Relaxation Effects in the Ferromagnetic Resonance*

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The spin-lattice relaxation time, T_1, has been determined in single crystals of nickel ferrite, by using the ferromagnetic resonance effect at a frequency of 9000 Mc/sec. At high levels of microwave power, the saturation effect is observed both in the resonance absorption and in the component of magnetization along the static field. T_1 is computed from these data.

The experimental method is described, and the results presented. Some of the results have not been encountered before in magnetic resonance, and are not predicted by available theories. Because of this, the relaxation time cannot be calculated from the classical theory of the magnetic resonance. By equating the energy absorbed to the energy transferred to the lattice, we obtain a value $T_1 \sim 3\times10^{-5}$ sec. This is longer than the decay time observed directly, which is less than a few tenths of a microsecond. The results are compared with available theories of the magnetic resonance and spin-lattice interaction.

I. INTRODUCTION

IN understanding the magnetic properties of solids, it is important to have information concerning the interaction between the system of spins, to which the magnetic properties are attributed, and the crystal lattice. In nuclear and paramagnetic systems, the spin-lattice coupling has been investigated by means of the magnetic resonance phenomenon.[1,2] According to Bloch's theory,[3] the transfer of energy from the electronic spin system to the crystal lattice can be described by the spin-lattice relaxation time, T_1, which is the characteristic time in which the spin system, when disturbed, returns to equilibrium with the lattice. We have observed the saturation effect in the ferromagnetic resonance absorption, analogous to measurements by which T_1 has been determined in other systems.[1,2] In addition, the change in the component of magnetization along the static field has been observed.[4] Both methods are applied to determining the spin-lattice relaxation time in a crystal of nickel ferrite.

For a ferromagnetic material in an externally applied field $H_x^{\text{ext}}=H_1e^{i\omega t}$, $H_y^{\text{ext}}=0$, $H_z^{\text{ext}}=H_0$, the classical steady-state solution for the x and y components of magnetization is[5,6]

$$M_x=\frac{\gamma^2M_z[H_0+(N_y-N_z)M_z]H_1}{\omega_0^2-\omega^2+i2\omega/T_2}, \tag{1a}$$

$$M_y=\frac{\gamma M_z[i\omega+1/T_2]H_1}{\omega_0^2-\omega^2+i2\omega/T_2}, \tag{1b}$$

$$\omega_0^2=\gamma^2[H_0+(N_x-N_z)M_z]\times[H_0+(N_y-N_z)M_z]+1/T_2^2. \tag{1c}$$

The quantities N_x, N_y, and N_z are demagnetizing factors for an ellipsoidal sample, and γ is the gyromagnetic ratio. The width of the resonance is described by T_2. We have neglected anisotropy effects and terms due to the inhomogeneous distribution of magnetization. In the low power resonance experiment, the former changes the value of ω_0,[5] and may have other effects in the saturation region. Neglecting high frequency components, and assuming a spherical sample ($N_x=N_y=N_z$), we find the time-average value of the z component of magnetization is[6]

$$M_z=M_0\left[1+\tfrac{1}{2}\gamma^2H_1^2T_1T_2\frac{\omega_0^2+\omega^2}{4\omega^2+T_2^2(\omega_0^2-\omega^2)^2}\right]^{-1}. \tag{2}$$

The ferromagnetic resonance experiment is usually performed at low levels of microwave power with $\gamma^2H_1^2T_1T_2\ll1$, so $M_z\approx M_0$ in (1) and (2). From measurements under these conditions T_2 can be determined from the relation $T_2=1/\gamma\Delta H$, where ΔH is the half-linewidth of the resonance line. In the present experiment, we utilize the saturation effect resulting from the term in H_1^2 as a means of determining T_1, and this approximation will not be made.

From (1) and (2), two methods of determining T_1 are apparent. The first utilizes the variation in M_x as a function of H_1^2, measured by observing the decrease in relative power absorbed as the microwave field-strength is increased. The quantity measured is the imaginary part of the complex permeability, μ'', defined by

$$\mu=\mu'-i\mu''=1+4\pi M_x/H_1. \tag{3}$$

Combining (1a), (2), and (3), and assuming a spherical sample, we obtain

$$\mu''=\frac{8\pi\omega T_2\gamma^2H_0M_0}{4\omega^2+T_2^2(\omega_0^2-\omega^2)^2+\frac{1}{2}\gamma^2H_1^2T_1T_2(\omega_0^2+\omega^2)}. \tag{4}$$

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[1] Bloembergen, Purcell, and Pound, Phys. Rev. **73**, 679 (1948).
[2] E. M. Purcell and C. P. Slichter, Phys. Rev. **76**, 466 (1949).
[3] F. Bloch, Phys. Rev. **70**, 460 (1946).
[4] N. Bloembergen and R. W. Damon, Phys. Rev. **85**, 699 (1952).
[5] C. Kittel, Phys. Rev. **71**, 270 (1947); **73**, 155 (1948).
[6] N. Bloembergen, Phys. Rev. **78**, 572 (1950).

At resonance,

$$(\mu''/\mu_0'')_{\text{res}}=(1+\tfrac{1}{4}\gamma^2H_1^2T_1T_2)^{-1}, \tag{5}$$

where $\mu_0''=2\pi T_2\gamma^2H_0M_0/\omega$ is the value of μ'' at resonance with no saturation. From measurements of $(\mu''/\mu_0'')_{\text{res}}$ *vs* H_1^2, with a knowledge of T_2 from line-width data, T_1 can be determined.

The second method is the more direct one of measuring M_z/M_0 as a function of H_1^2. This satisfies the same relation

$$(M_z/M_0)_{\text{res}}=(1+\tfrac{1}{4}\gamma^2H_1^2T_1T_2)^{-1}, \tag{6}$$

and T_1 should be obtainable alternatively in this way.

To interpret the experiment, the transient solutions of the equation of motion are also of interest. In the case when the microwave field is suddenly turned off the definition of T_1 implies an exponential return of magnetization to equilibrium, $M_z=M_0$; the time constant for the process is T_1. The case when the microwave field is suddenly turned on is more difficult to interpret because of induced transitions. The anisotropy and demagnetizing terms lead to a nonlinear equation of motion, but in spherical samples, the demagnetizing terms cancel. Some possible effects of anisotropy in ferromagnetic saturation have recently been discussed by Bloembergen and Wang.[7]

II. EXPERIMENTAL METHOD

Measurement of μ''

To determine T_1 by measurements of μ'' as a function of H_1^2 the sample is placed in a microwave cavity at a point of high microwave magnetic field, and μ'' is calculated from the change in the power dissipated in the cavity. By use of the perturbation theory for cavities, the relation

$$\mu''=\frac{8\pi u_1}{v}\left(\frac{1}{Q_u'}-\frac{1}{Q_u}\right), \tag{7a}$$

is obtained.[8] Here v is the volume of the sample, Q_u is the unloaded Q of the empty cavity, and Q_u' that under the conditions for which μ'' is to be measured. The quantity u_1 is a geometrical factor defined as

$$u_1=\frac{1}{8\pi}\int_{V_c}(H/H_1)^2d\tau, \tag{8}$$

where V_c is the cavity volume, H is the rf magnetic field amplitude in the cavity, and H_1 is the value of H at the sample position. In the rectangular cavities used, operated in a TE_{10n} mode, $u_1=(V_c/32\pi)(\lambda_g/\lambda)^2$.

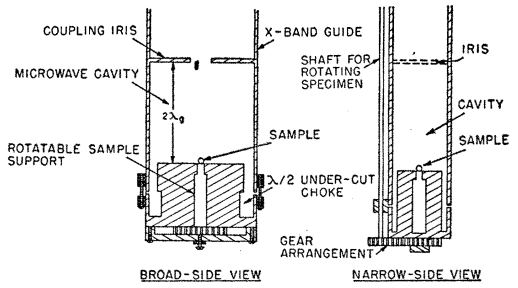

FIG. 1. Schematic cavity construction for measurement of μ'' along different crystal axes.

The various Q's for the empty cavity were determined by measurements of band width[9] and the cavity conductance at resonance.[10] With this information, μ'' can be determined from the cavity reflection coefficient, Γ, which was measured in terms of incident and reflected power for the cavity, $|\Gamma|=(P_r/P_i)^{\frac{1}{2}}$. The result, in the case of an undercoupled cavity,[10] follows from (7) as

$$\mu''=\frac{8\pi u_1}{Q_e v}\left[\frac{1+|\Gamma|}{1-|\Gamma|}-G\right], \tag{9}$$

where $Q_e=Q_uG$ is the external Q, and G is the resonant conductance of the empty cavity.

The microwave field strength is determined from the cavity parameters and a power measurement as

$$H_1^2=(Q_eP_r/\omega u_1)[(1/|\Gamma|)-1]^2. \tag{10}$$

Measurement of M_z

The other method used to determine the spin-lattice relaxation time involves a measurement of the z component of magnetization as a function of the microwave magnetic field strength. The principle of this novel method is as follows. If the sample is in a static field only, the magnetization is M_0. Applying a microwave field of resonant frequency will change the z component of magnetization to M_z, given by (6). This change will occur in a time determined by the relaxation processes, and the changing induction will induce a voltage proportional to M_0-M_z in a coil of wire near the sample. By measuring the induced voltage, M_z is determined as a function of microwave magnetic field strength. With knowledge of T_2 from line-width data, the spin-lattice relaxation time can be calculated from (6).

The induced voltage will also depend on the rate at which the magnetization approaches equilibrium. Since induced transitions complicate the response when the microwave field is turned on, the pulse obtained when the field is turned off appears to be most suitable for the measurements. It must be remembered, however, that the build-up and decay of H_1^2 has the time constant Q_L/ω, where Q_L is the loaded Q of the cavity. If this time is long, it will be the controlling factor for either the magnetization build-up or decay. The loaded Q also depends on μ'', and thus on H_1^2, so this will not yield a constant decay time. No attempt was made to correct for this effect.

[7] N. Bloembergen and Shyh Wang, Phys. Rev. **87**, 392 (1952).
[8] D. W. Healy, Jr., Phys. Rev. **86**, 1009 (1952).
[9] C. G. Montgomery, *Technique of Microwave Measurements* (McGraw-Hill Book Company, Inc., New York, 1947), p. 396.
[10] See reference 9, Chapter 5.

Experimental Equipment

Two microwave cavities were used in the experiments. The first was the rectangular cavity shown in Fig. 1, used only for measurements of μ''.‡ This cavity was two wavelengths long, coupled to the wave guide by an inductive iris. The sample is located in the center of the cavity end-wall, which is a region of maximum microwave magnetic field and of zero electric field. It is mounted on a cylindrical post, which can be rotated to change the orientation of the crystallographic axes of the sample with respect to the static field.

To observe the change in z component of magnetization, the sample is placed in another microwave cavity, shown in Fig. 2. This second cavity is also rectangular. The sample is located on the top of the cavity, one-half wavelength from the cavity end-wall, at a point of high microwave magnetic field. The pick-up coil is placed outside the cavity, behind a wall of the cavity which is a metalized sheet, thin enough to transmit the signal due to the change in magnetization. In order to maintain a high cavity Q, the wall must also be thick compared to the skin depth at microwave frequencies. Both requirements can be met by using wall thicknesses of a few microns.

A block diagram of the equipment is shown in Fig. 3. The cavity is connected to one side-arm of a magic-tee, and a matched load to the other side-arm. The output of the magic-tee is then $\frac{1}{2}P_r$. The input power to the magic-tee is from a 9000-Mc/sec magnetron oscillator, which delivers one-microsecond pulses with a peak power of 50 kilowatts.

Because of transient effects, due to ringing of the cavity and frequency variations of the magnetron at the start and end of the pulse, the reflected power is not constant throughout the pulse. This makes it inaccurate to use any of the standard power-measuring techniques that measure average power. To measure the steady-state reflected power, the output of the magic-tee is detected with a crystal and the envelope observed on an oscilloscope. In this way the center of the pulse, where steady-state conditions exist, can be observed.

The crystal and oscilloscope are calibrated for power measurements by replacing the cavity by a shorting plunger and measuring the power incident on the magic-tee with the calibrated directional coupler and thermistor bridge. The steady-state power reflected from the cavity can henceforth be determined from the attenuation required to reduce the reflected power to a reference scope deflection.

A measurement of the cavity reflection coefficient, $|\Gamma|$, is necessary in the determination of both the microwave field strength and the sample permeability, according to (9) and (10). To make this measurement, attenuator No. 3 was set to give roughly the desired value of H_1^2 according to (10), and attenuator No. 1

‡ The author is indebted to D. W. Healy, Jr., for the use of this cavity.

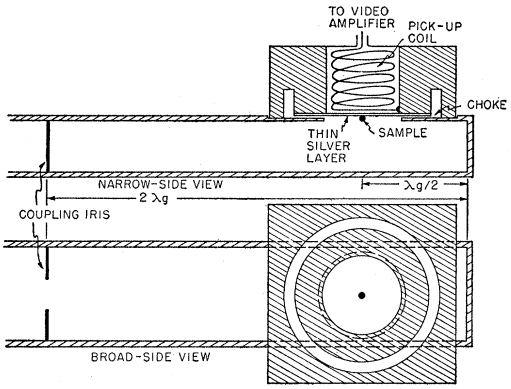

FIG. 2. Schematic cavity construction for measurement of change in z component of magnetization.

was used to set the incident power to the value which brings the scope deflection to the reference level, with the static field off. At the desired value of static field, attenuator No. 2 was adjusted to bring the crystal output back to the reference level, thus measuring only an increment in power, and from the three attenuator settings and the crystal calibration the quantities $|\Gamma|$, P_r, H_1^2, and μ'' were calculated. In plotting the μ'' data, all values were normalized by dividing by μ_0'', the permeability at resonance with no saturation.

For resonance-curve measurements, with varying static field, it would be desirable to maintain constant values of H_1^2 over a particular run. Owing to the complex dependence of H_1^2 on μ'', this was not possible by the method used. Instead, the resonance curves were taken at constant reflected power, and μ'' and H_1^2 were calculated for each point. By use of the saturation curves of μ'' *vs* H_1^2 at the resonant value of static field, these were then corrected to a constant value of H_1^2, chosen as the value of H_1^2 obtained at resonance. This procedure probably leads to a slight broadening of the curves, since H_1^2 varied by as much as a factor of two over some resonance curves, but this is probably not within the limits of accuracy of the experiment.

For measurements of M_z, the output voltage of the pick-up coil is connected through a video attenuator to the video amplifier[11] and pulse-stretcher.[12] The approximate wave shape at various points in the detecting system is shown in Fig. 4.

The output of the pulse-stretcher is fed through a cathode-follower into the lock-in detector. The lock-in reference signal is the sine-wave output of the synchroscope oscillator. Thus the lock-in detector is sensitive only to the fundamental frequency of the voltage induced in the pick-up coil. Because of the rectifier in the pulse-stretcher, the detecting system is nonlinear. For

[11] W. C. Elmore and M. L. Sands, *Electronics, Experimental Techniques* (McGraw-Hill Book Company, Inc., New York, 1949), pp. 3–49.

[12] Radio Research Laboratory Staff, *Very-High-Frequency Techniques* (McGraw-Hill Book Company, Inc., New York, 1947), p. 981.

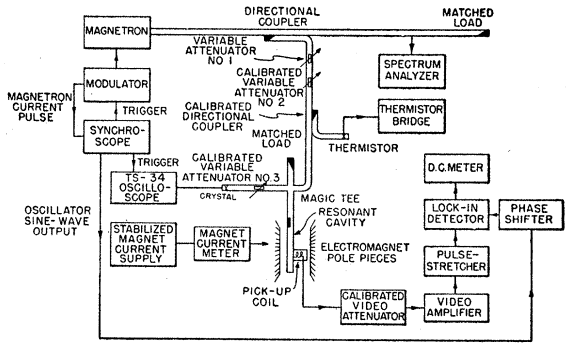

FIG. 3. Block diagram of equipment used for measuring both μ'' and M_z as functions of static and rf magnetic field strengths.

very small signals, the system was calibrated with the video attenuator. For larger signals, the signal was attenuated to a reference level, and measured by the amount of video attenuation required. The saturation curves for M_z were normalized by fitting the output of the lock-in as a function of H_1^2 at constant static field to (6).§

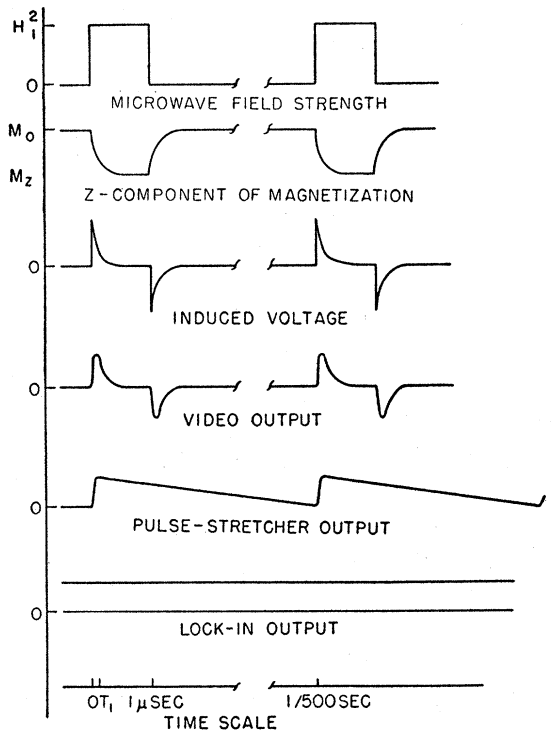

FIG. 4. Signal due to change in z component of magnetization at various points in the detecting system.

§ This is a somewhat questionable procedure of normalizing M_z, since it will be seen from the data to be presented that the classical theory does not explain the experimental results at all well. Dr. Shyh Wang has recently obtained a normalizing constant for the system by essentially the same method, but using a sample of paramagnetic $MnSO_4 \cdot 4H_2O$, for which the classical theory is apparently valid, and he finds that the actual change of magnetization is only about one-tenth as large as we calculate. This changes the calculated value of T_1, but leaves the results otherwise unchanged.

In choosing a material to be studied, it was felt that the ferrites would be particularly well suited to this experiment because of their low conductivity and the concomitantly large skin depth. Thus, samples of reasonable size could be used, with the field remaining uniform over the sample. Another advantage is that use of these materials practically eliminates the conduction electrons from consideration as a mechanism for the relaxation process, and so simplifies the theoretical problem.[6]

Single crystals of nickel ferrite were used.‖ These were made spherical in shape in order to have the demagnetizing field cancel the Lorentz local field. In this case the local field acting on a spin is equal to the field with no sample present. The samples had a diameter of about 0.5 mm, and were oriented by x-ray back-reflection techniques.

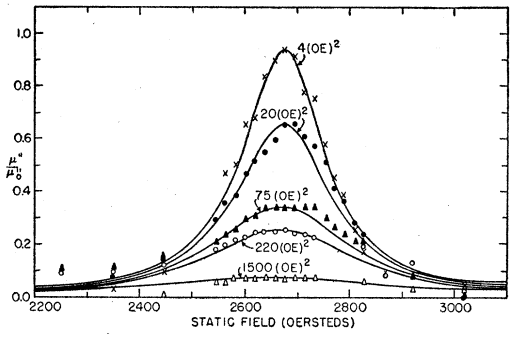

FIG. 5. Dependence of μ'' on static field, with H_1^2 as parameter. Sample 6, oriented with static field along [111] axis.

III. EXPERIMENTAL RESULTS

Results for Sample 6

Sample 6 was a good single crystal of $NiO \cdot Fe_2O_3$ as determined by x-ray techniques. All data on this sample were taken with the static field along the [111] axis, which is the direction of easy magnetization.[8,13] In Fig. 5, a set of resonance curves is shown. As previously discussed, each curve was taken with constant reflected power, and corrected to the given value of H_1^2. The curves drawn were calculated from (4) by obtaining T_2 from the width of the lowest power resonance curve and using the peak height to determine the value of $\frac{1}{2}\gamma^2 T_1 T_2$.

Figure 6 shows the z component of magnetization as a function of static field strength. According to the classical theory, M_z should show the same resonant behavior as μ''. It is found that although M_z increases rapidly above the resonant value of static field, there is a wide low field region where the change in magnetization is even larger than that at resonance.

It may be remarked here that there was some indication in the experiments of an increase in μ'' over this

‖ These were supplied through the courtesy of the Bell Telephone Laboratories, Inc.

[13] Yager, Galt, Merritt, and Wood, Phys. Rev. **80**, 744 (1950).

region of low static field at intermediate levels of microwave field strength; at higher power levels, this appeared to decrease again. This is noticeable in Figs. 5 and 8, and such an energy absorption is of course necessary to change M_z, but no quantitative measurements were obtained.

The most significant result of these measurements is that the values of microwave field required to change the z component of magnetization are considerably greater than the field strength which saturates the absorption line. Figure 7 shows the maximum absorption and the minimum z component of magnetization as a function of the microwave field strength. The values of H_1^2 required for half-saturation in the two cases are seen to differ by about a factor of 100.¶

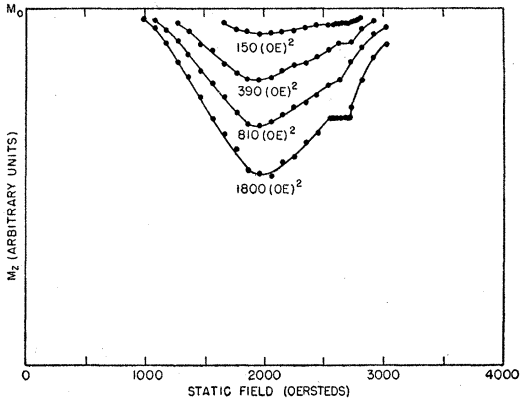

FIG. 6. Dependence of M_z on static field, with H_1^2 as parameter. Sample 6, with static field along [111] axis.

Experiments to Prove that Pick-Up Signal is Due to M_z

In view of the unexpected results obtained for the z component of magnetization, several simple experiments were performed to prove that the signal obtained is really due to the sample, and not to some spurious effect. The most convincing of these is that the output of the video amplifier as observed on the oscilloscope has the form shown in Fig. 4, and when the static field is reversed, thereby changing the sign of M_z, these pulses also change sign.

There is still some question as to whether the change in magnetization is due to true saturation of the spin system, the lattice remaining at constant temperature, or is simply due to heating the sample to the Curie point. Rough calculations indicate that during each pulse the temperature rise would be small, causing no appreciable change in magnetization; the time constant of the observed signal also is too short to be caused by thermal effects. This was further checked by setting H_1^2 to the region where μ'' or M_z changes most rapidly and varying the repetition rate of the magnetron modulator from 50 to 2000 pps. No measurable change in either μ'' or M_z was observed.

¶ This factor is even larger on the basis of Wang's calibration.

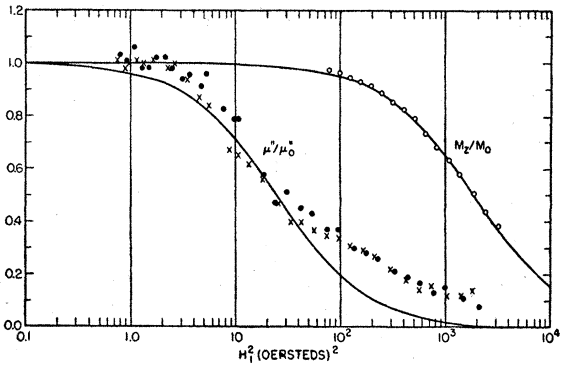

FIG. 7. μ'' and M_z as functions of H_1^2, at a fixed value of static field strength. Sample 6, with static field along [111] axis. Two successive runs for μ'' are shown. The curves are calculated from (5) and (6), and may be moved along the abscissa for best fit. (See reference §.)

Results for Sample 7

Since sample 6 did not behave at all as expected, data were taken on a second sample. The width of the absorption line for sample 6 indicated that it was not a very good sample. Sample 7 had been extensively investigated by Healy in the low power resonance and appeared to be satisfactory.[8] The results are shown in Figs. 8–10. For this sample there is a very definite minimum in the magnetization at about the resonant value of static field, but a large change also occurs at lower fields, just as for the first sample. The great difference between μ'' and M_z in the microwave field required for saturation also persists. The saturation values of H_1^2 are about the same as for sample 6.

Up to this point, all data on the z component of magnetization are observations of the rear peak, occurring when the microwave field is turned off at the end of a pulse. As discussed before, the relaxation time for this decay should be T_1, whereas the apparent relaxation time for the front peak depends on the microwave field strength. Data were also taken on the front peak, but no appreciable difference was observed in either the spectrum or the field required for saturation.

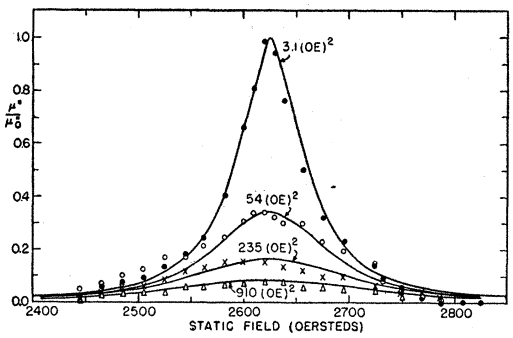

FIG. 8. Dependence of μ'' on static field, with H_1^2 as parameter. Sample 7, with static field along [111] axis.

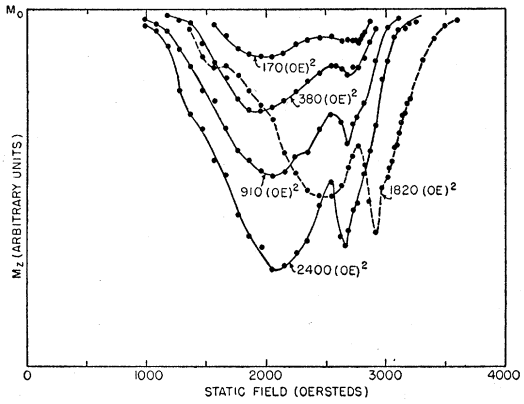

FIG. 9. Dependence of M_z on static field, with H_1^2 as parameter. Sample 7 —— static field along [110] axis; – – – static field along [100] axis.

Rotating the sample indicated that there is no basic dependence of the relaxation effects on crystallographic orientation. An example is shown in Fig. 9, for M_z *vs* static field. Note that the difference in static field between the two M_z minima is essentially constant, while the field required for resonance has changed by more than 300 oersteds. The orientation of the sample also had no effect on the dependence on microwave field strength, as shown in Fig. 10, and the absorption line, except for a shift of resonance field strength, was unchanged.

To find the effect of crystalline imperfections, sample 7 was heated to about 1000°C in air for five minutes and quenched in water. Subsequent measurements showed that the absorption line was broadened considerably. The unsaturated peak value was also reduced in about the same proportion, so the area under the curve remained approximately unchanged. The change in M_z at the resonant field was decreased, but the microwave field strength required for saturation was unchanged. This indicates that the wide absorption line and the large low field change in M_z are both due at least in part to sample imperfections.

Calculation of T_1

The experimental results make it apparent that the classical theory cannot be used directly to calculate the spin-lattice relaxation time. We can, instead, apply a more basic method of equating the power absorbed by the sample to the power transferred to the lattice in the steady state. At a microwave frequency, ν, the power absorbed by the spin system, per unit volume, is $\frac{1}{4}\mu''H_1^2\nu$ and the power transferred to the lattice is of the order $\Delta M_z(H_0+\alpha M_0)/T_1$, where αM_0 is the Weiss molecular field. If we take $\alpha M_0 \sim 3\times 10^6$ for nickel ferrite, and $\mu_0'' = 35$,[8,13] we find $T_1 \sim 3\times 10^{-5}$sec.** The decay time observed on an oscilloscope, as in Fig. 4, sets an upper limit to the value of T_1. This time was only a few tenths of a microsecond, most of which is attributable to the time constants of the apparatus. It thus appears that use of the Weiss molecular field is unjustified in this calculation, and the effective local field, during the times involved in the spin-lattice relaxation, is only a small fraction of the Weiss field.

IV. DISCUSSION

The experimental results obtained are not expected on the basis of the classical equations presented, and it does not appear that a more exact solution of the equation of motion would lead to significantly different results. Other classical equations of motion have been proposed,[5] differing in the form of damping used. These damping terms are based on the assumption that the total magnetization is a constant of the motion, and at low power levels give an absorption line-shape indistinguishable from that obtained with the Bloch damping terms.[8] However, our results strongly indicate that the total magnetization is not a constant of the motion. This is shown by the expression for the total magnetization at resonance, $M^2=(\mu''H_1/4\pi)^2+M_z^2$, which is found to decrease as the rf power level is increased. The classical results have also been derived in various ways from quantum-mechanical principles,[14–17] and Van Vleck[17] suggests contributions to the line-width which do not preserve the constancy of magnetization. These results, however, are all limited to the case of small changes in the z component of magnetization, and thus are probably not applicable to the present experiment.

The M_z spectrum observed can perhaps be explained by a breakdown of the selection rules for the transitions induced by the microwave magnetic field. This effect is

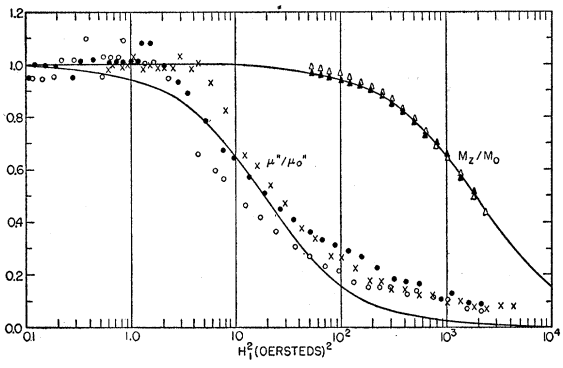

FIG. 10. μ'' and M_z as functions of H_1^2, at a fixed value of static field strength. Sample 7. ●▲ static field along [100] axis. ○△ static field along [110] axis. × static field along [111] axis. The curves are calculated from (5) and (6), and may be moved along the abscissa for best fit. (See reference §.)

** The author is indebted to Dr. Shyh Wang for discussion on the calculation of T_1. It should also be noted that on the basis of Wang's new calibration, $T_1 \sim 3\times 10^{-6}$ sec, and is still longer than the time obtained by direct observation of the decay.

[14] J. M. Luttinger and C. Kittel, Helv. Phys. Acta **21**, 480 (1948).
[15] J. M. Richardson, Phys. Rev. **75**, 1630 (1949).
[16] D. Polder, Phil. Mag. **11**, 99 (1949).
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apparently dependent on the microwave power level, since a corresponding energy absorption has not been observed in measurements at low power. Van Vleck[17] has suggested a mechanism for the breakdown of the selection rule for the x component of magnetization, based on dipolar coupling when the atoms are not all similarly situated. He suggests that some transitions, involving relatively small changes in exchange energy, will appear as wings on the resonance curve, and points out that anisotropic exchange coupling may be strong enough to make this effect significant. The effect of quenching lends support to this idea.

In the classical equations of motion, the relaxation times, T_1 and T_2, were introduced phenomenologically, with no attempt to estimate their magnitude or to inquire into their causes. The theory of the relaxation times in ferromagnetic materials has been treated by Van Vleck[17] and by Akhieser.[18] Van Vleck considers the contributions to the line-width due to spin-spin interaction. This is restricted to the case of small excitation, and will not be considered further.

Akhieser has treated relaxation times by making use of the spin-wave model, with the annihilation and creation of spin waves as the mechanism for the spin-spin and spin-lattice interactions. This occurs through the interaction of the spin waves with one another or with the normal modes of the lattice. Akhieser's results, unfortunately, are valid only at low temperatures, and cannot rigorously be applied to our room temperature data. Polder[16] has criticized Akhieser's calculation, stating that because of the selection rule for spin waves, one should consider only spin waves of long wavelength, rather than the entire spin-wave band. He finds that this leads to much longer spin-lattice relaxation times.

Akhieser's value of spin-spin relaxation time agrees quite well with the measured line-width, giving a time of 10^{-9} sec, but it must be emphasized that the temperature dependence of the line-width[8] is not explained. Extrapolation of Akhieser's results for the spin-lattice relaxation time to room temperature gives a time much shorter than we obtain. The extrapolation is so large, however, that the comparison is probably of little use. Akhieser's remark that the spin system reaches equilibrium in a time short compared to the spin-lattice relaxation time only at very low temperatures is a possible explanation of the discrepancy between the relaxation times obtained by energy absorption methods and by direct observation.

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