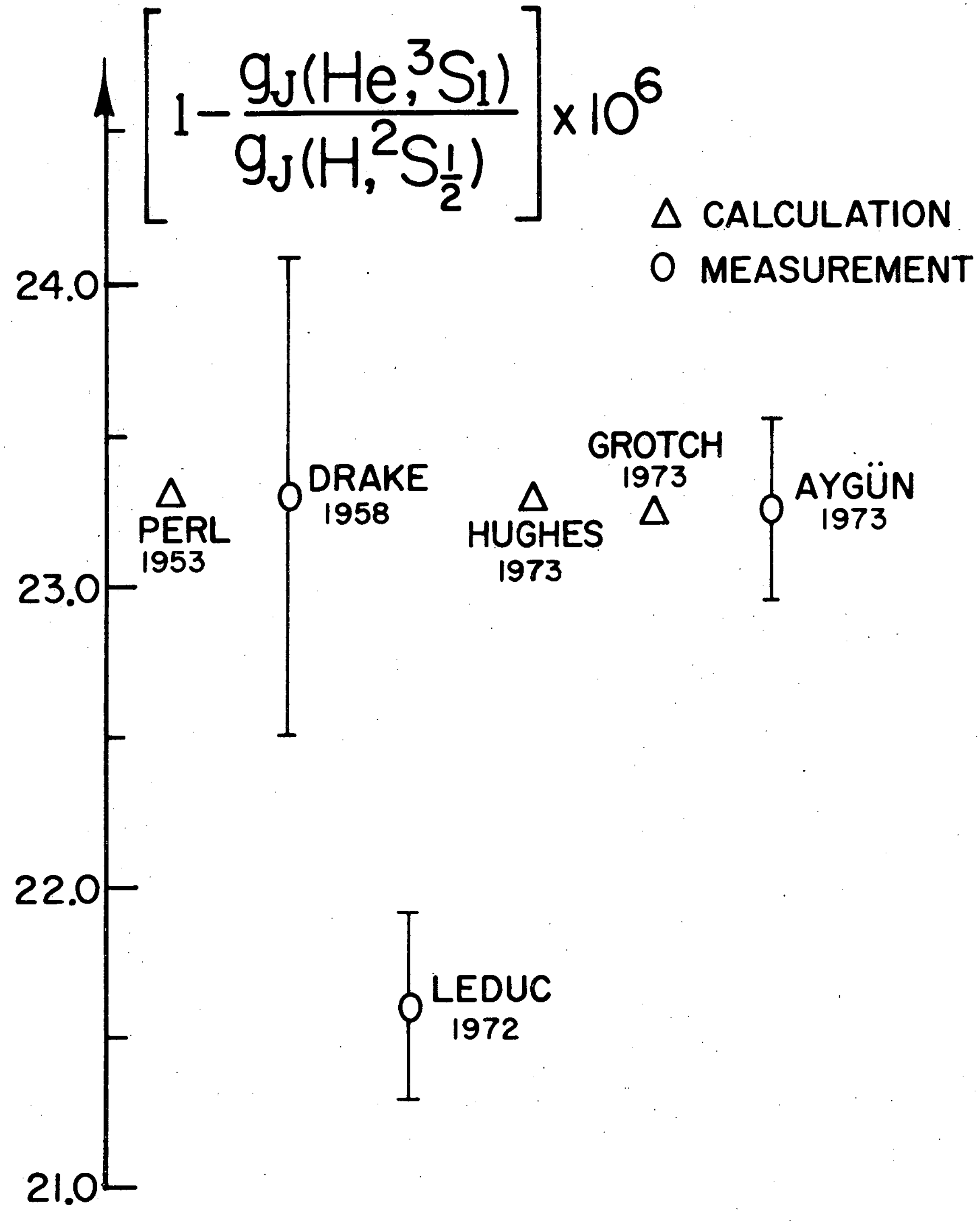
XBL 735-548

Fig. 2.



XBL 737-936

Fig. 3.



XBL 746-1041

Fig. 4.

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