duce vibration or distortion in the ion. If the ions can be formed both with and without this vibration or distortion, or if the distortion is such as to remove the degeneracy of the levels assigned to the core orbitals of the outer carbon atoms, then multiple electron lines would appear having separations probably of the order of tenths of an eV. An effect of this magnitude would result in a broadening of the line observed.

In an accompanying paper Shaw and Thomas,[9] from a study of gases, present conclusions similar to those given here about chemical influence on linewidth.

In summary, the widths of photoelectron lines from core levels lying just below the valence levels are greatly affected by chemically associated valence level changes. Furthermore, as indicated by the sulfur results, comparison of width changes for core levels of different l values may give information not only on the valence levels as a whole but specifically on components of the valence population. Measurements made at high resolution with improved spectrometers and narrow monochromatic photon lines should show these chemical effects dramatically.

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Cascade Radio-Frequency Spectroscopy of Excited *S* and *D* States of Rubidium; Anomalous *D*-State Hyperfine Structure*

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We report the first successful measurements by cascade radio-frequency spectroscopy of the hyperfine structures of excited S and D states of rubidium. We obtain the following magnetic dipole coupling constants (in MHz): for Rb^{87}, $A(7^2S_{1/2}) = 312.5 \pm 3.5$, $A(5^2D_{3/2}) = 14.1 \pm 0.5$, $A(5^2D_{5/2}) = -8.0 \pm 1.5$; for Rb^{85}, $A(7^2S_{1/2}) = 92.6 \pm 1.0$, $A(5^2D_{3/2}) = 4.1 \pm 0.5$. The anomalous, negative value of A for the $5^2D_{5/2}$ state may be related to the anomalously small fine-structure interval of the 5D state of rubidium.

In spite of the fundamental interest in alkali atoms, there are serious gaps in our knowledge of the properties of excited states of these atoms. Relatively little is known about excited-state radiative lifetimes and hyperfine structures. Only the excited P states, which can be produced by the absorption of resonance light, have been studied in any detail. A satisfactory picture of the alkali atoms cannot be gained without comparable experimental information about non-P excited states. There is no reason to suppose that the properties of non-P excited states are completely normal and predictable. For instance, the fine-structure intervals of the D and F states are known to be anomalously small and they are often inverted in all of the alkali atoms except lithium.[1] To lowest order, the hyperfine-structure intervals should be closely related to the fine-structure intervals, and it would be very interesting to measure the hyperfine structures of some non-P excited states with anomalous fine-structure intervals.

To our knowledge, the only previous attempt to measure D-state hyperfine structures in alkali atoms was made by Archambault *et al.*,[2] who used radio-frequency spectroscopy with electron excitation to investigate excited states of sodium and cesium. They obtained $A < 0.33$ MHz for the

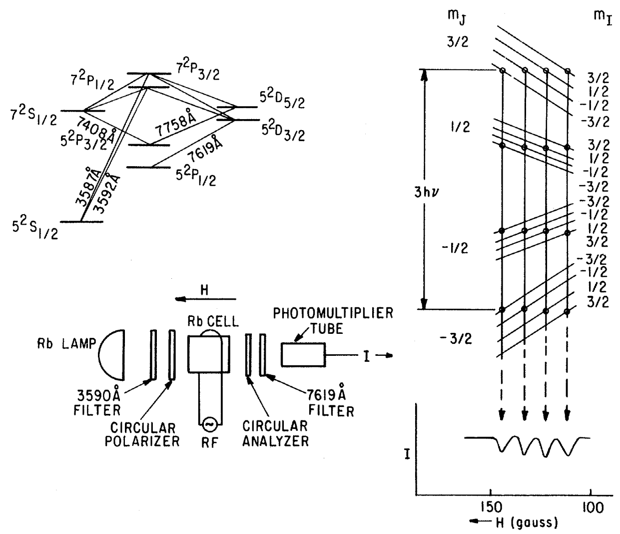

FIG. 1. Schematic diagram of our experimental arrangement (lower left). Spontaneous decay of the 7P states is used to populate $7^2S_{1/2}$, $5^2D_{3/2}$, and $5^2D_{5/2}$ states. The electronic polarization of these states is detected by monitoring the circular polarization of the 7408-, 7619-, or 7758-Å fluorescent radiation (upper left). Radio-frequency transitions between Zeeman hyperfine sublevels (right) are detected by observing the change in the intensity of polarized fluorescent light. For the $5^2D_{3/2}$ state of Rb^{87}, illustrated here, four three-quantum transitions are observed in the 7619-Å observation channel.

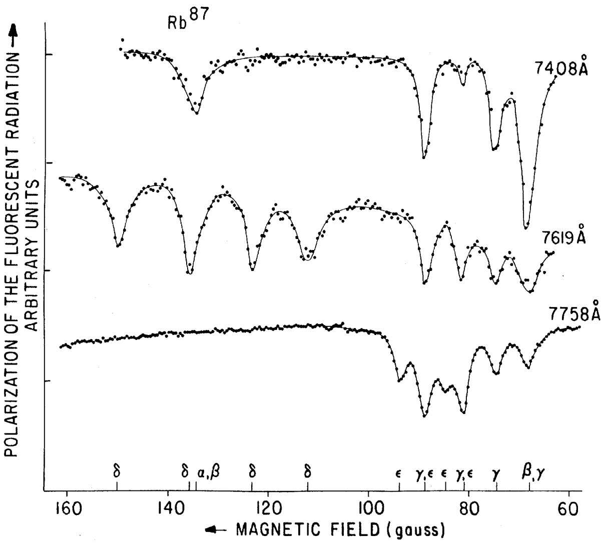

FIG. 2. Observed radio-frequency resonances in Rb^{87}. Wavelengths of the observed fluorescent radiations are indicated on the right. The symbols α, β, γ, δ, and ϵ refer to rf resonances in the $7^2S_{1/2}$, $7^2P_{1/2}$, $7^2P_{3/2}$, $5^2D_{3/2}$, and $5^2D_{5/2}$ states, respectively. One division on the ordinate corresponds to about a 20% change in the polarization of 7408- and 7619-Å radiations and corresponds to about a 60% change in that of the 7758-Å radiation.

$5^2D_{5/2}$ state of sodium and $0.195 \leq A \leq 0.45$ MHz for the $9^2D_{5/2}$ state of cesium. Although these rough measurements are useful, more precise experiments are clearly desirable.

In this Letter we report the first successful measurements by cascade radio-frequency spectroscopy of the hyperfine structures of excited S and D states of alkali atoms. The experimental apparatus and the states involved in these experiments are shown in Fig. 1. Rubidium atoms in the $5^2S_{1/2}$ ground state are excited by circularly polarized 3587- and 3592-Å resonance radiation into the $7^2P_{1/2}$ and $7^2P_{3/2}$ excited states. The 7^2P states can decay into all of the lower-lying S and D states, and in particular, the $7^2S_{1/2}$, $5^2D_{5/2}$, and $5^2D_{3/2}$ states are populated by spontaneous decay of the 7P states. By inserting the proper optical filters into our apparatus we can monitor the polarizations of the $7^2S_{1/2}$, $5^2D_{5/2}$, or $5^2D_{3/2}$ state (see Fig. 1). The atoms are subject to a steady radio-frequency ($\nu = 147.5$ MHz) magnetic field, which is generated near the shorted end of a quarter-wave resonator by a 2-m amateur radio transmitter. The field amplitude is adequate to cause near saturation of magnetic dipole transitions between sublevels of the excited atomic states. The atoms are also subject to a quasistatic longitudinal magnetic field H, which can be varied over the region where magnetic resonance transitions are expected. Saturation of a transition in the S or D states will cause a decrease in the polarization of the fluorescent light emitted by the S- or D-state atoms. Since the S- and D-state polarizations depend on the polarization of the 7P state, magnetic resonance transitions in the 7P state will also be detected. The change in the polarization of the fluorescent light at resonance depends on the sublevels involved in the transition and ranges from a few percent to as much as 40% in our experiments.

Experimental data for Rb^{87} are shown in Fig. 2. We have obtained similar data for Rb^{85}. Resonances in the 7P states are observed in addition to the S- and D-state resonances. The P-state resonances serve as a useful consistency check, since the 7P hyperfine structure has been measured previously.[3] The curious intensity ratios for the $7^2P_{3/2}$ resonances in the 7408-Å observation channel are understood and will be discussed more fully in a later paper.

One well-defined resonance, which corresponds to the high-field transition ($m_J = \frac{1}{2}, m_I = -I \rightarrow m_J = -\frac{1}{2}, m_I = -I$), is observed in the $7^2S_{1/2}$ states of both Rb^{85} and Rb^{87}. Unfortunately, a $7^2P_{1/2}$ resonance accidentally overlaps the $7^2S_{1/2}$ resonance in Rb^{87}. However, we have determined that the magnitude of the $7^2P_{1/2}$ resonance is too small to affect seriously the position of the $7^2S_{1/2}$ resonance. Assuming $g_J = 2.00$ we deduce the magnetic dipole coupling constants listed in the abstract for the $7^2S_{1/2}$ states of Rb^{85} and Rb^{87} from the magnetic resonance data. These results are in good agreement with our preliminary measurements[4] by the cascade decoupling method.

The D-state resonances are too poorly resolved to allow a determination of the electric quadrupole coupling constants B, but good values for the magnitudes of the magnetic dipole coupling constants can be obtained for all but the $5^2D_{5/2}$ state of Rb^{85}, where the magnetic resonance spectrum is not resolved. All of the D-state data were taken in the high-field regime where m_I and m_J are approximately good quantum numbers. One can identify $2I+1$ resonances for each D state. Each resonance corresponds to partial randomization of m_J for a fixed value of m_I; and the observed resonances might be more properly described as poorly resolved multiple quantum resonances.[5] We have assigned the center of the observed resonance to the multiple quantum transition of highest multiplicity ($2J$) since such transitions cause the greatest change in the polarization of fluorescent light, and the frequency of the $2J$-quantum transition is also equal to the average frequency of the single-quantum transitions. For example, the group of transitions assigned to each of the four observed resonances in the $5^2D_{3/2}$ state of Rb^{87} is indicated in Fig. 1. Assuming g_J values of 0.8 and 1.2 for the $^2D_{3/2}$ and $^2D_{5/2}$ states, we obtain the magnitudes of the magnetic dipole coupling constants listed in the abstract from the data of Fig. 2 and from similar data for Rb^{85}.

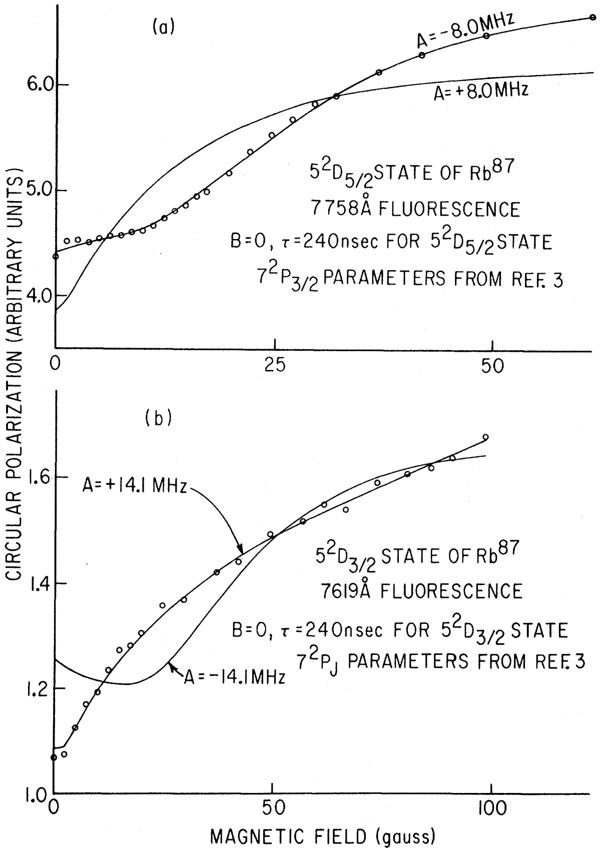

FIG. 3. Cascade-decoupling data for the $5D$ states of Rb^{87}. The data were obtained with the apparatus sketched in Fig. 1, but no radio-frequency field was used. The solid lines were calculated from the hyperfine parameters and lifetimes indicated in the figure. The points are experimental data. These data determine the signs and the approximate magnitudes of the D-state A values.

The data of Fig. 2 can be used to determine the magnitude but not the sign of A. One can determine the sign of A by cascade decoupling spectroscopy.[6] For example, the experimentally measured circular polarization of the 7758-Å fluorescence of Rb^{87} is plotted in Fig. 3(a) as a function of the static magnetic field H. The best fitting theoretical curves are plotted for A values of +8 and −8 MHz, the two A values most consistent with the data of Fig. 2. It is clear that the curve for $A = -8$ MHz is in good agreement with the experimental data, but the curve for $A = +8$ MHz does not fit the experimental data. Similarly, the circular polarization of the 7619-Å fluorescent light from the $5^2D_{3/2}$ state is plotted as a function of the static magnetic field H in Fig. 3(b), and the best fitting theoretical curves for $A = +14.1$ and -14.1 MHz are drawn in. Our radio-frequency spectroscopy experiments on the $5^2D_{3/2}$ state have proved that this state is populated by spontaneous decay of both the $7^2P_{1/2}$ and $7^2P_{3/2}$ states, and we varied the percent contribution from the $7^2P_{1/2}$ and $7^2P_{3/2}$ states to obtain the best possible theoretical fit to the data of Fig. 3(b). It is clear that the curve for $A = +14.1$ MHz is in excellent agreement with the decoupling data, but the curve for $A = -14.1$ MHz simply does not fit. We should mention that the data of Fig. 3 are just a sample of a larger body of independent experimental data which show unequivocally that A is *positive* for the $5^2D_{3/2}$ states of Rb^{87} and Rb^{85}, *negative* for the $5^2D_{5/2}$ states, and *positive* for the $7^2S_{1/2}$ states.

The anomalous D-state hyperfine structure of rubidium is reminiscent of the anomalous P-state hyperfine structure of lithium.[7] Since core polarization[8] is believed to be responsible for the anomalous P-state hyperfine structure of lithium, core polarization may also be at least partially responsible for the D-state hyperfine-structure anomaly in rubidium. Also, it is probably not coincidental that the fine-structure interval (2.96 cm^{-1}) for the $5D$ state of rubidium is about an order of magnitude smaller than one would expect from the Landé formula.[9]

These experiments demonstrate that some very interesting physics is to be found in the non-P excited states of the alkali atoms. They also demonstrate that cascade decoupling and cascade radio-frequency spectroscopy can be used to measure the properties of these states with the same sort of precision and convenience that characterized the optical double resonance and level-crossing experiments on excited P states.[3] We are presently extending these experiments to other S and D states and perhaps to F states, and we shall improve our resolution by operating at higher frequencies. We shall also set limits on the quadrupole coupling constants of these states and measure their radiative lifetimes by analyzing the widths of the resonances.

We are indebted to Dr. Alan Lurio for reading an initial draft of this paper and for suggesting that we check the signs of the A values. We are also grateful to W. Nagourney for his help with the signal-averaging computer program used to accumulate some of our data.

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Neoclassical Transport in Tokamaks in Banana/Plateau Regimes*

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The predictions of the full two-regime neoclassical transport theory have been obtained by numerical computation; they are compared with observations on the ST Tokamak.

Several publications[1-4] have presented computations of radial transport in Tokamak discharges, based upon incomplete or approximate sets of neoclassical transport coefficients. In Ref. 4 a code was used which incorporated the complete neoclassical transport theory, but limited itself to the lowest-collision-frequency ("banana") regime.[5] There were two important deficiencies in this treatment: First, the "banana" equations are singular at the axis where the high-collision-frequency ("plateau") regime is always entered in the complete theory; second, present-day