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Determination of $g_J(^4\text{He}, 2^3S_1)/g_J(^1\text{H}, 1^2S_{1/2})$: Resolution of a Discrepancy*

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A new measurement of the g_J factor in the 2^3S_1 metastable state of ^{4}He has been made using an optical-pumping technique. Our result is $g_J(^4\text{He}, 2^3S_1)/g_J(^1\text{H}, 1^2S_{1/2}) = 1 - 23.15(10) \times 10^{-6}$. This value agrees with theory and provides confirmation of a recent atomic-beam measurement. Further doubt is cast on an earlier optical-pumping determination, thereby resolving a possible discrepancy between theory and experiment.

In 1972, an optical pumping measurement of the ratio of g factors, $g_J(^4\text{He}, 2^3S_1)/g_I(^3\text{He}, 1^1S_0)$, was reported by Leduc, Laloë, and Brossel[1] (LLB). Combining their result with the results of two other measurements gave the ratio $R = g_J(^4\text{He}, ^3S_1)/g_J(^1\text{H}, ^2S_{1/2})$. The value differed not only from that of theory[2] by -1.6 ppm, or by almost three times their quoted uncertainty, but also from an earlier, less accurate, atomic-beam magnetic-resonance experiment.[3] This apparent disagreement between theory and experiment stimulated additional theoretical and experimental work. Higher-order terms in the theory were considered by Grotch and Hegstrom[4] and by Lewis and Hughes[5]; however, the disagreement remained. Subsequently, an improved atomic-beam experiment by Aygün, Zak, and Shugart[6] (AZS) confirmed the theoretical value but differed significantly from the LLB value. We report on a unique, new, optical-pumping experiment which provides convincing evidence toward the resolution of this discrepancy.

Our method[7] polarizes atoms in the 2^3S_1 metastable state of helium through spin-dependent Penning collisions with optically pumped ground-state Rb in a 30-cm^3 cylindrical glass cell. Although, previously, other species have been polarized by collisions with optically pumped metastable helium,[8] we believe that this is the first case of metastable helium being polarized by collision with an optically pumped alkali. Zeeman transitions of He(2^3S_1) are monitored by observing the Rb light transmitted through the cell. These transitions result in a decrease of the Rb polarization and therefore a decrease in transmitted light. Metastable He(2^3S_1) is produced by means of a weak, pulsed, electrodeless, rf discharge. In an applied magnetic field of 50 G, the He(2^3S_1) and the free-electron Zeeman resonances are sufficiently narrow to be essentially resolved in this experiment. Depending upon the polarization of the Rb pumping light, the Rb($^2S_{1/2}$) resonance used is either $(F, m_F \leftrightarrow F', m_F') = (2,2 \leftrightarrow 2,1)$ or $(2,-1 \leftrightarrow 2,-2)$. For each of the Rb($^2S_{1/2}$) and He($2^3S_1$) resonances, data are taken at fifteen frequencies spread over about 4 linewidths. Modified Lorentzians are fit to the data, and the ratio of g_J factors, $g_J(^4\text{He}, 2^3S_1)/g_J(^{87}\text{Rb}, ^2S_{1/2})$, is extracted using the Breit-Rabi formula.

Four cells, containing helium at pressures of 5, 7, 9, and 14 Torr, were constructed. Motivated by the desire to obtain a weaker discharge, each cell was placed in North Carolina State University's nuclear reactor and irradiated for 6 min at a flux of 10^{11} neutrons/cm^2/sec. Systematic effects were examined for each cell, both before and after irradiation, by varying the Rb pumping light intensity and polarization, the discharge intensity as determined by the rate, width, and amplitude of the pulse driving the discharge, the homogeneity of the applied magnetic field, and the rf power driving the Zeeman resonances. For the 9- and 14-Torr cells before irradiation, a systematic shift of the He(2^3S_1) resonance was observed as the discharge intensity was varied. This shift, typically ~ 0.2 ppm in size, is related to a small asymmetry of the resonance, which decreases as the discharge intensity and consequently the resonance linewidth is reduced. Although the tail of the He(2^3S_1) resonance slightly overlaps that of the free-electron spin resonance which is 41 ppm above the He(2^3S_1) resonance, the electron resonance does not completely account for the asymmetry of the He(2^3S_1) resonance if the fitting function used is the simple sum of two Lorentzians, one having the observed parameters of the free-electron resonance. The He$^+$($^2S_{1/2}$) resonance which is predicted to be 30 ppm below the He(2^3S_1) resonance is not observed for our operating conditions.

As the discharge intensity is reduced in a particular cell, the discharge extinguishes itself at some lowest limit long before the density of He(2^3S_1) atoms has decreased to unfavorably limit the signal-to-noise ratio. However, a much weaker discharge was possible in the 9- and 14-Torr cells after the neutron bombardment altered the structure of the glass. Before irradiation, the 9- and 14- Torr cells had a minimum He(2^3S_1) resonance linewidth of about 400 Hz; after irradiation, the minimum linewidth was 250 Hz. This same narrow linewidth of 250 Hz, and correspondingly weak discharge, is possible in the 5- and 7-Torr cells both before and after irradiation. Diffusion to the cell walls, three-body conversion, inhomogeneous magnetic field, and collisions with Rb give an estimated residual width of about 100 Hz for the He(2^3S_1) resonance in all four cells.

The weaker discharge intensity, and consequently narrower He(2^3S_1) linewidth, obtainable in the two lower-pressure cells, and also in the two higher-pressure cells after neutron bombardment, results in a much smaller shift of the resonance as the discharge intensity is varied. In fact, this shift, now ~ 0.02 ppm, is almost obscured by the scatter of the results for g_J(^{4}He, 2^3S_1)/g_J(^{87}Rb, $^2S_{1/2}$) when they are plotted versus He(2^3S_1) linewidth as in Fig. 1. Here, the He(2^3S_1) linewidth is used as a measure of the discharge intensity. A variety of widths, repetition rates, and amplitudes of the discharge pulse were used. Each g_J-factor ratio plotted is the average of the two values obtained for both polarizations of the Rb pumping light, thereby correcting for shifts (~ 0.2 ppm) due to pumping-light intensity and polarization.

The average of the data shown in Fig. 1 is our experimental result:

$$g_J(^4\text{He}, 2^3S_1)/g_J(^{87}\text{Rb}, ^2S_{1/2}) = 1 - 46.73(10)\times 10^{-6}.$$

The error has been chosen to include not only our estimate of magnetic field inhomogeneity, but also of any remaining systematic effect related to the discharge intensity. Although the data taken for the two higher-pressure cells before irradiation were not used, they agree with the above result when extrapolated to the same He(2^3S_1) resonance linewidth region as the data of Fig. 1.

Using the previously determined ratio[9]

$$g_J(^{87}\text{Rb}, ^2S_{1/2})/g_J(^1\text{H}, ^2S_{1/2}) = 1 + 23.5855(6)\times 10^{-6}$$

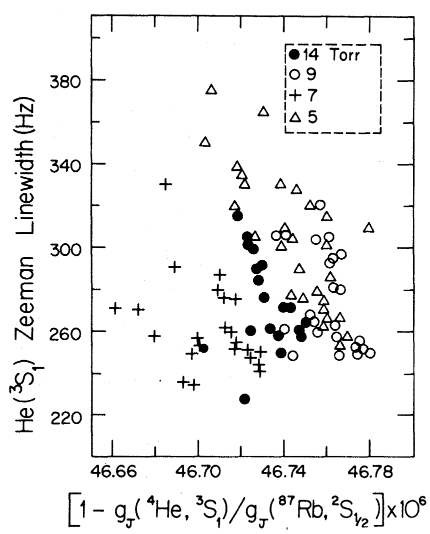

FIG. 1. g_J-factor ratio data plotted versus He(2^3S_1) linewidth, where the linewidth is used as a measure of the discharge intensity. Data taken both before and after neutron bombardment are plotted for the 5- and 7-Torr cells, while the data for the 9- and 14-Torr cells are those taken only after irradiation.

TABLE I. Comparison between precision experiments to determine $R = g_J(^4\text{He}, 2^3S_1)/g_J(^1\text{H}, ^2S_{1/2})$.

Authors	LLB[a]	AZS[b]	KRJ[c]
Method	$\text{He}(2^3S_1)$ optical pumping	Atomic beam	Rb optical pumping
Applied field (G)	150	3161 and 4306	50
He pressure (Torr)	0.4 to 1.2	0	5 to 14
Discharge	Continuous	None	Pulsed
$\text{He}(2^3S_1)$ linewidth (kHz)	40	100	0.25
Width-to-frequency ratio	0.9×10^{-4}	1.1×10^{-5}	2×10^{-6}
Fractional splitting of linewidth	0.001	0.03	0.05
Quantity measured	$g_J(^4\text{He}, 2^3S_1)/g_I(^3\text{He}, 1^1S_0)$	$g_J(^4\text{He}, 2^3S_1)/g_J(^{85}\text{Rb}, ^2S_{1/2})$, $g_J(^4\text{He}, 2^3S_1)/g_J(^{133}\text{Cs}, ^2S_{1/2})$	$g_J(^4\text{He}, 2^3S_1)/g_J(^{87}\text{Rb}, ^2S_{1/2})$
$(1-R)\times 10^6$	21.6(5)	23.25(30)	23.15(10)

[a]Ref. 1. [b]Ref. 6. [c]This paper.

yields

$$R = g_J(^4\text{He}, 2^3S_1)/g_J(^1\text{H}, ^2S_{1/2}) = 1 - 23.15(10)\times 10^{-6},$$

which agrees with both theoretical values; Grotch and Hegstrom[4] report $R = 1 - 23.212\times 10^{-6}$, while Lewis and Hughes[5] give $R = 1 - 23.220\times 10^{-6}$.

A comparison of the three high-precision experiments is given in Table I. Unique features of our method (KRJ) are the narrow linewidth for the metastable $\text{He}(2^3S_1)$ resonance, and the conservative ratio of quoted error to linewidth. According to theory,[10] the free-electron and the $^4\text{He}^+(1^2S_{1/2})$ resonances are, respectively, 40.9 ppm above and 29.9 ppm below the $\text{He}(2^3S_1)$ resonance. The experiment of LLB had a $\text{He}(2^3S_1)$ linewidth which overlaps both of these possible resonances; however, we do not know whether these nearby resonances were present to a significant degree in their experiment. These resonances were not present in the experiment of AZS.

All three experiments indirectly determine the ratio R. Two intermediate ratios needed by LLB were $g_I(^3\text{He}, 1^1S_0)/g_I(\text{H}_2)$ and $g_J(^1\text{H}, 1^2S_{1/2})/g_I(\text{H}_2)$, while AZS required $g_J(^{133}\text{Cs})/g_J(^{87}\text{Rb})$, $g_J(^{87}\text{Rb})/g_J(^{85}\text{Rb})$, and $g_J(^{87}\text{Rb})/g_J(^1\text{H})$. (Two determinations of R were obtained by using both Cs and Rb as reference atoms.) Finally our result uses $g_J(^{87}\text{Rb})/g_J(^1\text{H})$. It is possible, of course, that the disagreement between experiments arises from the intermediate ratios, although those used by AZS and us have quoted errors too small to make a significant contribution to R at the current level of precision.

In conclusion, a new experimental method has been used to present evidence for agreement between theoretical and experimental values of the g_J of the metastable 2^3S_1 state of helium at the 0.1 ppm level of precision. This confirms the latest atomic-beam experimental value of AZS, and therefore is interpreted as resolving a possible conflict between theory and experiment, as suggested by LLB. The extremely narrow linewidth achieved in our experiment is about 100 times narrower than in previous experiments.

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