PHYSICAL REVIEW VOLUME 113, NUMBER 2 JANUARY 15, 1959

Radiation Damping in Nuclear Magnetic Resonance

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(Received August 1, 1958)

The effect of radiation damping on nuclear magnetic resonance spectra has been demonstrated experimentally. Observations on a nuclear two-level maser, obtained by flipping the magnetization through about 180 degrees, are reported.

INTRODUCTION

BLOEMBERGEN and Pound[1] have pointed out that radiation damping can be of importance in high-resolution nuclear magnetic resonance. The effect is closely related to the maser principle.[2] A simple theory treating both radiation damping and transient maser operation in a form directly applicable to nuclear magnetic resonance has been given by Bloom.[3] This theory owes its simplicity to the assumption $T_1=\infty$. Although this is of course not true for the case of nuclear magnetic resonance in liquids, the theory gives a good approximation if $T_1 \gg \tau_R$ [defined in Eq. (1)].

A quantity characterizing the radiation damping is[1,3]

$$\tau_R=(2\pi\eta M_0 Q\gamma)^{-1}, \tag{1}$$

where η is the filling factor, M_0 the magnitude of the nuclear magnetization of the sample, Q the quality factor of the receiver coil, and γ the gyromagnetic ratio of the nuclei. For small deviations from equilibrium magnetization, the line width in the presence of radiation damping can be described by an effective T_2' given by

$$1/T_2'=1/T_2+1/\tau_R, \tag{2}$$

where T_2 is the transverse relaxation time in the absence of radiation damping. In practice, T_2 includes the contribution due to inhomogeneity of the external magnetic field.

The condition for maser operation following inversion of the nuclear magnetization is

$$T_2>\tau_R. \tag{3}$$

If this condition is fulfilled, the magnetization vector will return to equilibrium through radiating states in which its transverse component is different from zero. The detailed behavior of the magnetization vector in this case has been given by Bloom.[3] The effect has been observed for the case of electron spin resonance by Feher *et al.*[4] and by Chester, Wagner, and Castle.[5]

* Taken in part from the dissertation submitted by A. Szöke to the Hebrew University, Jerusalem, in partial fulfillment of the requirements for the Ph.D. degree.
[1] N. Bloembergen and R. V. Pound, Phys. Rev. **95**, 9 (1954); see also, Bruce, Norberg, and Pake, Phys. Rev. **104**, 419 (1956).
[2] Gordon, Zeiger, and Townes, Phys. Rev. **99**, 1264 (1955).
[3] S. Bloom, J. Appl. Phys. **28**, 800 (1957).
[4] Feher, Gordon, Buehler, Gere, and Thurmond, Phys. Rev. **109**, 221 (1958).
[5] Chester, Wagner, and Castle, Phys. Rev. **110**, 281 (1958).

In this paper some observations on transient maser operation and radiation damping in nuclear spin resonance will be reported.

EXPERIMENTAL

Transient maser operation was observed subsequent to inversion of the nuclear magnetization by an rf pulse of adjustable length and amplitude. The gate used in forming the rf pulses was the same as described in a previous paper.[6] The Q of the receiver circuit was improved by relocation of the tuning condenser near the receiver coil. The cable leading to the receiver input was connected to the receiver coil through a capacitive voltage divider. A further increase of Q was achieved by introducing feedback in the first stage of the receiver. This increased Q by a factor of about 3, without introducing instability.

A synchronous detector was used in the receiver, and accordingly the records show the beat note between the free precession signal of the nuclei and the constant rf of the transmitter. The signal was recorded on a Sanborn recorder.

The experimental setup also allowed observation of the proton resonance under ordinary slow- or fast-passage conditions, using the same coil arrangement.

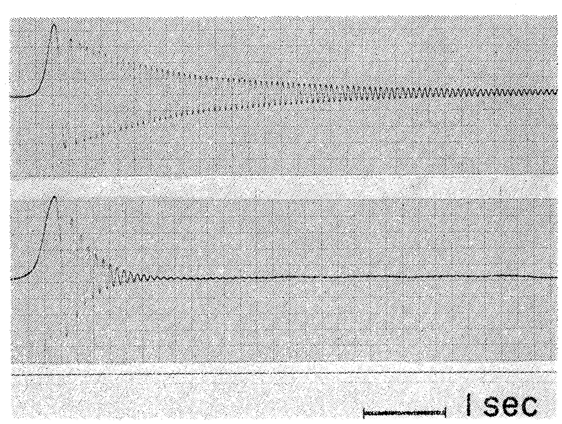

FIG. 1. Measurement of effective T_2 from the decay of the "wiggles" after fast passage. The top record was made in the absence of appreciable radiation damping. In the bottom record radiation damping is present.

[6] S. Meiboom and D. Gill, Rev. Sci. Instr. **29**, 688 (1958).

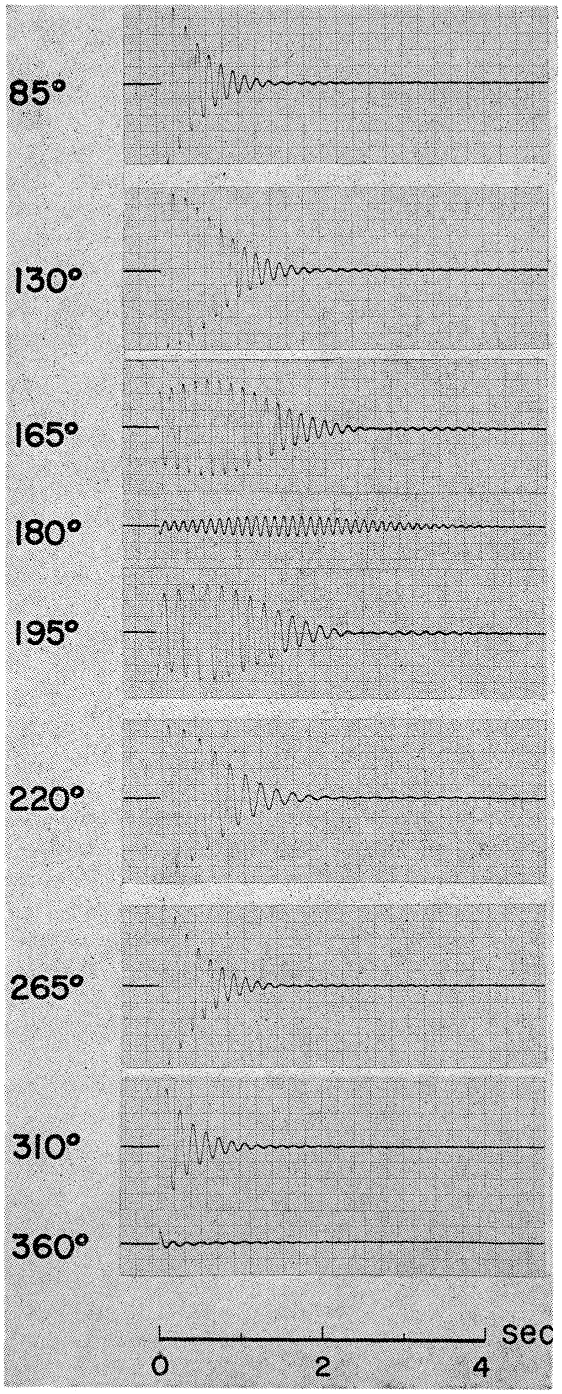

FIG. 2. Nuclear two-level maser operation. The records show the signal obtained after a flip of the nuclear polarization through the angle indicated at the left of the figure.

The decay of the "wiggles" after fast passage served as a measure of the effective T_2' [Eq. (2)].

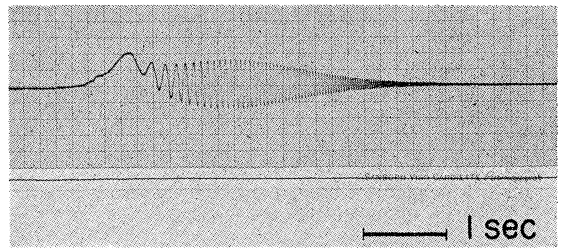

FIG. 3. Nuclear two-level maser operation. The record shows the nuclear signal during and after adiabatic passage.

The sample was contained in a glass tube, of 4 mm i.d., rotated by a small air turbine at about 1000 rpm. The receiver coil had a diameter of 9.5 mm and a length of 7 mm. The filling factor (η) was about 0.17.

All measurements were made on a benzene sample. The sample was not degassed, and had a T_1 value of 3.0 sec.

RESULTS

(a) Radiation Damping

Figure 1, recorded by the fast-passage method, shows the effect of radiation damping. The upper record was made with the receiver coil off resonance, so that the radiation damping could be neglected. The decay of the "wiggles" gives an effective T_2' of 1.7 sec. The bottom record was made after the receiver coil was tuned to resonance. It gives a T_2' of 0.3 sec. From Eq. (2) τ_R is found to be 0.36 sec.

(b) Transient Maser

Figure 2 gives the observed free decay signal, obtained after flipping the magnetization from its equilibrium position through the angle indicated in the figure. The value of the angle was determined from the length of the pulse, which was observed on an oscilloscope. The length of a 360° pulse, which could be identified by the absence of signal, served to calibrate the angle of flip in terms of pulse length. The records given in Fig. 2 fit the theoretical curves given by Bloom[3] reasonably well. An exact quantitative agreement cannot be expected in view of Bloom's assumption of infinite T_1.

(c) Adiabatic Fast Passage

A 180° flip of the nuclei can also be achieved by adiabatic fast passage. Figure 3 shows a record made using this technique. The radiative return to equilibrium is evident.

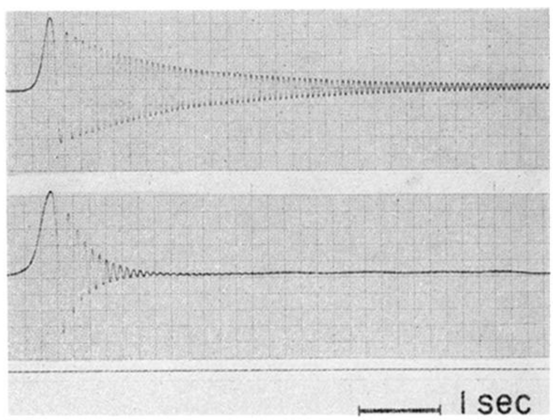

FIG. 1. Measurement of effective T_2 from the decay of the "wiggles" after fast passage. The top record was made in the absence of appreciable radiation damping. In the bottom record radiation damping is present.

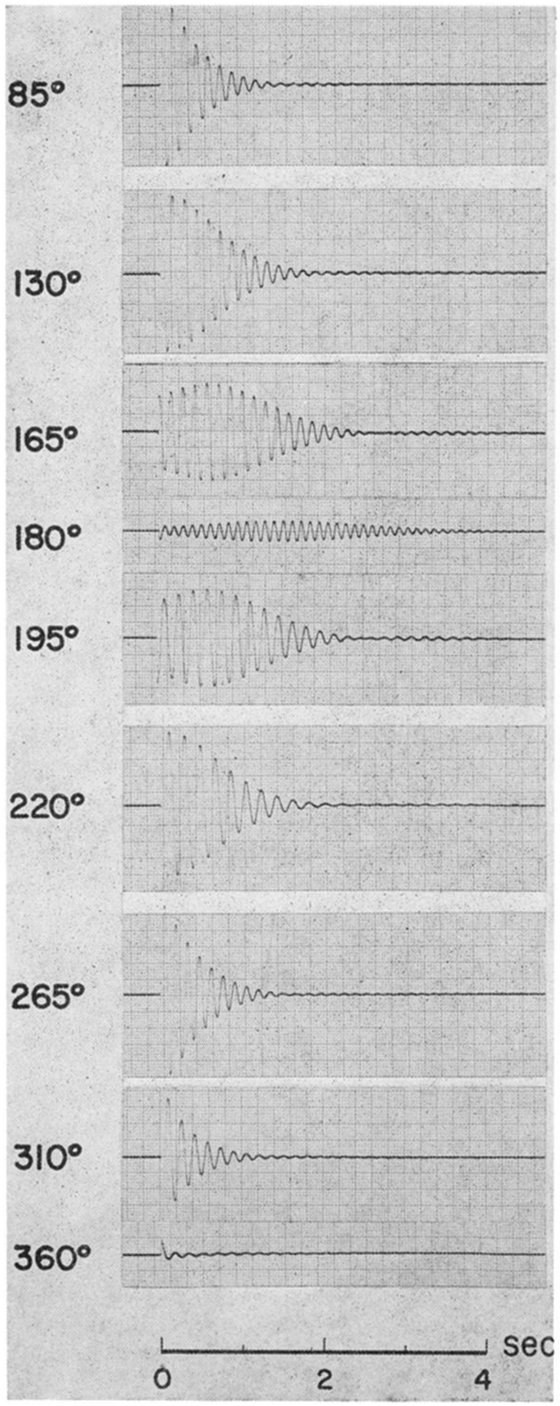

FIG. 2. Nuclear two-level maser operation. The records show the signal obtained after a flip of the nuclear polarization through the angle indicated at the left of the figure.

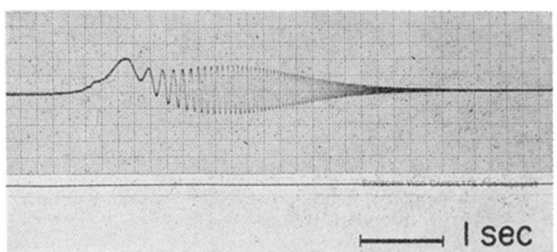

FIG. 3. Nuclear two-level maser operation. The record shows the nuclear signal during and after adiabatic passage.