Fine Structure and Diamagnetic Zeeman Effect in He. II. Measurements in the $4\,^3P$ and $5\,^3P$ States

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We have observed transitions between Zeeman levels of fine-structure states of He, excited and aligned by electron impact in a magnetic field, for both the $4p\,^3P$ and $5p\,^3P$ states. An improved apparatus has reproduced the six previously observed $4p\,^3P$ resonance lines with an improved signal-to-noise ratio. It has also made possible observation of two "forbidden" transitions in the $4p\,^3P$ state and the eight corresponding transitions in the $5p\,^3P$ state. The following fine-structure constants have been derived:

$$4\,^3P_0 - 4\,^3P_1 = 3306.4 \pm 0.7 \text{ MHz}, \quad 4\,^3P_1 - 4\,^3P_2 = 270.4 \pm 0.7 \text{ MHz},$$

$$5\,^3P_0 - 5\,^3P_1 = 1660.0 \pm 0.8 \text{ MHz}, \quad 5\,^3P_1 - 5\,^3P_2 = 137.4 \pm 0.7 \text{ MHz}.$$

The anisotropic portion of the diamagnetic Zeeman interaction has been measured and used to derive values for the atomic radius and quadrupole moment. These values are *larger* than the corresponding expectation values calculated from hydrogenic orbitals. Further calculations and experiments are planned to determine if these discrepancies are apparent or real.

INTRODUCTION

In a previous paper[1] (I) we have reported values for the fine-structure constants $\Delta\nu_{01}$ and $\Delta\nu_{12}$, the orbital angular momentum g factor g_L, and the diamagnetic Zeeman effect in the $4p\,^3P$ rydberg state of He. In both the previous and present work we have excited and aligned rydberg He states by electron bombardment of ground-state He residing in a microwave cavity in a magnetic field. The magnetic field allows the tuning of the atomic Zeeman levels to resonance with the microwave frequency. Such resonances are observed *via* changes in the polarization of the emitted uv radiation when the state decays. Since our original work, a greatly improved version of the apparatus has been constructed and used to measure two new "forbidden" transitions in the $4\,^3P$ state as well as to remeasure the six allowed transitions reported in I. Furthermore, it has been used to measure the eight corresponding transitions in the $5\,^3P$ state. Similar measurements on the He $n\,^3P$ states to $n=8$ or 9 are planned so that the variation of atomic parameters and collisional cross sections can be followed through the rydberg series.

THEORY

In order to fit the observed spectral lines the same Hamiltonian as was used in I is employed, i.e.,

$$\mathcal{H} = \mathcal{H}_{FS} + g_L \mu_B \vec{H} \cdot \vec{L} + g_S \mu_B \vec{H} \cdot \vec{S} - \chi_A T^2(\vec{H},\vec{H}) \cdot T^2(\vec{L},\vec{L}). \qquad (1)$$

$\mathcal{H}_{FS}$ is a phenomenological fine-structure Hamiltonian containing the two adjustable fine-structure splittings $^3P_2 - {}^3P_1$ ($\Delta\nu_{12}$) and $^3P_1 - {}^3P_0$ ($\Delta\nu_{01}$).

The next two terms constitute the linear Zeeman effect. The orbital angular momentum g factor g_L is again treated as an adjustable parameter. In I we noted that the transition frequencies were insensitive to g_S and thus it is again held constant at its free-spin value.[2]

The final term represents the observable anisotropic portion of the diamagnetic (quadratic) Zeeman interaction. For any ^3P state,

$$\chi_A = \sum_i \frac{e^2}{4mc^2} \times \langle L = M_L = 1\ \eta |\, r_i^2 (3\cos^2\theta_i - 1) \,| L = M_L = 1\ \eta \rangle ,$$

where the sum is over the two electrons i in He and η denotes which ^3P state is being observed.

EXPERIMENTAL

The method and concept of the apparatus remain unchanged from I, but the actual equipment has been rebuilt with numerous improvements. This apparatus will be described in more detail elsewhere.[3] The prinicpal improvements are a water-cooled cavity to prevent thermal drift, an improved electron gun capable of better than 10 times the current of the previous model, an improved pumping system capable of pressures below 10^{-7} Torr, an improved light-collection scheme, and a microwave-modulation capability.

These improvements have resulted in at least a 20-fold increase in the signal-to-noise ratio on the $4p\,^3P$ He lines as compared to I. Moreover, under low-power conditions, the widths of the observed lines are significantly reduced at low pressure ($\lesssim 10^{-4}$ Torr) and have been observed with widths

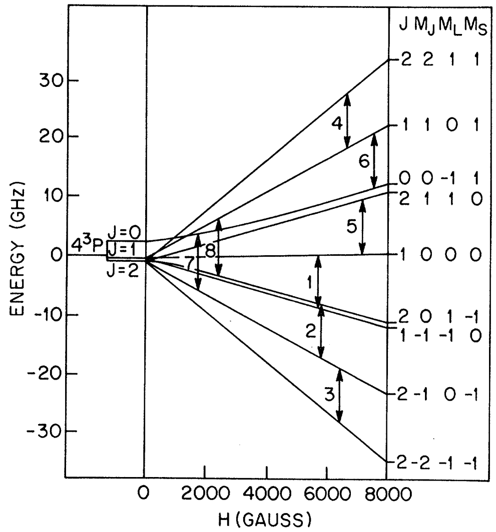

FIG. 1. Energy levels of He $4\,^3P$ in the presence of a magnetic field. The $5\,^3P$ energy levels have essentially the same appearance except transition 2 takes place at lower magnetic field than 1.

only 10–20% greater than the values expected from their known radiative lifetimes. The measurements reported here, however, were taken in a somewhat pressure-broadened region [with the power level set to roughly optimize the signal strength, i.e., such that the magnitude (in frequency units) of the microwave magnetic field perturbation was about equal to the reciprocal of the radiative lifetime[4]] to improve the signal-to-noise ratio.

The only deficiency of the new apparatus, as compared to the old one, lies in the larger currents needed to heat the cathode. This current causes a magnetic field shift whose magnitude can only be determined by field measurements (with the heater current on and off) at a point removed from the sample. Such measurements indicate a shift of 0.2–0.3 G.

Such a current should, however, to a first approximation, shift all lines equally, and the parameters reported, except g_L, are expected to be quite insensitive to such a shift. This insensitivity was verified by performing least-squares fits (see the Results section) with the field positions shifted by 0.2–0.3 G. In all cases the computed parameters were within the parameter error limits determined with the original data. The error values reported for g_L are based on a 0.2-G uncertainty rather than the statistical consistency of the fit upon which the error limits for the other parameters are based.

In the present experiment light from the $4p\,^3P$ state at 3188 Å and the $5p\,^3P$ state at 2945 Å is viewed through an interference filter centered at 2990 Å with a bandwith (full width at half-height) of 100 Å. Radiation at 3188 Å is approximately 7% transmitted while radiation at 2945 Å is about 27% transmitted. Since the 3188-Å line in He has about three times the intensity of the 2945-Å line, the $4p\,^3P$ resonances are expected to have about $\frac{3}{4}$ the intensity of the $5p\,^3P$ ones (provided both lines have the same polarization). The experimental results are in agreement with this prediction.

RESULTS

The eight observed resonances are indicated schematically in the energy-level diagram of Fig. 1. The transitions numbered 1–6 were observed for the $4p\,^3P$ state of He in paper I. These transitions have been observed again with an improved signal-to-noise ratio. The corresponding six transitions have now also been observed for the $5p\,^3P$ state. (In the $5p\,^3P$ state the transition numbered 2 actually occurs at a lower field than that numbered 1 in Fig. 1.) Besides these six "allowed" transitions we have also observed two low-field "forbidden" transitions, numbered 7 and 8 in Fig. 1, for both the $4p\,^3P$ and $5p\,^3P$ states. These transitions are forbidden in the sense that they violate the high-field selection rule $\Delta M_S = 0$. As can be seen from Fig. 1 the initial and final states involved in these transitions correlate with states of M_S differing by two. However, at these relatively

TABLE I. Observed line positions and the residuals from least-square fits for the $4p\,^3P$ and $5p\,^3P$ states of He.

No.	Transition $JM \leftrightarrow J'M'$	$4\,^3P$ Frequency (F) (MHz)	$4\,^3P$ Field (H) (G)	$4\,^3P$ $H_{obs} - H_{pred}$ (G)	$5\,^3P$ Frequency (F) (MHz)	$5\,^3P$ Field (H) (G)	$5\,^3P$ $H_{obs} - H_{pred}$ (G)
2	2 0 ↔ 2 −1	9205.57	5879.57[a]	−0.05	9205.59	6186.88[a]	−0.02
1	1 0 ↔ 1 −1	9205.57	5851.12[a]	−0.09	9205.60	6204.11[a]	−0.15
3	2 −1 ↔ 2 −2	9205.58	6484.30	0.02	9205.60	6432.70	−0.04
4	2 2 ↔ 1 1	9205.59	6674.84	0.04	9205.61	6624.40	0.05
5	2 1 ↔ 1 0	9205.60	7316.69	−0.09	9205.57	6953.00	−0.10
6	1 1 ↔ 0 0	9205.63	7570.31	0.01	9205.60	7046.26	0.13
7	0 0 ↔ 2 −1	9204.49	1702.89	−0.02	9204.49	2000.39	0.00
8	1 1 ↔ 2 0	9204.49	2362.07	−0.14	9204.49	2298.34	−0.12

[a]Relative field positions of these two transitions are interchanged in the $4\,^3P$ and $5\,^3P$ states.

TABLE II. Experimental parameters determined for $4p\,^3P$ and $5p\,^3P$ states of He. The uncertainties indicated for all parameters, except g_L, are twice the standard error. error . g_s is taken to be 2.002 32.

Parameter	$4p\,^3P$	$5p\,^3P$
$\Delta\nu_{01}$	3306.4 ± 0.7 MHz	1660.0 ± 0.8 MHz
$\Delta\nu_{12}$	270.4 ± 0.7 MHz	137.4 ± 0.7 MHz
g_L	0.999 869 ± 0.000 030	0.999 861 ± 0.000 030
χ_A	− 0.086 ± 0.014[a] Hz/G^2	− 0.212 ± 0.014[a] Hz/G^2

[a]See text for discussion of possible systematic errors.

low-resonance fields, the $\Delta M_S = 0$ selection rule is not rigorous, and the use of the maximum microwave power available made these lines easily observable.

Table I gives the observed frequencies and fields of the 8 lines for the $4p\,^3P$ and $5p\,^3P$ states. A least-squares calculation, as described in I, was used to adjust the four parameters in Eq. (1). The results are given in Table II. The difference between the observed magnetic field at the given frequency and the predicted from the constants of Table II is given in columns 4 and 7 of Table I. The rms deviation for all the measured lines is less than 0.15 G and is usually in the range 0.05–0.10 G. As noted in the Experimental section, the absolute field position is uncertain to at least twice this error, but only the parameter g_L is sensitive to the absolute values. One can see from Table I that any differences between observed and predicted magnetic fields lie within the bounds of likely experimental error.

Comparing the results in Table II for the $4p\,^3P$ state of He with the results of I, we see that all the constants are identical to well within the two standard-error limits quoted. We believe that this strongly indicates the reliability of these data since, though the method used in both cases is the same, the new data were taken with a different apparatus, at a different microwave frequency, and include lines not previously observed. Since the $5p\,^3P$ data were taken simultaneously with the new $4p\,^3P$ data, they probably have the same reliability.

A discussion of previous work on the $4p\,^3P$ states was given in I. We have subsequently become aware of work by Kaul[5] which reports $\Delta\nu_{01}$ for the $n = 3$–$6\,^3P$ states. This work and the works by Descoubes and co-workers[6] are the only previous measurements of the $4\,^3P$ and $5\,^3P$ fine structure. They are compared in Table III with the present results and those of paper I. Kaul's value for $\Delta\nu_{01}$ for $4\,^3P$ lies just within the error limit of our present measurement. The previous values for both $5\,^3P$ fine-structure intervals disagree with the present ones. We can offer no explanation for these discrepancies. Recently calculated values by Accad *et al.*[7] and slight improvements to them by Pekeris[8] are also given in Table III.

The absolute value of g_L for both states is precise to only about 30 ppm, but within this limit they both agree with theoretical predictions.[9] The relative determination of the g_L's should be nearly twice as accurate, and we believe that we can set an upper limit of 15 ppm on the deviation of their ratio from unity.

From the value of χ_A, the quadrupole moment Q_L of the state may be derived [Eq. (25) of I]. In Table IV we have listed the values of Q_L for both the $4p\,^3P$ and $5p\,^3P$ states of He. Since the angular factor in Q_L should be very closely approximated by $-\frac{2}{5}$ for the p electron and 0 for the s electron, we can obtain from Q_L the value of $\langle r^2\rangle$ for the p electron. The expectation values of $\langle r^2\rangle$ for the two states are listed in Table IV. We have also included the value of Q_L and $\langle r^2\rangle$ which were calculated assuming the p electron is in a hydrogenic

TABLE III. Comparison of measured and calculated fine-structure intervals for He $4\,^3P$ and $5\,^3P$.

	$4\,^3P$		$5\,^3P$	
	$\Delta\nu_{01}$	$\Delta\nu_{12}$	$\Delta\nu_{01}$	$\Delta\nu_{12}$
Galleron-Julienne and Descoubes[a]	2970 ± 300	270.7 ± 0.2	1500 ± 200	135.5 ± 0.1
Maujean and Descoubes[b]	3231 ± 500	269.0 ± 0.1	1415 ± 300	···
Kaul[c]	3305.72 ± 0.28	···	1662.13 ± 0.42	···
Paper I[d]	3306.6 ± 1.0	270.7 ± 0.8	···	···
This work	3306.4 ± 0.7	270.4 ± 0.7	1660.0 ± 0.8	137.4 ± 0.7
Accad *et al.*[e]	3307	270	1667	144
Pekeris[f]	3307.0[g]	269.0[g]	1661[h]	129[h]

[a]Reference 6(a).
[b]Reference 6(b).
[c]Reference 5.
[d]Reference 1.
[e]Reference 7. A 364-term wave function was used.
[f]Reference 8.
[g]Extrapolation from 220-, 364-, and 560-term wave functions. $^1P_1$–$^3P_1$ interaction included.
[h]Extrapolation from 120-, 220-, and 364-term wave functions.

TABLE IV. Comparison of derived values of quadrupole moment and mean-square radius of the $4p\,^3P$ and $5p\,^3P$ states of He with those predicted from hydrogenic wave functions.

Parameters	Observed	Hydrogenic	Ratio
$Q_L(4p)$	-389 ± 61[a]	-322[a]	1.22 ± 0.20
$\langle r^2\rangle_{4p}$	205 ± 33 Å^2	168 Å^2	
$Q_L(5p)$	-950 ± 60[a]	-805[a]	1.19 ± 0.08
$\langle r^2\rangle_{5p}$	501 ± 33 Å^2	420 Å^2	

[a]In units of 10^{-26} esu cm^2.

orbital about an effective nuclear charge of unity. We see that for the $4p$ and $5p$ states there is an approximately constant ratio of 1.2 between the observed and hydrogenic values. This result is in agreement with the measurements in I, but now a reduced (statistical) experimental error makes this discrepancy significant. We do not understand why this ratio should be greater than unity because core penetration by the $4p$ and $5p$ electrons should make the effective nuclear charge slightly greater than one, which would decrease the calculated values of $\langle r^2\rangle$ even more. A possible source of error might lie in the existence of an electric field, either static or microwave, in the interaction zone. Preliminary calculations of the resulting Stark shift from such a field, however, indicate that inclusion of this effect does not lessen the discrepancy in $\langle r^2\rangle$. We plan to pursue this matter further, and hope that measurements in higher rydberg states will help clarify this anomaly. Until such experiments are carried out, we believe that the error limits quoted for χ_A, Q_L, and $\langle r^2\rangle$ should be considered significant in only a statistical sense and that the parameters may reflect an, as yet, unknown systematic error. However, the fine-strucutre intervals are relatively insensitive to these effects and are presumably free of systematic error.

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Fresnel Drag in a Ring Laser: Measurement of the Dispersive Term

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The Fresnel drag has been measured in a triangular ring laser at a wavelength of 0.6328 μ. The drag coefficient in fused silica is $\alpha = 0.541\pm 0.003$, while the theory, including the dispersion term, gives $\alpha_{\text{theor}} = 1-(1/n^2)-\beta(\lambda/n)\,dn/d\lambda = 0.5423$ with $\beta=1$. The coefficient β is thus determined as $\beta = 0.87\pm 0.22$, which includes the classical value $\beta=1$. Thus the magnitude of the drag in a ring laser is within the errors equal to that given in an inertial frame of reference (linear drag).

I. INTRODUCTION

The ring laser is an extremely sensitive instrument for measuring nonreciprocal phenomena in light propagation.[1] As an example, a rotation of the ring produces a beat frequency which is large enough that the rotation of the earth can be detected in simple Sagnac-type arrangements.[2] The drag phenomenon of light in moving matter also introduces a nonreciprocity into the ring laser, and therefore produces a frequency difference between the two contracirculating beams. (Born noted[2a] that