Direct Observation of Domain Rotation in Ferrites

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A direct experimental observation of domain rotation in the initial permeability region of sintered nickel ferrite has been made using a technique similar to that originated by F. Bloch to observe nuclear precession. A 5-mm diameter sphere of ferrite is surrounded by crossed transmitter and receiver loops adjusted for minimum rf signal when the sample is demagnetized. Application of an external steady field (as low as 5 oersteds, perpendicular to both loops) then causes a measurable receiver loop output which cannot be eliminated by readjusting the planes of the loops. The motion of the net magnetic moment is thus rotational. In the present case, the external field is needed only to polarize the sphere, the field for Larmor precession being supplied by the equivalent anisotropy fields seen by each individual domain. Since the applied field is much smaller than these anisotropy fields, a plot of the detector loop output (per unit applied field) *vs* frequency delineates the rotational resonance spectrum of the polycrystalline sample. Measurements have been made from 20 Mc/sec to 800 Mc/sec and can be described qualitatively using the theory of domain rotation. In order to understand the relatively low dispersion frequency indicated by the measurements, it is hypothesized that intermediate conditions exist in some polycrystalline ferrites between the situation in which the initial permeability is purely a result of domain rotation and that in which motion of domain walls is the dominant mechanism. The distinction between the models is thus probably not very sharp.

I. INTRODUCTION

THE permeability spectrum of sintered ferrites has been the subject of a number of investigations.[1–6] In all studies previous to that of Rado,[5] the single dispersion of the permeability which was observed in the region of several megacycles to several kilomegacycles was attributed to a natural ferromagnetic resonance in which the domains were considered as precessing in an internal anisotropy field under the influence of external excitation. Wijn *et al.*[7] have also studied the magnetic spectra of ferrites under mechanical stress and have obtained results pointing toward domain rotation as the principal mechanism.

In contrast to this work, Rado has found that the permeability spectrum of Ferramic *A* has two dispersion regions at room temperature, one at about 50 Mc/sec, and the other at 1400 Mc/sec.[8] In this study, the loss peak at lower frequency was ascribed to a resonance of domain walls as suggested by Döring[9] and Becker,[10] whereas the higher frequency one was attributed to domain rotation. This conclusion rested in part on a comparison of the magnetic spectrum of the solid ferrite with the spectrum of the same material measured in powdered form. In the latter case the 50-Mc/sec peak was absent, whereas the 1400-Mc/sec peak remained but in altered form. Rado's identification of the peak at 50 Mc/sec was thus based on the assumption that this resonance, if due to domain rotation in an anisotropy field, would be a fundamental aspect of the material and thus would not be affected by grinding. Its disappearance was thus taken to exclude domain rotation, leaving domain wall motion as the responsible mechanism. Inasmuch as ferromagnetic anisotropy arises from structurally dependent properties (strain and internal demagnetizing fields), as well as from the fundamental magnetocrystalline anisotropy, the argument does not appear entirely convincing. This is especially true in the light of recent work[6,11] in which the magnetic spectrum is found to depend markedly on demagnetizing effects which could certainly be applied either to the sample as a whole or to individual particles within a heterogeneous sample, and which would thus operate differently in a sintered mass and in a powder-wax mixture.

The present writers have studied the magnetic spectrum of nickel ferrite,[6] in an attempt to identify the mechanisms contributing to the initial permeability. As the finely divided and pressed ferrite powder was sintered at increasing maximum temperatures, the single observed loss peak was found to move to lower frequencies. Quantitative comparison of the characteristic frequency of this dispersion with the susceptibility at low frequencies in each case was made using a relation proposed by Snoek[1] and recently analyzed by Park.[12] Agreement between theory and experiment was taken as indicating the existence of domain rotation in the sample studied. Since the polycrystalline grain size was relatively small (0.5 to 3 microns), domain walls were not considered to contribute significantly in the particular comparison made.

The present work originated in an attempt to obtain more direct evidence of the mechanism involved and

[1] J. L. Snoek, Nature **160**, 90 (1947); Physica **14**, 207 (1948).
[2] Brockman, Dowling, and Steneck, Phys. Rev. **77**, 85 (1950).
[3] J. B. Birks, Proc. Phys. Soc. (London) **B63**, 65 (1950).
[4] Welch, Nicks, Fairweather, and Roberts, Phys. Rev. **77**, 403 (1950).
[5] G. T. Rado, Revs. Modern Phys. **25**, 81 (1953); this reference refers to earlier work of Rado and others.
[6] F. Brown and C. L. Gravel, Phys. Rev. **95**, 652 (1954).
[7] Wijn, Gevers, and van der Burgt, Revs. Modern Phys. **25**, 91 (1953).
[8] Principally magnesium ferrite.
[9] W. Döring, Z. Naturforsch. **3a**, 374 (1948).
[10] R. Becker, Physik. Z. **39**, 856 (1938); Ann. Physik (5) **36**, 340 (1939).
[11] D. Park, preceding paper [Phys. Rev. **98**, 438 (1955)] in which a derivation is given of effective values of κ_e and μ_e in terms of their values for bulk material. This paper is hereafter referred to as II.
[12] D. Park, Phys. Rev. **97**, 438 (1955).
[13] Bloch, Hansen, and Packard, Phys. Rev. **70**, 474 (1946).

makes use of a technique similar to the first used by Bloch[13] to observe nuclear precession. By arranging two mutually perpendicular loops around a small sphere of ferrite, an attempt has been made to observe the induction signal which results from precession of the net ferrimagnetic moment in an external steady field. Inasmuch as it is possible to show that wall motions, at least as normally visualized in a multidomain sample could produce no appreciable signal under these circumstances, such a device may be used to demonstrate and measure domain rotation in ferrites.

In the present case the induction signal results from a superposition of individual signals from domains, each of which can be thought to precess independently within its own effective anisotropy field. When a small external steady field is applied to the sample, the magnetic moments of the domains rotate slightly in the field direction giving rise to a magnetic moment for the sample as a whole. However, for small steady fields, the effective field experienced by individual domains does not depart appreciably from its zero external field value, and the natural ferrimagnetic resonance frequencies of the domains remain essentially unaltered. The external field is here employed only to give sufficient polarization to the sample to permit measurement. Under these conditions the signal induced in the secondary loop can be expected to be proportional to the net moment, and thus to the size of the external steady field (for small fields), and is also a measure of the extent to which the net magnetic moment departs from the steady field direction during precession. If the initial susceptibility of the ferrite throughout the radio-frequency spectrum is principally due to domain rotations, the secondary output per unit steady field should be connected in some understandable way with the observed magnetic permeability spectrum of the material. The present work is an attempt to observe this connection.

As to whether or not domain wall motion may give a measurable output from such a device and thus yield ambiguity in interpretation, it is important to notice that for a polycrystalline sample such as that here employed, the individual domains are oriented in random directions, and it can be expected that, if true domain walls actually exist, clockwise and counter-clockwise spin distributions will be found in equal numbers in traversing the walls between domains. Thus even though wall motion may be gyroscopic in nature, the bulk material is isotropic, since for every domain wall oriented in such a way that the composite spins may contribute to the induction signal, there will exist another wall which will induce an equal and opposite signal. It is also expected that the material will respond only in the signal direction, i.e., be nonrotational, even under conditions of partial magnetic saturation, since the only effect of a small steady field would be to move existing domain walls without a net alteration in their number or change in the balance between clockwise and counter-clockwise spin distributions. Therefore even under these conditions the precession of spins within moving walls cannot contribute to the output. The possibility of a signal contribution arising from special conditions of crystalline orientation, strain, inclusions, shapes, or other inhomogeneities which might be expected to affect wall motion can be ruled out, since the present sample may contain 19^9 to 10^{10} domains, assuming a single domain to encompass only one or, at most, two to three crystallites. Microscopic anisotropies are therefore also expected to statistically cancel for the bulk sample.

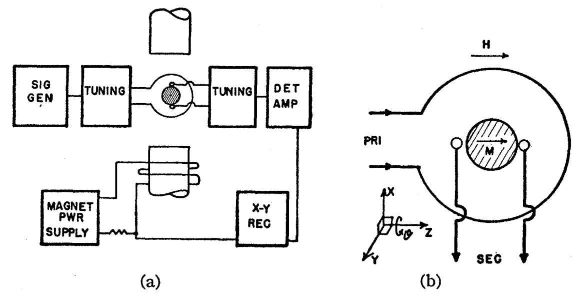

FIG. 1. (a) Block diagram of apparatus for observing domain rotation. (b) Diagrammatic sketch of rf head.

II. EXPERIMENTAL

A. Apparatus

The crossed-coil ferrimagnetic induction device is represented schematically in Fig. 1(b). The primary and secondary coils are normally in the x-z and y-z directions, respectively, and the steady field H_0, used to produce the net magnetic moment, M, is in the z-direction. If it is assumed that domain rotation occurs within the spherical sample, the magnetic moments of domains will each precess in response to an applied alternating field h_y, with the result that M will also precess and induce a secondary signal. To connect the signal with the permeability spectrum of the ferrite thus requires measurement over the entire frequency range of the dispersion.

In the case of nickel ferrite the dispersion occurs between approximately 20 Mc/sec and several thousand Mc/sec, so that it is necessary to make measurements at frequencies where voltages are difficult to determine. This situation is further aggravated by the fact that *effective* values of the permeability components are actually measured, as opposed to values characteristic of infinite media, the demagnetizing effect here involved causing the dispersion region of the material to be removed to much higher frequencies.[6,11] We have therefore used the microwave practice of arranging the measurement in such a way that results are obtained as voltage ratios. This can readily be seen from the following theory of measurement.

As has been shown,[14] a ferrimagnetic material under

[14] D. Polder, Phil. Mag. 40, 99–115 (1949).

conditions of magnetic polarization obeys the relation

$$b_i = \mu_{ik} h_k, \tag{1}$$

where the tensor, μ_{ik}, has the components

$$\mu_{ik} = \begin{bmatrix} \mu & j\kappa \\ -j\kappa & \mu \end{bmatrix}, \tag{2}$$

when the net magnetic moment of the bulk sample, M, is in the z-direction and h is applied in the x-y plane.

In Fig. 1(b), if transmitter and receiver loops are at right angles to each other and parallel to the coordinate planes, Eq. (1) may be written

$$b_x = j\kappa_e h_{y0}, \tag{3a}$$

$$b_y = \mu_e h_{y0}, \tag{3b}$$

where μ_e and κ_e are effective values of the permeability components appropriate to the spherical sample, and h_{y0} is the applied alternating field exterior to the sphere. Under these conditions, the voltage induced in the receiver loop is obtained from (3a) as

$$E_1 = SMnA\omega h_{y0}\kappa_{e1}, \tag{4}$$

where n is the number of secondary turns, A is secondary loop area, and ω is the frequency. The expected dependency of E_1 upon M has been introduced by defining $\kappa_e \equiv M\kappa_{e1}$, and the proportionality constant, S, accounts for the over-all sensitivity of the secondary detection system. S takes account of secondary tuning characteristics, primary-secondary coupling coefficient, detector-amplifier gain and relates the final output meter indication to the actual induced secondary emf. We assume h_{y0} proportional to $e^{-i\omega t}$ throughout the discussion.

On the other hand, if it is arranged that $M=0$ by carefully demagnetizing the sphere, and if the transmitter loop is rotated away from its position perpendicular to the receiver loop by a small angle, θ, the emf induced in the secondary can be derived from Eq. (3b) as

$$E_2 = jS\theta nA\omega h_{y0}\mu_e. \tag{5}$$

It is assumed in (5) that all conditions of measurement are kept fixed as in (4) so that the constants may be eliminated. Defining $e_s \equiv E_1/M$ and $e_\theta \equiv E_2/\theta$, we have

$$e_s/e_\theta = \frac{|\kappa_{e1}|}{|\mu_e|}, \tag{6}$$

where magnitudes only are considered since the two measurements described by (4) and (5) are not related in phase.

Using Eq. (6) and values of $|\mu_e|$ as calculated from the independently determined permeability spectrum,[11] values of $|\kappa_{e1}|$ are obtained at each frequency. It is this quantity which has been chosen for comparison with theory, both because it is unique to domain rotation, as distinct from domain wall movement, and because it is a quantity which has already proven interesting in describing the ferromagnetic Faraday effect.

With the measurement procedure as outlined by Eq. (6), it is possible to reach frequencies at which ordinary loops cannot be used since all spurious effects which may occur can be made to cancel, provided the measurement is restricted to small values of M, and provided θ is so small that the conditions described by S are actually fixed throughout and can thus be eliminated. In the present case a single turn was used for both primary and secondary circuits, which were mounted directly between the poles of a small laboratory electromagnet. The secondary was wound tightly around the 5-mm diameter sphere of nickel ferrite and was cemented in place. The primary loop, diameter 1.0 cm, was mounted in a polystyrene holder and pivoted between the magnet poles. Its angle was adjustable by means of a 30-cm attached lever arm and micrometer screw. It is important to recognize that even though the loops can and do undergo self-resonance, and although primary-secondary capacitive coupling may be noticeable, the ratio procedure used nevertheless permits a measurement to be made. Inability to tune the loops affects the measurement only by reducing sensitivity.

The remainder of the apparatus is straightforward and is indicated schematically in Fig. 1(a). It was found necessary to include provision for tuning the magnet to 60-cycle series resonance in order to demagnetize the specimen thoroughly. Initial attempts by successive dc current reversals were unsuccessful, since it was difficult to avoid a small erratic residual magnetization from interfering in the application of Eq. (3b).

B. Operation

With the arrangement described, it has been possible to observe quite sizable signals. For instance employing 20 milliwatts of rf, the minimum leakage signal is about 1 μv (crystal output at 1 kc/sec modulation frequency) with the sphere demagnetized. Application of a steady field, sufficient to cause appreciable saturation, then causes the detector output to rise as high as a millivolt. It has, in addition, been possible to make measurements with steady fields as low as 5 oersteds external to the sphere indicating that the induction device can yield sensitivities adequate to permit study of effects in the initial permeability region.

The qualitative behavior of the observed signal for various loop angle adjustments is particularly significant in the present experiment, since it yields direct evidence of rotation independent of theoretical comparisons. When a steady field is applied and the comparisons. When a steady field is applied and the output signal rises above its minimum leakage value, it has been found impossible to reduce the signal to its original value by readjusting the planes of the loops. The changing rf field responsible for the induced signal must therefore have components in both time and space quadrature, i.e., be rotational; if the inducing field were plane polarized, it could still be reduced to a minimum by proper loop-angle readjustment. The behavior thus cannot be explained by assuming a change in minimum leakage conditions, and the rotating rf field is thus probably attributable to the precessional nature of the polarized ferrite. In making measurements we have further found that changes in sample permeability resulting from partial saturation do not alter the tuning characteristics of the loops. Both primary and secondary have been broadly enough tuned so that the small changes in permeability do not appreciably change tuning conditions.

In making use of Eq. (6) to determine the ratio $|\kappa_e|/\mu_e|$ and thus $|\kappa_e|$ as a function of frequency,[11] the following procedure should apply under ideal operating conditions. With the loops adjusted to such an angle that a null signal results, the dc field is applied and the output indication per unit field, e_s, recorded. Then, with the sphere completely demagnetized and all other conditions unchanged, e_θ is measured by recording the output signal per unit angle as the primary loop is moved away from its normal position. Equation (6) may then be applied.

However, it has been found impossible in practice to reduce the minimum leakage signal to an absolute null. Experience has been similar to that described[12] in the case of nuclear induction in that voltages induced by currents flowing in surrounding conductors (pole faces, shields, etc.) may have a component out of phase with that resulting from the desired loop pick-up. In the present case, however, the signal from the ferrite is comparable with the leakage so that the total output, including both leakage and true signal, is not a linear function of the true signal itself. In order to obtain an output proportional to the voltage induced by the ferrite, a vector subtraction has been performed to eliminate the leakage voltage. This can be seen in Fig. 2(a) where the leakage voltage resulting after adjustment of the planes of the loops is shown as the

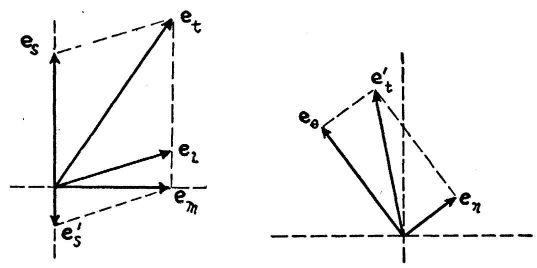

FIG. 2. Ac vector diagrams showing correction for effects of leakage signal. In (a) leakage is indicated by e_l, the desired precession signal by e_s, and the total observed signal by e_t. In (b) e_n is the residual leakage, e_θ is the signal induced by loop angle deflection, and their result is shown as e_t'.

ac vector e_l. Here e_l represents the minimum leakage obtainable for zero M by adjusting the relative loop angle. In practice it has been found that the total output signal becomes larger than e_l when M is increased from zero in one direction, whereas in the opposite direction the output at first decreases and then rises as before. In order to account for this behavior, it has been assumed that e_l remains fixed for all values of M encountered in the measurement, and that the output signal is composed of e_l plus a signal due to the precession of M. In Fig. 2(a) the situation is represented by showing the precession signal as e_s along the vertical axis and the leakage, e_l, at an arbitrary phase angle. The observed behavior can then be understood if it is noted that e_s is along the positive vertical axis for values of M of one direction but must be represented as e_s' along the negative vertical axis, i.e., be 180° out of phase with e_s, for values of M in the other. Since e_l has been assumed fixed, for one polarity of M the total output initially increases as shown by e_t, whereas for reversed values of M (and induced signals e_s') the total output at first decreases. The minimum value of total signal mentioned above can thus be seen to occur when the signal vector is at right angles to e_s and e_s'. This is indicated as e_m in the figure. Since it is the precession signal, e_s, which is desired for comparison with the theory of domain rotation, the correction for the contribution of e_l must be made as follows:

$$e_s=(e_t^2-e_m^2)^{\frac{1}{2}}-(e_l^2-e_m^2)^{\frac{1}{2}}. \qquad (7)$$

In this way values of e_s have been obtained for use in Eq. (6).

The procedure for correcting e_θ is somewhat similar to that just outlined. In this case M is kept zero for all loop angles, and the minimum leakage can be represented as e_n of Fig. 2(b). Again, if it is assumed that the leakage signal is independent of loop angle for small changes in angle, the observed output signal, shown as e_t', can be assumed to be comprised of e_n plus the desired signal e_θ. The correction for leakage is therefore

$$e_\theta=[(e_t')^2-e_n^2]^{\frac{1}{2}}. \qquad (8)$$

It is noted that the leakage vector e_l of Fig. 2(a) is identical with e_n of Fig. 2(b) although otherwise the two diagrams are independent.

In practice the use of the correction formulas (7) and (8) has led to values of e_s and e_θ which are proportional to the steady field, H, and to the loop angle (for small angles) respectively. This proportionality has been taken as evidence to justify the assumed leakage corrections.

Before describing the results obtained at various frequencies, it is of interest to consider qualitatively the output signal from the apparatus when the ferrite is not close to the demagnetized state, as above, but approaches magnetic saturation. As indicated in Fig. 1(a), an x-y chart recorder has been used during part of the work to aid in making adjustments. The arrange-

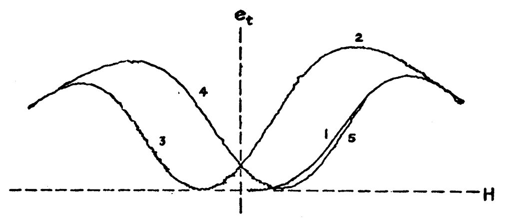

FIG. 3. Tracing from original x-y recorder chart showing total output of magnetic induction apparatus for various applied steady fields extending into region of saturation. Starting from demagnetized state (origin) the branches were numbered in sequence as recorded.

ment makes it possible to plot the output signal, designated as e_t in Fig. 2(a), for various magnet currents.

Starting at the origin in Fig. 3 (demagnetized condition) the output at first increases (curve 1) with applied field in a manner similar to the normal magnetization curve. However, when the external field approaches saturation, the effect of increasing net moment and attendant augmented signal is overcome by the shift in ferrimagnetic resonance frequency which accompanies the applied field. The latter effect tends to remove the dispersion region from the proximity of the measurement frequency toward the microwave region causing the precession of M at 50 Mc/sec to be considerably reduced. The maximum in branch No. 1 of Fig. 3 thus represents a balance between the two effects. Returning to lower applied fields along branch No. 2, a typical hysteresis pattern is apparently superimposed on the resonant frequency shift just mentioned. Back at zero applied field, the remanent magnetization (associated with the spherical sample as opposed to that of the infinite medium) yields a very noticeable signal as shown. Following branch No. 2 for reversed fields, the output drops to a value close to that associated with the initial completely demagnetized state. This occurs at the coercive field. The parabolic shape of the output signal around this point results from the square law response of the crystal. Branch No. 3 is also positive, since magnitudes only are observed. The rest of the hysteresis loop, branches No. 4 and 5, are similar to No. 1 and 2 with the exception that branch No. 4 does not rise as high as No. 2. We attribute this to the effect of leakage which may add to signals of one sense but subtract from those of the other.

C. Results

The qualitative results of this work have already become apparent from the description of operation. Essentially they are that an observable signal is induced in the secondary loop when a state of steady polarization is produced in the sample. When corrected for the effects of leakage, this signal has been found to be proportional to the applied field for fields such that the ferrite remains in the region of initial permeability. Under conditions of partial magnetic saturation, it has been found impossible to restore the minimum leakage signal achieved under demagnetized conditions. This behavior is consistent with the assumption of a precessing net magnetic moment, and has been associated with the precession of elementary domains comprising the net moment. On the other hand it has been found difficult to picture a way in which domain walls, as generally conceived, may produce the observed effect. The argument is essentially that the large number and random distribution of domain walls, if they were to exist in a polycrystalline sample, would cause cancellation of gyromagnetic effects and prohibit the formation of a rotating magnetic moment, an essentially cooperative phenomenon. If it is also assumed that the only effect of applying a steady field to the sample is to move the position of domain walls without changing the direction of spins within the domains (no domain rotation), then the bulk material must respond isotropically to an applied rf field and no induction signal could be observed. The qualitative behavior of the apparatus thus points toward domain rotation in the initial permeability region and discourages the concept of conventional domain walls as the sole contributing mechanism.

Quantitatively we have attempted to relate the size of the induction signal obtained to the predictions of the theory of domain rotation as given in II. To do this we have multiplied the observed values of $|\kappa_{e1}|/|\mu_e|$, as obtained from Eq. (7) for each frequency, by $|\mu_e|$ as obtained from a separately determined permeability spectrum of the material. Here $|\mu_e|$ is an effective permeability of the spherical sample obtained from the true permeability components, μ_a' and μ_a'' using the procedure of II. Thus $|\kappa_{e1}|$, again an *effective* permeability component, is obtained for the spherical sample. It represents the x-component of B produced by a y-component of H *external* to the sphere. The procedure of II may again be employed to obtain $|\kappa_a|$ from $|\kappa_{e1}|$, and this in turn may be compared with theory. $|\kappa_a|$ is the off-diagonal permeability component for an infinite magnetically saturated medium.

In Fig. 4 the values of $|\kappa_a|/M$ determined in this way have been plotted as a function of frequency, and it can be seen that they are approximately proportional to frequency at low frequencies and that a rather broad maximum is reached around 200 Mc/sec. At higher frequencies the extent of the internal precession, as measured by $|\kappa_a|/M$, appears to drop off slowly. The large errors indicated around the experimental points arise principally from uncertainties in magnetic field measurements, but are increased by the conversion from effective to true values of μ and κ, using the procedures of II, and by mechanical instabilities in the apparatus. In certain cases, a number of independent determinations have been made to test reproducibility and the average of such readings has been used. The points at 250, 400, and 600 Mc/sec were obtained this way, and the errors plotted represent the spread of individual measurements.

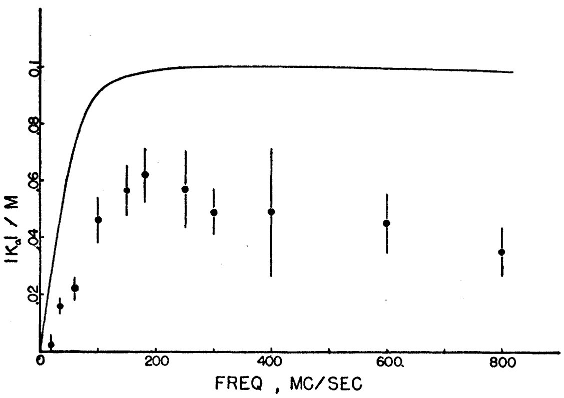

FIG. 4. Off-diagonal permeability component, $|\kappa_a|$, per unit magnetic moment *vs* frequency. Points are from present experiment on nickel ferrite, curve is from theory of domain rotation.

III. DISCUSSION

Also in Fig. 4 we have plotted theoretical values of $|\kappa_a|/M$ as obtained from Eq. (29) of II. The theory is based on an assumed frequency distribution of crystallites characterized by four parameters. Values of these parameters have been taken from the ordinary permeability spectrum of the particular nickel ferrite used in the experiment. Since the toroidal sample used to measure the magnetic spectrum and thus determine the parameters to be used in the theory had experienced similar but not identical processing to that experienced by the material used in our spherical sample, and since processing, particularly firing temperature, is very important in establishing the high-frequency characteristics of the material, the numbers chosen for insertion in the theory may be subject to error. They have, nonetheless, been used in order to compute the theoretical values shown.

In general, the experimental data agree qualitatively with prediction in that in both cases a distinct "knee" occurs at around 200 Mc/sec followed by a gradual decrease in $|\kappa_a|/M$ at higher frequencies. Although not shown in Fig. 4, the corresponding values of a μ'' as measured for the particular nickel ferrite here used also goes through a maximum close to this frequency; this is consistent with the domain rotation hypothesis in that the frequency at which the domain magnetic moments precess most strongly will also be the frequency at which the losses are greatest. This is clearly shown in Figs. 2 and 3 of II.

We cannot, however, attach any special significance to the factor of two discrepancy between theory and experiment. There are a number of ways in which it might be understood. As stated earlier, we have applied a correction factor giving $|\kappa_a|$ from the actually measured $|\kappa_{e1}|$ values. This amounts to a factor of the order of 20 which is quite sensitive to the choice of demagnetizing factor. In our case, we have assumed the rf field of the circular primary loop to be equivalent to a uniform field, since the sample diameter was less than half that of the primary. This assumption is only approximately valid and the resultant error might be included in the value of demagnetizing factor used to get $|\kappa_a|$ from $|\kappa_{e1}|$. Further, the theoretical curve represents a calculation which has been found to be most applicable in cases where the ferrite is sintered at a slightly lower temperature than the sample here used. There are therefore a number of considerations requiring further experimental study before any detailed quantitative comparison is possible. The qualitative results, however, clearly indicate the existence of domain rotation.

Possibly the most striking feature of the above results is the relatively low frequency at which this domain rotation in an equivalent internal anisotropy field appears to exist. This is striking because measurements on single crystals of nickel ferrite show the internal magneto-crystalline anisotropy field to be around 300 oersteds, corresponding to a natural ferrimagnetic resonance frequency of about 900 Mc/sec, using effective g-values and the fact that the bulk anisotropy field governs the precession of the two-sublattice ferrite.[15] Ordinarily one would expect the other contributions to the equivalent anisotropy of crystallites to *increase* this value rather than to decrease it making it hard to reconcile the present observations of a rotational resonance at 200 Mc/sec with other findings on single crystals.

In order to understand this discrepancy, it is important to distinguish clearly between the behavior of single crystals and that of the polycrystal we have studied. On a microcrystalline scale, a single crystallite may be subject to quite inhomogeneous demagnetizing fields, resulting from neighboring crystallites, of the order of the natural magneto-crystalline fields themselves. Thus the thickness of a domain wall, as ordinarily considered, may be quite different from that calculated for a single crystal. In fact the crystallites of our sample, being of the order of 1 to 3 microns in size, may well be of transition size between very small crystallites around a half micron where pronounced single domain behavior can be expected and larger sizes where a genuine multidomain situation exists. By using the procedure of Herring and Kittel,[16] the domain wall thickness in a large single crystal is found to be around a tenth micron. However, if an appreciable volume fraction of each crystallite contains spins directed away from directions of easy magnetization, as may be the case if the crystallites are of transition size, the magnetization of the crystallite as a whole may experience an average effective internal field much smaller than the 300 oersteds found in the very special case of a macroscopic single crystal. The dispersion region of such a polycrystal may thus occur at frequencies well below the expected 900 Mc/sec.

[15] F. Brown and D. Park, Phys. Rev. **93**, 381 (1954).
[16] C. Herring and C. Kittel, Phys. Rev. **81**, 869 (1951).

The hypothesis here considered thus removes the clear distinction between domain wall motion and domain rotation as the mechanism responsible for high frequency dispersion. It permits a large domain rotation effect to exist and cause natural ferrimagnetic resonance at relatively low frequencies as found here and elsewhere[1,6] and which is attributed to rotation of spins within regions of inhomogeneous magnetization. However, these inhomogeneous regions themselves may also be thought of as incipient domain walls which undergo resonant response in the applied rf field. If one accepts the above picture, it is possible to understand those cases where two distinct dispersion regions exist in the high-frequency magnetic spectrum of a ferrite[5] without introducing additional mechanism. Such materials may be thought of as those in which the polycrystalline sizes and magnetic parameters are such that genuine domain walls can form and respond in the manner usually visualized. However, in cases such as that studied here and elsewhere,[1,6] where only a single dispersion region may exist, conditions can be considered such that multidomain structures are only slightly approached, the largest contribution to initial permeability being from domain rotation. In this way it seems quite possible that the theory of domain rotation can achieve the observed degree of confirmation even when applied to magnetic spectra also describable in terms of moving domain walls.

IV. CONCLUSIONS

From this study it is possible to conclude that a phenomenon describable in terms of domain rotation definitely exists in the sample of nickel ferrite we have studied. This conclusion rests solely on the qualitative behavior of the ferrimagnetic induction apparatus. Quantitative application of domain rotation theory further yields a favorable comparison of gross features of the observations. In attempting to understand the existence of a natural ferrimagnetic resonance dispersion at frequencies as low as the presently observed 200 Mc/sec, it is suggested that a transition region between pure domain rotation and pure domain wall motions may exist in polycrystalline samples within which region a ferrite may exhibit aspects of both mechanisms. To this extent, the distinction between the two mechanisms becomes less physical than previously considered, and the high-frequency magnetic behavior of ferrites can be understood only after careful consideration of internal polycrystalline structure.

Note added in proof.—The present experiment cannot distinguish the situation in which domain wall motions throughout the sample are distributed in space and time quadrature so as to simulate the effects of domain rotation. Such a situation could occur, however, only if the walls were excited through coupling with domain rotation in agreement with the above conclusions.