whose resonant frequencies lie nearest to the saturated line take the place of the Ce. It should be pointed out, however, that an unknown impurity with a broad resonance could account for a similar behavior.

The third distinct relaxation process occurs at a point where the Ce transition overlaps a Gd transition differing by $\Delta M=1$ from the saturated line (see point B, Fig. 1). This involves a three-step process. First the saturation is partially passed on from the $-\frac{3}{2}\rightarrow-\frac{1}{2}$ levels to the $-\frac{1}{2}\rightarrow+\frac{1}{2}$ levels via a spin-spin interaction. The $-\frac{1}{2}\rightarrow+\frac{1}{2}$ levels then relaxes via the Ce as discussed earlier.

In the absence of strong interactions between different levels ($\theta=0$ in Fig. 1), the relaxation times are approximately proportional to the inverse transition probabilities as one would expect.

We would like to thank Dr. P. W. Anderson for helpful discussions and Mr. E. A. Gere for his assistance in the experiments.

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Operation of a Solid State Maser

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(Received December 3, 1956)

A MASER of the same type as that proposed by Bloembergen[1] has been successfully operated at 9 kMc/sec. Since the basic theory has been covered in the reference, it will not be reviewed here.

We require a magnetically dilute paramagnetic salt having at least three energy levels whose transitions fall in the microwave range and which may be easily saturated. The ion $Gd^{+++}|4f^7, {}^8S\rangle$ seems a suitable choice since its eight energy levels give the choice of several modes of maser operation. Of the three salts of Gd^{+++} which have been investigated by paramagnetic resonance[2] the diluted ethyl sulfate appears very desirable. This salt has been investigated in detail by Bleaney *et al.*,[3] Buckmaster,[4] and Feher and Scovil.[5]

If an external magnetic field is applied perpendicular to the magnetic axis, the spin Hamiltonian may be written[3]

$$\mathcal{H}=g\beta H_0\cdot S_z-\tfrac{1}{2}B_2^0[S_z^2-\tfrac{1}{3}S(S+1)]+\tfrac{1}{4}B_2^0[S_+^2+S_-^2], \quad (1)$$

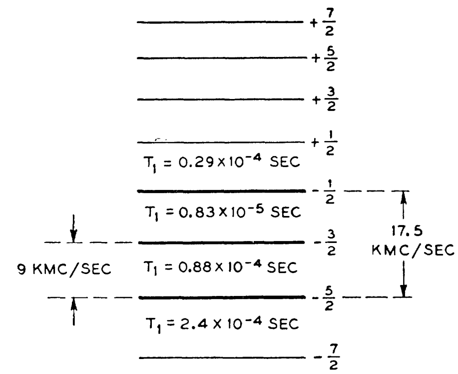

FIG. 1. The energy levels of the ground state of Gd^{+++} in the ethyl sulfate for a large applied magnetic field. The heavy lines identify the maser levels. Spin-lattice relaxation times between levels are shown.

where some small terms have been neglected, $g=1.99$, $B_2^0\approx0.02$ cm^{-1}, and the axis of quantization is parallel to H_0. The first term is the usual Zeeman energy and is varied to bring the transitions to the desired operating frequency. The second term disturbs the equality of the level spacings (essential for the device) as shown in Fig. 1. The third term admixes states, thereby permitting $\Delta S_z=\pm2$ transitions which are also essential. The angle between the dc magnetic field and the microwave magnetic field should be zero for the $\Delta S_z=\pm2$ transitions and 90° for the $\Delta S_z=\pm1$ transitions. A convenient compromise of 45° between both microwave fields and H_0 was chosen for the structure employed.

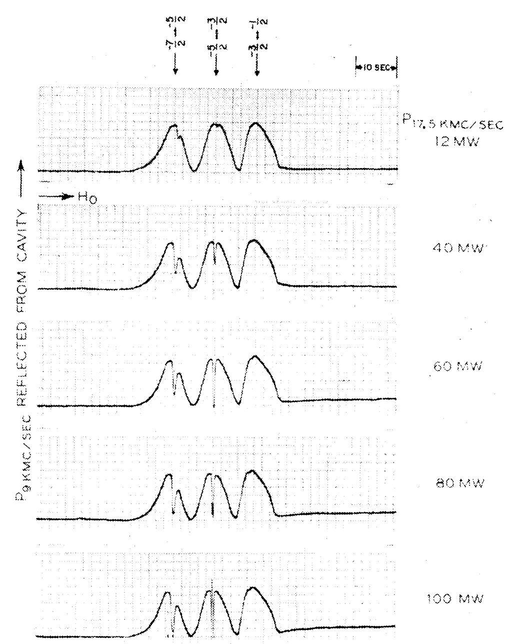

FIG. 2. The power reflected from the 9-kMc/sec cavity as the magnetic field was swept to cover three $\Delta S_z\pm1$ transitions for different 17.5-kMc/sec power levels. The spacing between two lines is about 200 oersteds.

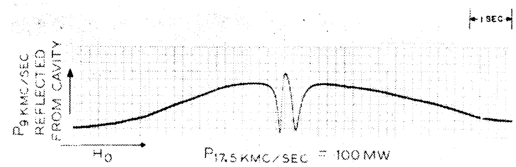

FIG. 3. The central line of the last trace of Fig. 2 is shown on an expanded time scale.

The negative temperature (a term introduced by Purcell and Pound[6] to designate the fact that a higher energy level is more densely populated than the lower one) at complete saturation of the $\Delta S_z=\pm 2$ transition will depend essentially upon two parameters: the separations of the energy levels and the ratio of the relaxation times. In a given material the first parameter is fixed. Our attempts were directed toward varying the second parameter in order to obtain lower negative temperatures. A relaxation time ratio of 1:10 between two neighboring transitions was obtained by introducing cerium into the crystal.[5] In order to obtain the full benefit of this large relaxation time ratio for a 9-kMc/sec maser, a dc magnetic field of 2850 oersteds was applied at an angle of 17° from the perpendicular direction of the crystal.[5] Although Eq. (1) refers to the perpendicular direction, the energy levels and transition probabilities are only slightly modified at this small angle. A 90-mg (8% filling factor) lanthanum ethyl sulfate crystal containing $\approx 0.5\%$ Gd^{+++} and $\approx 0.2\%$ Ce^{+++} was used in contact with liquid helium at 1.2°K. A saturating magnetic field at 17.52 kMc/sec was used to induce transitions between the $|-5/2\rangle$ and $|-\frac{1}{2}\rangle$ states as shown in Fig. 1. The signal at 9.06 kMc/sec was applied between the $|-5/2\rangle$ and $|-3/2\rangle$ states. The maser embodies a microwave cavity simultaneously resonant at these two frequencies. The almost critically coupled 9-kMc/sec cavity had a loaded $Q\approx 8000$. The 17.5-kMc/sec cavity perversely supporting a spurious mode provided a $Q\approx 1000$; this fortunately proved sufficient.

Figure 2 shows the 9-kMc/sec monitoring signal reflected from the cavity as a function of H_0. In the first trace three $\Gamma S_z=\pm 1$ transitions are shown, the peaks representing essentially complete reflection as a result of the high magnetic losses associated with the material. The observed resonance line appears broadened since the absorption is not a small perturbation on the cavity as resonance is approached. The succeeding traces show the reflections associated with the $|-5/2\rangle\rightarrow|-3/2\rangle$ transition as the 17.5-kMc/sec power is increased. In the third trace the salt is lossless, corresponding to an essentially infinite spin temperature. The fourth trace shows the onset of negative spin temperatures and the partial overcoming of the losses associated with the empty cavity. In the fifth trace the reflected power exceeds the incident power and oscillations have commenced. Before oscillations commence, a region of amplification must exist. Figure 3 shows the last trace on an expanded time scale.

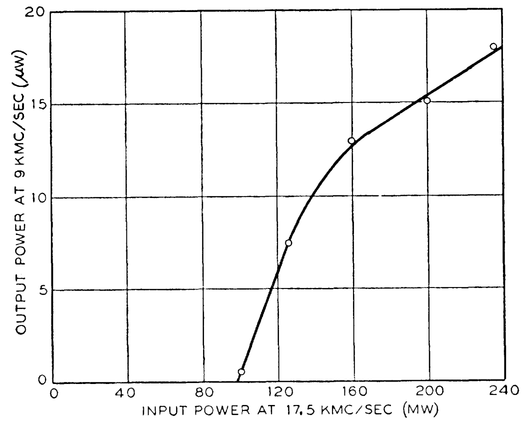

FIG. 4. The 9-kMc/sec output power of the oscillating maser as a function of the saturating power.

At this stage, the 9-kMc/sec monitoring signal was turned off. The dc magnetic field was adjusted to a value resulting in maximum 9-kMc/sec output power from the oscillating maser. The power output was measured with a barretter as a function of the saturating 17.5-kMc/sec power. The results are shown in Fig. 4.

The required saturating power could be materially reduced by the use of a 17.5-kMc/sec cavity having a higher Q. The purpose of this work was merely to show the feasibility of this device.

We should like to acknowledge the generous cooperation of many members of the Bell Telephone Laboratories, and in particular, to thank Mr. M. G. Gussak.

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Electron Scattering by the Deuteron

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(Received November 15, 1956)

THE object of this note is to point out that the recent Stanford experiments of electron scattering by the deuteron[1] do not necessarily imply any of the far-reaching conclusions drawn in the paper that describes them. The inability to fit the experimental scattering cross sections by those calculated from potentials leading to the correct deuteron binding energy and low-energy neutron-proton scattering phase shift, is the result merely of the special nature of the potentials used.

Let us assume that the tensor force can be neglected for the present purpose. (According to reference 1 this is a justified assumption.) Then we may easily write

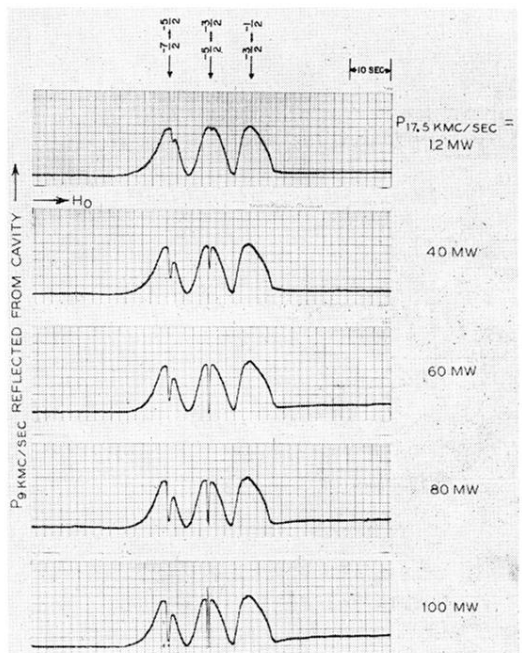

FIG. 2. The power reflected from the 9-kMc/sec cavity as the magnetic field was swept to cover three $\Delta S_z \pm 1$ transitions for different 17.5-kMc/sec power levels. The spacing between two lines is about 200 oersteds.

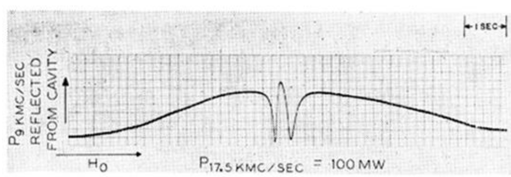

FIG. 3. The central line of the last trace of Fig. 2 is shown on an expanded time scale.