with a standard deviation 0.29 G. In order to take account of systematic effects which have not yet been fully investigated, for example, pressure and electron current shifts, errors for the crossings are quoted as 0.8 G and 1.5 G, respectively. Using the theory of the Zeeman effect, the splittings $S_{1/2}$-$G_{7/2}$ and $S_{1/2}$-$G_{9/2}$ in zero magnetic field are found to be $15\,924.4 \pm 5.9$ and $17\,040.5 \pm 8.0$ MHz, respectively. From these a value of 1116.1 ± 14.0 MHz for $G_{7/2}$-$G_{9/2}$ is deduced, in agreement with the theoretical splitting of 1123.6 MHz.

We gratefully acknowledge the support given by the Science Research Council.

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Microwave-Optical Determination of Rydberg-State Fine Structure: The 7^1D-$7F$ Intervals in He^4†

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(Received 9 December 1971)

We have measured the He^4 electrostatic fine-structure intervals 7^1D_2-7^1F_3 and 7^1D_2-7^3F_3 neat 31.5 GHz. The latter transition appears because of spin-orbit mixing of singlet and triplet $7F$ states of the same J. The 3-ppm precision represents a 10^4-fold improvement over the mean 7^1D-$7F$ spectroscopic value. We have also measured the mean $7F$-$7G$ and $7G$-$7H$ intervals. The microwave-optical method used appears widely applicable to atomic and molecular Rydberg states.

Two general types of fine structure can be distinguished in atomic and molecular systems. The first is relativistic fine structure, in which we include spin-spin, spin-orbit, and quantum-electrodynamic contributions. The second is electrostatic fine structure. This term covers inner-electron screening, electron exchange, and core-polarization effects, which occur in all systems except hydrogen-like atoms. Although relativistic fine structure has been studied extensively with modern methods, our knowledge of electrostatic-fine-structure intervals comes primarily from grating spectroscopic work done a number of years ago. In helium, relativistic–fine-structure intervals have been measured directly to as high as $n=9$.[1] By contrast, the only He electrostatic intervals known from direct observation are the triplet and singlet $2P$-$2S$ emission lines at 1 and 2 μm, respectively,[2] and 95.8-μm 3^1P_1-3^1D_2 and 216.3-μm 4^1P_1-4^1D_2 laser transitions.[3] Other intervals are obtained by taking differences of the wave numbers of optical-frequency transitions.[2] These values rapidly lose accuracy as the respective principal and orbital–angular-momentum quantum numbers n and l of the excited electron increase and the intervals shrink.

Atomic and molecular states with one electron highly excited, or Rydberg states, are of special theoretical interest because they are quasihydrogenic, with the remaining particles in the system appearing to the excited electron as a charged core of relatively small dimensions. The problem is interesting also because of its relation to the scattering of a slow free electron by the charged core.[4] However, few accurate calculations have been made, even for helium, which is the simplest case.[5] This is presumably because of the paucity of accurate data.

In a previous note[6] we have reported the first observation by the microwave-optical method[7] of a large number of electrostatic fine-structure resonances seen in the unresolved vacuum-ultraviolet principal-series emission from helium. In that work, unequivocal assignment of states was prevented by the plethora of transitions. We have now improved the apparatus, and are able to report the precise measurement of two transition frequencies: the $1s7d\,^1D_2$-$1s7f\,^1F_3$ and $1s7d\,^1D_2$-$1s7d\,^3F_3$ intervals in He^4 near 31.5 GHz. The latter transition, though spin forbidden, appears through singlet-triplet mixing in the F states.[8] The two $7F$ levels, unresolved in the best spec-

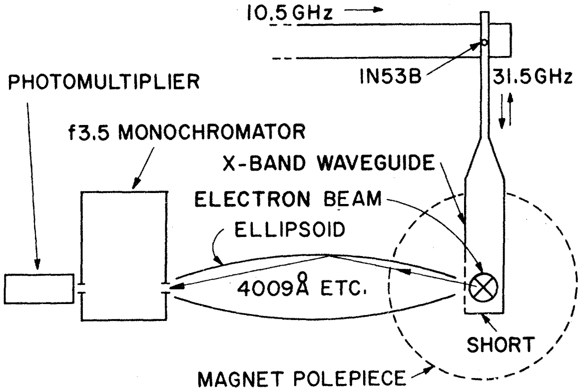

FIG. 1. Apparatus. The magnetic field (when used) and bombarding electron beam are normal to the plane of the figure. For precision work the magnetic field is carefully adjusted to zero. The following operating conditions are typical of precision runs: bombarding current, 200 μA; voltage, 60 V; helium pressure, 1.5 mTorr; incident microwave power, 0.3 μW; residual magnetic field, <0.2 G.

troscopic data, are clearly distinct in our work.

The apparatus, shown in Fig. 1, is similar to that used in recent fine-structure experiments on the H atom and He$^+$ ion.[9] Excited helium atoms are produced in an X-band waveguide by 60-eV electron bombardment of helium gas at 1-2-mTorr pressure, with 7^1D atoms more populous than $7F$. Decay light is collected by a hollow ellipsoidal light pipe with polished metal walls. A fast (f3.5) $\frac{1}{4}$-m monochromator coupled to a blue-sensitive photomultiplier has been added to monitor a single visible emission line. Microwave-induced electric-dipole transitions produce a net population transfer out of the 7^1D state, which causes a reduction in intensity of the 4009-Å line 7^1D-2^1P. The microwave power is switched on and off at 37 Hz, and the resonance signals are synchronously detected. Our microwave source is a 1N53B diode tripler driven by a stabilized 10.5-GHz X-band oscillator. Lower harmonics are filtered out by a beyond-cutoff waveguide section. An incident power level of a few microwatts saturates the transitions thoroughly because of their large electric-dipole matrix elements and the long lifetimes of the $n=7$ states.

A 30.5-cm-diam iron-core electromagnet is available for Zeeman tuning. This has proved useful for locating transitions initially, since it provides a 24-GHz equivalent tuning range (8500 G at ± 1.4 MHz/G). However, because of the large electric-dipole matrix elements, even a few-hundred-gauss magnetic field produces a thermal (≈ 400°K) distribution of motional Stark shifts, which broadens the observed resonances considerably. Accordingly, for precision data the magnetic field is carefully cycled and biased to zero (residual field < 0.2 G in any direction), and the resonances are swept by tuning the microwave frequency. The resulting resonances are 2-4 MHz wide. Over this frequency range the variation of microwave energy density in the bombardment region is less than 1%. Besides simplifying interpretation, operating at zero magnetic field increases signal size by coalescing the Zeeman transitions.

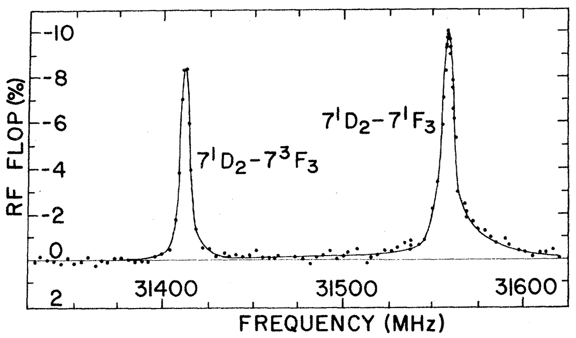

FIG. 2. Microwave resonances observed near 31.5 GHz in the 4009-Å emission from helium. Conditions for these data were similar to those listed in the caption of Fig. 1, except for much higher microwave power (4-6 μW incident) which broadened the resonances to ≈ 8 MHz (full width at half-maximum). A curve has been drawn through the data points as a guide to the eye.

A highly power-broadened signal trace near 31.5 GHz at zero magnetic field is shown in Fig. 2. For precision data the power level was reduced to nearer the "optimum" value (50% saturation). The relevant energy levels are shown in Fig. 3. Of the four $7F$ states, the two with singlet admixtures can undergo electric-dipole transition to 7^1D_2. Thus, the two resonances 7^1D_2-7^1F_3 and 7^1D_2-7^3F_3 appear in the 4009-Å light, with the first having the higher microwave frequency.

Thirteen precision runs were taken at various values of bombarding current, gas pressure, and microwave power. A run consisted of ten to twenty points taken over a range of 2 to 3 linewidths. The signal-to-noise ratio of points near a resonance center was typically 30 for a 10-sec observing time. A reasonably good computer fit with a Lorentzian function could be obtained, as predicted by the Lamb-Sanders-Wilcox model[7] for rf resonances in a decaying two-level system.

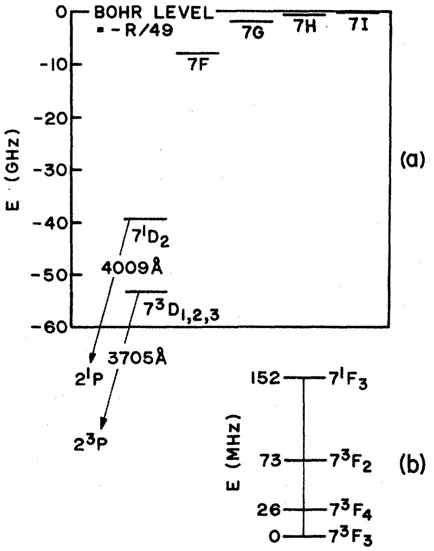

FIG. 3. (a) Structure of singly excited He^4, $n=7$, according to a quantum-defect fit for the D states (Ref. 10) and a polarization model for states of higher L (Ref. 11). The S and P states are beyond the boundaries of the figure. (b) Fine structure of the $7F$ term calculated using the method of Araki (Ref. 8). For $L \leq 2$ the exchange splitting is much larger than the spin-orbit interactions, so the $7D$ term is composed of essentially pure singlet and triplet states. In the $7F$ term the exchange and spin-orbit interactions are comparable, so the two $J=L$ states become superpositions of 7^1F_3 and 7^3F_3 basis states, while the 7^3F_2 and 7^3F_4 states remain pure triplet. We apply the designation "singlet" to the upper $J=L$ state, which has the larger singlet component.

TABLE I. Various results for 7^1D_2-$7F$ intervals in He^4. The $7F$-term sublevels are not resolved in previous work.

Source	Transition	Interval (GHz)
Optical data[a]	7^1D_2-$7F$ mean	33
D-state experimental,[b] F-state theoretical[c] values	7^1D_2-$7F$ mean	31.1
Present work	7^1D_2-7^1F_3	31.558 26(10)
	7^1D_2-7^3F_3	31.412 07(8)

[a] Ref. 2.

[b] Quantum-defect fit (Ref. 10) to spectroscopic data (Ref. 2).

[c] Polarization model, Ref. 11.

In some of the fits a slight overall linear trend in the residuals appeared, possibly caused by the small variation of microwave power over the resonance.

We have extrapolated the fitted centers and widths to zero operating conditions to obtain our final results, which are listed in Table I. The maximum center shift obtained by varying any parameter was approximately 0.4 MHz. By comparison, our final estimated 70% probable errors for the centers are around 0.1 MHz, which represents roughly 5% of the linewidth (full width at half-maximum) and 3 ppm of the center frequencies.

Also listed in Table I are the best previous values for the 7^1D-$7F$ interval. Only the mean interval is given since the $7F$-term fine structure has not been previously resolved. The first value listed results from direct measurement of spectroscopic wavelengths by a number of workers, summarized in the compilation by Martin.[2] The second is a mixed experimental-theoretical value, in which the $7D$-state energy is obtained from Seaton's quantum-defect model fit[10] to Martin's table. This has the effect of smoothing the spectroscopic data on the various D states. The F-state energy is obtained from Edlén's polarization model,[11] which, despite its simplifications, is regarded[12] as more reliable than the spectroscopic data on F states.

The 7^1F_3-7^3F_3 splitting obtained from our results is 146.19(13) MHz. The best theoretical estimate of this quantity appears to be implicit in the 1937 work of Araki,[8] which yields the value 152 MHz [Fig. 3(b)].

Resonance linewidths were also returned by the computer fits, although with less accuracy. After extrapolating to zero operating conditions and applying small corrections for Doppler broadening and residual magnetic-field Zeeman broadening, we obtained the values 1.5(5) and 2.3(5) MHz for the 7^1D_2-7^1F_3 and 7^1D_2-7^3F_3 transitions, respectively. By comparison, the hydrogenic value for the sum of the $7D$ and $7F$ natural widths is 1.2 MHz.[13] Scaling to compensate for slightly different transition energies in helium does not change this value significantly. It seems possible, therefore, that some residual sources of broadening exist in the experiment.

If a magnetic field of several hundred gauss is applied, motional electric-field mixing of states of different L allows rf transitions with $|\Delta L| > 1$ to appear. In this way we have seen the transitions 7^1D_2-$7G$ and 7^1D_2-$7H$ and have obtained preliminary mean intervals $\nu(7F\text{-}7G) = 5.60(7)$ GHz and $\nu(7G\text{-}7H) = 1.06(7)$ GHz. Here the relativistic fine structure is obscured by the motional Stark broadening of the ensemble mentioned above. By comparison, the polarization theory[11] values for these mean intervals are 6.07 and 1.38 GHz, respectively. At fields around 40 G, magnetic mixing of F states of different J brings out weak 7^1D_2-$7F$ Zeeman transitions leading to the pure triplet zero-field states. However, no accurate data on these have been taken.

We have also seen resonances with unequivocal assignments in several other helium singlet and triplet states between $n=6$ and $n=11$. Precise results for these will be presented in future publications. It will be interesting to see both how low and how high in n the method will reach; in the former case the limitation is the high microwave frequency required, and in the latter it is the weakness of the signal and the effects of external perturbations.

It should be noted that we are by no means limited to helium, and that in fact other systems should require very little change in experimental technique. Thus, the microwave-optical resonance method appears to be widely applicable to the study of atomic and molecular Rydberg states.

We gratefully acknowledge the collaboration of D. L. Mader in an investigation preliminary to this one, the assistance of M. A. Stroscio in taking data, the calculations for Fig. 3(b) by T. O. Siu, and the kind loan of the monochromator by W. R. Bennett, Jr.

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†Research sponsored by the U. S. Air Force Office of Scientific Research under Grant No. F44620-71-C-0042.

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Comments on "Demonstration of Collisionless Interactions Between Interstreaming Ions in a Laser-Produced–Plasma Experiment"*

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(Received 1 October 1971)

It is shown that the results of a recent laser-produced–plasma interaction experiment by Dean *et al.* can be explained by collisional processes.

On the basis of the long mean free path of laser-produced ions in the background gas, Dean *et al.*[1] have concluded that a collisionless interaction occurs between the expanding laser plasma and the background ions. They apparently have failed to consider the fact that, in the region where their measurements were taken (distances less than 2 cm from the target), the laser-produced plasma