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[9]E. J. Öpik and S. F. Singer, Phys. Fluids 2, 653 (1959); 3, 486 (1960).
[10]Reference 3, Eqs. (2) and (3).
[11]C. Y. Fan, P. Meyer, and J. A. Simpson, in Space Research, Proceedings of the COSPAR Symposium, Nice, January, 1960 (North Holland Publishing Company, Amsterdam, 1960).
[12]The critical value x_c of the Alfvén discriminant, ρ gradB/B, is determined empirically as 0.08 from the location of the "slot" at $r_e = 2$ earth radii in the experiments of the Chicago group.[11] The maximum momentum trapped is then given as $\sim 1500/r_e^2$ (Mev/c) and is greater than the value used in reference 3. This simple treatment applies to the basic inhomogeneity of the dipole field. Scattering effects produced by "noise" of the geomagnetic field, i.e., spatial inhomogeneities and temporal fluctuations, cannot be taken into account on an a priori basis, but are believed to be included when the Alfvén discriminant is obtained empirically.

COHERENCE, NARROWING, DIRECTIONALITY, AND RELAXATION OSCILLATIONS IN THE LIGHT EMISSION FROM RUBY

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Schawlow and Townes[1] have proposed that, with a sufficiently great inverted population density in a radiating assembly of atoms, enclosed in a suitable cavity, stimulated emission of light will occur cumulatively, leading to (1) decrease in lifetime, (2) spectral line narrowing, (3) coherence in the electromagnetic field, and (4) sharp directionality of the radiation leaving a Fabry-Perot cavity. The use of a ruby rod for the observation of these effects has been proposed by Schawlow.[2] Recently Maiman[3] has observed a decrease of the lifetime and a narrowing of the line shape for ruby fluorescence. The present experiments extend this work to verify the coherence and directionality of the radiation and to measure the linewidth. In addition we have observed a relaxation oscillation in the fluorescence.

The samples of Linde Al_2O_3 containing approximately 0.05% chromium oxide were prepared in the form of rods 0.5 cm in diameter and 4.0 cm in length, cut either parallel or perpendicular to the c axis. The ends were optically polished and were flat and parallel to one minute and were silvered so as to transmit 1 to 5%. At room temperature, the samples were set in the middle of a GE $FT524$ flashtube, which was surrounded by a cylinder coated with magnesium oxide; the flashtube was fired by connecting to a bank of condensers charged from a high-voltage supply. In the low-temperature measurements a small Dewar containing the sample was held inside the lamp coil. A typical discharge condition was a capacity of 400 μf and 4 kv.

In the first experiment, arrangements were made to look in turn at fluorescent light emitted through the silvered ends and from the sides of the rod. The light was allowed to fall on the entrance slit of a Jarrell-Asch 78-400 grating spectrometer adequate to resolve the R_1 and R_2 lines, occurring at wave numbers 14 400 cm^{-1} and 14 430 cm^{-1}, respectively. The output of the photomultiplier detector was displayed on a dual-beam oscilloscope. The collector circuit time constant was of the order of 10^{-6} second. Under low excitation conditions the oscilloscope traces showed simply the expected fluorescent rise and decay [Fig. 1(a)], the ratio of the intensity of the

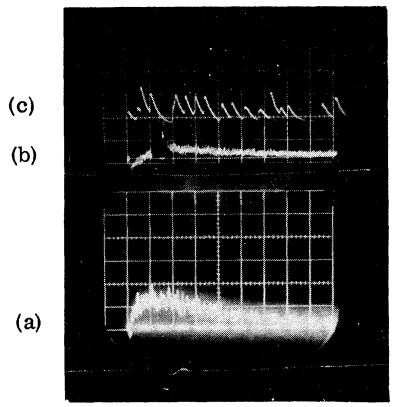

FIG. 1. Trace (a) shows decay of fluorescence of the R_1 line for low excitation level (time scale 1 msec/div). Trace (b) shows patterns at high excitation level. Note the break in trace after 500 μsec when stimulated emission begins (time scale 500 μsec/div). Trace (c), with a 10^3 decrease in gain compared to (b), shows 100 μsec of the stimulated emission region (time scale 10 μsec/div).

R_1 and R_2 lines being of the order of unity both for light emerging through the ends and from the sides of the rod. When the energy discharged through the lamp exceeded some value in the vicinity of 2000 joules, the ratio (R_1/R_2) for the light seen through the silvered ends, was found to increase by as much as three orders of magnitude. The light emerging from the sides of the rod, however, still showed a ratio of the order of unity. Under these conditions the time dependence of the R_1 signal, as observed through the ends, was of a character entirely different from that observed below the threshold. In Figs. 1(b) and 1(c) are shown two traces of the R_1 signal. One trace shows the complete fluorescent emission on a time-base 5×10^{-4} sec/div; on the other, an interval between 5×10^{-4} and 1×10^{-3} second is displayed on a faster time-base. It will be seen that the excess signal in the R_1 line consists of a series of very intense, very short spikes in the emission. Note that this observation differs in an interesting way from the "lifetime decrease" reported by Maiman.[3] In our experience the spike phenomenon was more pronounced, the heavier the silvering and the more nearly perfect the geometry. The duration of each spike is not greater than the instrumental resolving time (10^{-6} sec). The interval between spikes has been found to decrease as the exciting intensity is increased. Phenomena of this sort have been observed at microwave frequencies in ruby masers.[4] One possible explanation[5] which can be given is that the stimulated emission, once it sets in, proceeds at a rate greater than that at which atoms are being excited to the $\bar{E}(^2E)$ state. When this occurs, the stimulated emission may drive the inverted population below the level at which the process first sets in, so that, when the stimulated emission is finally quenched, some definite time interval will be required for the negative population to be restored.

In order to explore the directionality and line narrowing of the light emitted through the ends, arrangements were made to focus the light through a 500-mm telephoto lens set to infinity, on a photographic film. Photographs could be taken either directly or through a Fabry-Perot etalon placed in front of the lens. The direct photographs made with an excitation below the stimulated threshold gave practically uniform darkening of the negative; above threshold, the darkening was confined to a roughly circular patch of the order of 0.3 to 1.0 cm in diameter. This shows that the stimulated emission light is confined to an angle of the order of 0.3° to 1° from the axis perpendicular to the silvered faces of the sample. In some photographs structure is visible in this spot, occasionally consisting of a large number of dots, each of the order of 10^{-2} cm in diameter, and occasionally of a mosaic structure. With the Fabry-Perot etalon, with a spacing of up to 10 mm, fringes could be seen in the area of the spot. Figure 2 shows a typical fringe pattern obtained with a 10-mm etalon. The etalon was inclined at an angle of about 1° to the axis of the telescope in order to show segments of several rings within the cone of illumination. From the width of the fringes, the spectral linewidth is estimated at about 0.2 cm^{-1} as compared with the normal R_1 linewidth of 6 cm^{-1}. Note that the fringes do not become broader at the edges of the illuminated patch; thus, all of the light emerging in the stimulated emission cone is narrowed to the same extent. Note also that the frequency of the stimulated emission is constant to the above-quoted wave-number figure in spite of the existence of a large number of spikes. In some experiments at higher excitation levels the negatives showed not one but several ring systems, some of which were at least a factor of three sharper than others.

To investigate the coherence of the stimulated emission across the silvered end of the crystal, an experiment was carried out to look for Fraunhofer diffraction. A rectangular aperture 50 μ $\times 150\ \mu$ in size was left in a heavy silver coating on one end of the rod, and the light emerging therefrom was inspected with a camera set to

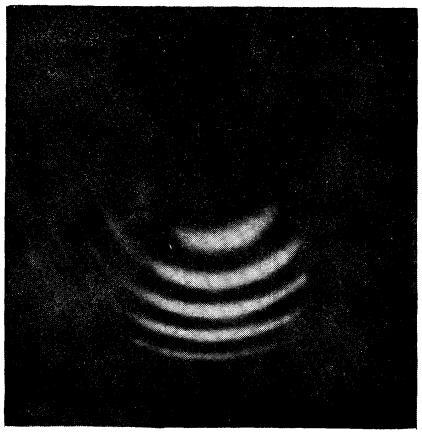

FIG. 2. Interference fringes obtained with a Fabry-Perot etalon of the R_1 line at high excitation level and with the sample in liquid nitrogen. The interorder spacing is 0.5 cm^{-1}.

infinity. The image was found to consist of the anticipated Fraunhofer diffraction pattern for a rectangular aperture illuminated by wavefronts approximately plane and approximately coherent. This pattern disappeared when the excitation was reduced below threshold. The choice of the small dimension of the aperture was such as to lead to an angular spacing of the diffraction fringe of the order of the angular divergence of the stimulated emission light.

We believe that the approximate parallelism of the light and the existence of the Fraunhofer fringes are clear evidence for coherence over a distance across the end surface of the order of 100 wavelengths.

Some further experiments were carried out with the crystal immersed in liquid nitrogen. Under these conditions it was found (1) that the threshold for the appearance of the stimulated emission phenomenon was ~30% lower than at room temperature, (2) that the R_1 line was narrowed by a further factor of 2 or more (but note that the unnarrowed line is itself a factor of 5 or so sharper than at room temperature), and (3) that the degree of parallelism was not significantly changed.

The degree of perfection of the crystals was investigated by x-ray techniques. The orientation of the c axis was found to vary down the length of the rod by as much as $\pm 1°$; this may correspond to local variations in refractive index of the order of several parts per million. In addition the investigation revealed the presence of strain. Therefore, even though the ends are flat and parallel to one minute or so, the optical path lengths from end to end must vary by at least five wavelengths. Thus it seems unlikely that there is coherent excitation of a single decay mode of the crystal etalon. Rather it is probable that there is a coherent excitation of a large number of modes at once, although a small fraction of the total modes.

The energy emitted through the silvered ends and within the cone during a single pulse, as has been shown, was highly monochromatic and consisted of $\sim 10^{-2}$ joule. For such a light source this corresponds to an effective temperature of $\sim 10^{10}$ °K.

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[3]T. H. Maiman, Nature, 187, 493 (1960); British Communications and Electronics 7, 674 (1960).

[4]C. Kikuchi, J. Lambe, G. Makhov, and R. W. Terhune, J. Appl. Phys. 30, 1061 (1959).

[5]H. Statz and G. deMars, in Quantum Electronics (see reference 2).

NUCLEAR SPIN-LATTICE RELAXATION IN VANADIUM METAL

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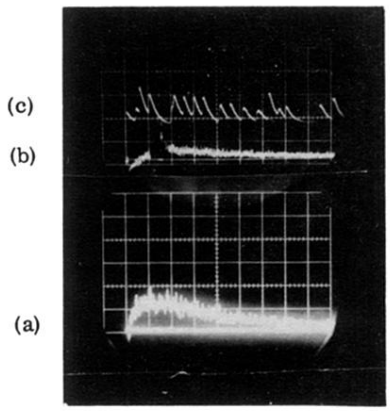
From a comparison of the measured values of the Knight shift, $\Delta H/H$, and the spin-lattice relaxation time, T_1, of the nuclear magnetic resonance in a metal, information can be derived about the state of the electrons in the metal. For, as Korringa showed,[1] if the electrons responsible for the shift and the relaxation behave as uncorrelated electrons of largely s character, the following simple relation exists between T_1 and $\Delta H/H$:

$$T_1(\Delta H/H)^2 = (\hbar/\pi k T)(\beta I/\mu)^2, \qquad (1)$$

where T is the absolute temperature, and β and μ are the magnetic moments of an electron and nucleus, respectively, while the other symbols have their conventional meanings. Conversely, departure from the Korringa relation indicates departure of the electrons from such simple behavior.

This note reports the results of measurements of T_1 in vanadium metal, and some inferences drawn from them. The results are of some interest because they are the first reported accurate measurements of T_1 in a transition metal, where the unfilled shell of d electrons might be expected to influence strongly the nuclear magnetic resonance. As a probable consequence of these electrons, the results show much the largest departure from the Korringa relation observed so far.



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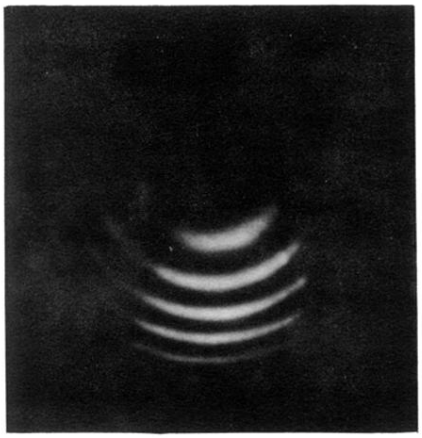

FIG. 2. Interference fringes obtained with a Fabry-Perot etalon of the R_1 line at high excitation level and with the sample in liquid nitrogen. The interorder spacing is 0.5 cm^{-1}.