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# Precise Measurement of the $2^3P_0$-$2^3P_1$ Fine-Structure Interval of Helium*

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The $2^3P_0$-$2^3P_1$ fine-structure interval $\nu_{01}$ of helium has been measured by the atomic-beam optical-microwave magnetic-resonance method. The result is $\nu_{01} = 29\,616.864(36)$ MHz (1.2 ppm), in which the error is 1 standard deviation. This precision is more than a factor of 10 better than that obtained by any other method. Comparison with the present theoretical value of $\nu_{01}$ is given, and the possibility of obtaining a value for the fine-structure constant $\alpha$ accurate to better than 1 ppm from our experimental result is emphasized.

This Letter reports a measurement of the $2^3P_0$-$2^3P_1$ fine-structure interval $\nu_{01}$ of the helium atom to a precision of about 1 ppm. This experimental result, together with our earlier measurement[1] of the $2^3P_1$-$2^3P_2$ fine-structure interval $\nu_{12}$, provides the experimental data needed for a very sensitive test of the quantum-electrodynamic theory of the electron-electron interaction in helium, and also for a determination of the fine-structure constant $\alpha$ to a precision of better than 1 ppm.[2-4]

It has been possible to determine the fine-structure intervals $\nu_{01}$ and $\nu_{12}$ of helium to a considerably higher precision than that to which the intervals in the $n = 2$ state of hydrogen are known[5] because the $2^3P$ state of helium has a mean lifetime which is about 60 times longer than that of the $2^2P$ state of hydrogen. All of the theoretical calculations for helium which are necessary to utilize our experimental accuracy have not yet been done, but it seems reasonable to expect that the needed theoretical accuracy can be achieved.[4]

We measured the fine-structure interval $\nu_{01}$ by the method of atomic-beam optical-microwave magnetic resonance, which has been described in Ref. 1. The energy levels of the $2^3P$ state as functions of magnetic field are shown in Fig. 1. The transition $(J, M_J) = (0, 0) \leftrightarrow (1, 0)$ at a magnetic field of about 300 G was observed; and hence, using the theory of the energy levels[6] and the measured Zeeman effect,[7] the interval $\nu_{01}$ was determined.

A beam of $1^1S_0$ ground-state helium atoms was excited to the $2^3S_1$ metastable state by electron bombardment in an electron gun. The three com-

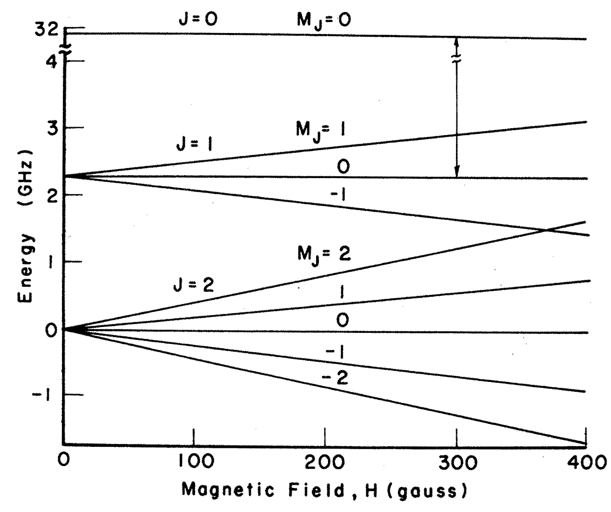


FIG. 1. Zeeman energy-level diagram of the $2^3P$ state of helium. The observed microwave transition is indicated at a typical value of magnetic field used.

ponents ($M_J=0, \pm 1$) of the $2^3S_1$ level were resolved spatially by an inhomogeneous magnetic field and a collimator, and beam stops blocked out the $M_J=\pm 1$ components. In the region of the homogeneous static magnetic field, resonance radiation from a helium discharge lamp excited $2^3S_1(M_J=0)$ atoms to the $2^3P$ Zeeman levels. Spontaneous radiative decay with a mean lifetime[8] of $1.0\times 10^{-7}$ sec back to the $2^3S_1$ state resulted in a distribution of atoms in the three $M_J$ levels of the $2^3S_1$ state. In the second inhomogeneous magnetic field, atoms with $M_J=\pm 1$ were deflected out of the main beam. Our detector was positioned to observe the deflected $M_J=+1$ atoms. In the homogeneous-field region a microwave cavity was present, and a magnetic dipole transition was induced between the $2^3P$ Zeeman levels $(J, M_J)=(1,0)$ and $(0,0)$. These two levels have unequal optical-excitation probabilities from the $2^3S_1(M_J=0)$ level, and also unequal decay probabilities to the $2^3S_1(M_J=+1)$ level, and hence a change was produced by the induced microwave transition in the intensity of the detected $M_J=+1$ beam. The signal for a particular value of the static magnetic field $H$ was the normalized difference in counts at the detector with the microwave power on and off. A resonance curve was obtained by varying $H$ with the microwave frequency and power kept constant.

Much of the apparatus used has been described in previous papers.[1,7] However, the electron gun used for the $1^1S_0$ to $2^3S_1$ excitation and the microwave system were different for the present experiment. The cathode of the electron gun consisted of several thoriated tungsten filaments placed parallel to the height of the ribbon-shaped atomic beam, and the anode was a block of stainless steel. The intensity of the metastable atomic beam was more than a factor of 2 greater than that in the earlier experiments. The source of microwave power was a 10-W two-cavity klystron tuned to about 29.6 GHz.[9] The frequency was stabilized to 0.1 ppm by frequency locking to a 1-MHz crystal oscillator through an intermediate $X$-band (10-GHz) klystron.

A typical resonance curve is shown in Fig. 2. Data points were taken in pairs equally displaced from the estimated line center, and the high- and low-field points were alternated in order to minimize the effects of any long-term drifts. Measurement of the magnetic field $H$ was done by observing the Zeeman transition $M_J=0\rightarrow 1$ of the $2^3S$ state of helium, whose frequency is given by $\nu(^3S_1)=\mu_B g_J(^3S_1)H/h$. The observed peak signals

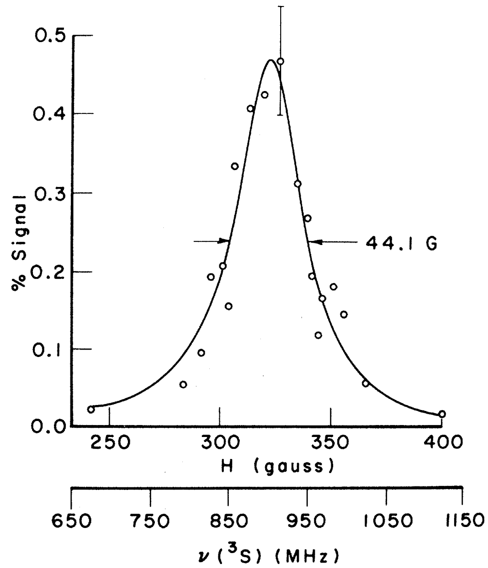


FIG. 2. A typical observed resonance line showing percent signal versus magnetic field as measured by the Zeeman transition frequency $\nu(^3S)$. The experimental points are indicated by the circles, and a typical statistical error bar is shown. The solid curve is a Lorentzian curve fitted to the data points. The klystron frequency was set at 29 596.704 MHz.

ranged from 0.3% to 0.8%. The detected atom intensity with microwave power off (background) is contributed principally by atoms in the wing of the undeflected $M_J=0$ component of the beam and by atoms which made the transition $M_J=0\rightarrow M_J=+1$ through optical excitation from the $2^3S$ to the $2^3P$ state and radiative decay back to the $2^3S$ state. In view of our knowledge of the background, the observed signal size is consistent with theoretical expectations. The linewidth of 44.1 G (full width at half-maximum) corresponds to a frequency width of 4.4 MHz; the natural linewidth is 3.2 MHz, and the additional width of 1.2 MHz is due to microwave power broadening.

For each resonance line a Lorentzian line shape was fitted to the data points using a least-squares procedure. The fitting involved the use of the equations for the energy levels as functions of magnetic field and yielded directly a value of $\nu_{01}$. Before making the fit to the data points, a correction was made for the variation of the signal with magnetic field associated with the variation of the optical and microwave matrix elements with magnetic field[1] (the so-called slope correction).

We obtained 73 resonance curves, and a statistical analysis yielded the weighted mean of $\nu_{01}$ and its standard deviation: $\nu_{01}=29\,616.864\pm 0.035$

MHz. The error in our measurement is principally a statistical counting error. The only additional significant error, amounting to 7 kHz, is that associated with the slope correction mentioned above. Hence we take as our final result

$$\nu_{01} = 29\,616.864 \pm 0.036 \text{ MHz (1.2 ppm)},$$

where the error is 1 standard deviation. Brief preliminary reports of this work have been made.[10] This value is in agreement with, but represents an order-of-magnitude improvement in precision compared to, the value $\nu_{01} = 29\,616.76 \pm 0.40$ MHz obtained by an optical–level-crossing experiment.[11]

The theoretical expression for $\nu_{01}$ can be written in the form[4,12]

$$\nu_{01} = \alpha^2 c R_{\mathrm{He}^4}[K_1 + \alpha K_2 + \alpha^2(K_3 + K_3') + \alpha(m/M)K_4 + \alpha^3(\ln\alpha)K_5 + \cdots]$$

in which $R_{\mathrm{He}^4}$ is the Rydberg constant for helium, $c$ is the velocity of light, $\alpha$ is the fine-structure constant, and the $K$'s are dimensionless numerical constants. The leading term with the constant $K_1$ arises from the electron spin-spin and spin-orbit interactions (the Breit interaction).[3,12,13] The second term with the constant $K_2$ is a virtual radiative correction which arises from the anomalous magnetic moment of the electron.[14,15] The term with the constant $K_3$ is a second-order contribution associated with the Breit interaction (and a correction term due to nuclear motion).[16,17] The term with the constant $K_3'$ comes from higher-order relativistic and virtual radiative effects.[18] The term with $K_4$ is a relativistic recoil term.[19] Higher-order terms are expected to be negligible, but the term with $K_5$ should also be calculated.

The present status of the theoretical calculations for $\nu_{01}$ (and also for $\nu_{12}$) is shown in Table I. The constant $K_1$ has been calculated to an accuracy of about 1 ppm by two groups using variational wave functions.[12,13] Their results differ by 3.0 ppm. To obtain the value of $\nu_{\mathrm{theor}}$ we have used the mean of these two values. The theoretical value of the term with constant $K_2$ is known to better than 30 kHz and hence would contribute an inaccuracy to $\nu_{01}$ of less than 1 ppm. The term with $K_3$ has been partially worked out,[16,17] and the Hamiltonian for evaluating the $K_3'$ and $K_4$ terms has recently been formulated.[20] The values available for the $K_3$ and $K_3'$ terms are given; they are not yet sufficiently well-known to yield $\nu_{01}$ to an accuracy of 1 ppm. Since these terms with $K_3$ and $K_3'$ are of order $\alpha^2$ relative to the leading term, they need be calculated only to about 1% accuracy to achieve an overall theoretical accuracy of 1 ppm. With regard to the theoretical value for $\nu_{12}$, the leading term with $K_1$ has only been calculated with an accuracy of 10 ppm. The absolute accuracies with which the other terms are known is about the same as for $\nu_{01}$.

Comparison of the theoretical and experimental values for $\nu_{01}$ and $\nu_{12}$ indicate discrepancies of 209 and 1128 ppm, respectively. These discrepancies are presumably due principally to the incompleteness in the calculations of the terms $K_3$, $K_3'$, and $K_4$. It is expected that the theoreti-

Table I. Fine structure of the $2^3P$ state of helium. The values of $\alpha^{-1}$, $c$, and $R_{\mathrm{He}^4}$ as given in Ref. 5 are 137.036 02(21) (1.5 ppm), $1.097\,222\,69(11)\times10^5$ cm$^{-1}$ (0.1 ppm), and $2.997\,925\,0(10)\times10^{10}$ cm sec$^{-1}$ (0.3 ppm), respectively. $\alpha^2 c R_{\mathrm{He}^4} = 175.164\,47(53)$ GHz (3.0 ppm).

| Interval | $\alpha^2 c R_{\mathrm{He}^4} K_1$ (MHz) | $\alpha^3 c R_{\mathrm{He}^4} K_2$ (MHz) | $\alpha^4 c R_{\mathrm{He}^4} K_3$ (MHz) | $\alpha^4 c R_{\mathrm{He}^4} K_3'$ (MHz) | $\nu_{\mathrm{theor}}$ (MHz) | $\nu_{\mathrm{expt}}$ (MHz) | $\nu_{\mathrm{expt}} - \nu_{\mathrm{theor}}$ (MHz) |
|---|---|---|---|---|---|---|---|
| $\nu_{12}$ | 2316.885[a] | −22.524[a,b] | −4.774[c] | −0.989[d] | 2288.612 | 2291.196 ± 0.005 | 2.584 |
| | 2316.912[b] | | | | | (2.2 ppm) [e] | (1128 ppm) |
| $\nu_{01}$ | 29 560.513[a] | 54.654[a,b] | 9.817[c] | −1.979[d] | 29 623.047 | 29 616.864 ± 0.036 | −6.183 |
| | 29 560.596[b] | | | | | (1.2 ppm) [f] | (209 ppm) |

[a]Ref. 12. The values given in the table are all based on the use of values of the fundamental constants as shown.

[b]Ref. 13. The $K_2$ contributions are not given separately by the authors, but should be identical to those given in Ref. 12. The values quoted are for the even-$\omega$ extrapolation.

[c]The $K_3$ contributions include all the terms given in Tables V and X of Ref. 17, and the result for the $2^1P_1$ admixture given in Ref. 13.

[d]Ref. 18.

[e]Refs. 1 and 7.

[f]This experiment.

cal value for $\nu_{01}$ can be calculated to an accuracy of about 1 ppm and hence, together with the use of our reported experimental value for $\nu_{01}$, should determine the fine-structure constant $\alpha$ to an accuracy of better than 1 ppm.

A more detailed report of our experiment will be submitted for publication later.

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# Anomalous Microwave Absorption Near the Plasma Frequency*

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Measurements in a highly ionized plasma of anomalously large absorption and the threshold field required for its onset are presented as a function of plasma density for conditions free of electron inelastic effects. In the weak-field limit the measured absorption is in good agreement with the classical theory for the high-frequency resistivity.

Absorption of intense electromagnetic waves near the critical density on a plasma profile, where the electron plasma frequency $\omega_p$ approximately equals the wave frequency $\omega$, has recently become important in connection with laser and rf heating of plasmas. Theory indicates the possibility of enhanced absorption[1] when the intense fields excite high-frequency instabilities.[2,3] This Letter reports such absorption measurements made on the highly ionized plasma column of the single-ended Los Alamos $Q$ machine. By operating over a large range of electric fields and plasma densities, our measurements yield (1) a quantitative value for the classical resistivity, (2) the threshold electric field for the onset of instability and anomalous dissipation, and (3) an experimental estimate for the anomalous dissipation under conditions shown to be free of electron inelastic effects.

In our experiment, potassium ions, produced by contact ionization on a grounded 2500°K tungsten hot plate (HP), drift along the applied magnetic field $\boldsymbol{B}_0$ until they are collected on a cold copper collector biased negatively to the potential $V_c$. The plasma is limited by a 2.45-cm-diam aperture near the HP. The electrostatic sheath at the HP reduces the current of thermionic electrons by the Boltzmann factor $\exp(e\varphi/kT)$, where