180-kv x-rays and interpreted a broad intense peak ($g=2.020$) as due to V centers, while ascribing a subsidiary resolved set of lines to the hyperfine structure of F centers.

We have studied the magnetic resonance in LiF single crystals, with some samples irradiated by x-rays at 50 kv and others bombarded by a cyclotron proton beam at approximately 360 Mev. The sample, usually less than 0.4 cc in volume, is placed on one end plate of rectangular cavity, oscillating in the TE_{011} mode and resonating at the frequency of a stabilized klystron around 9130 Mc/sec. The signal showing the magnetic resonance is derived from a modulation of the static field at 400 cps. The resonance is exhibited either in the form of the derivative of the absorption curve or in the form of the dispersion effect shown by the shift in the resonance frequency of the cavity. The steady magnetic field, measured by a proton resonance probe, is varied slowly through the resonance value while the signal is being recorded automatically. All our experiments have been carried out at room temperature.

In each of our samples a single, broad, approximately Gaussian, resonance peak has been observed. The signal-to-noise ratios ranged from about 30 for an x-rayed sample to 500 for a proton-bombarded sample. No resolved hyperfine structure lines have been detected in any of our recordings. The g factor calculated from a large number of recorded curves is $g=1.999 \pm 0.001$ for the x-rayed samples, and $g=2.002 \pm 0.001$ for the proton-bombarded ones. As a simple measure of the absorption line width, we use the field separation between two points of maximum slope, designated here as ΔH_m. The value of ΔH_m for a given resonance curve is obtained by extrapolating to zero field modulation. The observed values of ΔH_m are 65 oersteds for the x-rayed samples and 110 oersteds for the proton-bombarded samples. Both the g factor and the line width have been shown experimentally to be independent of the concentration of the color centers for samples subjected to the same kind of radiation. Consequently, the effects of dipolar interaction appear to be negligible.

Using the approximate theory of Kahn and Kittel,[3] one can show that the g factor for an F-center resonance in LiF should be smaller than the free electron g by not more than about 10^{-5}. This prediction agrees with the g value obtained for the proton-bombarded sample, but not with the g value of the x-rayed sample.

Kip *et al.*[4] assumed the line width to be caused by hyperfine interactions and predicted a nearly Gaussian shape for the envelope of the hyperfine components. They showed that the width of the envelope at half-maximum ($\Delta H_{\frac{1}{2}}$) was $1.12\xi A$ cm^{-1} for a nuclear spin of 3/2. Here ξ is the fractional effective s character of the valence electron and A is the hyperfine interaction constant. For Li^7 (95 percent abundant), we have $I=3/2$ and $A=0.0134$ cm^{-1}.[5] This gives $\Delta H_{\frac{1}{2}}=161\xi$ oersteds. Our experimental values of ΔH_m give $\Delta H_{\frac{1}{2}}=76.5$ oersteds for the x-rayed sample and 130 oersteds for the bombarded sample if Gaussian line shape is assumed. This would require $\xi \approx 0.5$ for the x-rayed sample if the resonance is to be attributed to F centers. Such a value for ξ seems to be reasonable for Li^7. The value $\xi \approx 0.8$ required to account for the line width of the proton-bombarded sample appears to be somewhat high. It is to be noted, however, that Hutchison has also observed a line width of approximately 160 oersteds for his neutron-bombarded sample.

The results on the x-rayed LiF strongly favor the F center interpretation. The g factor is less than the free electron value and the line width agrees well with the theory of Kip *et al.*[4] for F centers. While this evidence does not exclude the presence of other one-electron color centers, it does eliminate any sizable contribution from V centers. The case of the proton-bombarded LiF is far less clear cut. It may be that the resonance is still due to F centers with their environment drastically changed by heavy particle bombardment. It is also conceivable that the contributions of M centers, R_1 centers, and possibly other one-electron centers are large enough to affect the line shape.

We wish to thank Miss M. C. Williams, Jr., for preparing the x-rayed samples and Dr. W. J. Leivo of the Carnegie Institute of Technology for the proton-bombarded samples. We are also indebted to B. S. Gourary and S. N. Foner for some stimulating discussions.

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Measurement of the Complex Tensor Permeability of Ferrites

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Artman and Tannenwald[1] have described a method for determining the components of the permeability tensor of a ferrite by measuring the frequency shift and change in Q produced by the insertion of a small spherical sample in a degenerate-mode cavity. The cylindrical TE_{111} mode cavity permits splitting of the cavity resonance into two frequencies corresponding to the resonance of the cavity for each of the counter-rotating circular components of the incident linear polarization. We have found that there are several advantages to be gained by using a very thin disk in a similar cavity. Not only is it possible to pro-

duce larger effects without violating the basic assumptions of the perturbation theory but the results obtained can more readily be interpreted in terms of the intrinsic properties of the material.

In a sphere placed in a uniform field, H^0, the internal field, H^i, is determined from the boundary conditions to be:

$$H^i = H^0 - 4\pi M/3.$$

If we write the perturbation equations in terms of this internal field and assume a tensor permeability, we find that the frequency shift in a degenerate cavity is given by

$$\frac{2\delta\omega}{\omega_0} = \frac{[(\mu-1)(\mu+2)-K^2]C_1}{(\mu+2)^2-K^2} \pm \frac{KC_2}{(\mu+2)^2-K^2}, \quad (1)$$

where the $\pm$ sign refers to the two senses of circular polarization, where C_1 and C_2 are constants of the geometry, and where μ and K are the components of the *intrinsic* permeability tensor. An alternate procedure sometimes suggested refers to Kittel's[2] equation of motion for magnetization to show that all the demagnetization factors cancel out for a spherical sample. Then, one can write

$$2\omega/\omega_0 = (\mu_1-1)C_1 \pm K_1C_2 \quad (2)$$

and expect μ_1 and K_1 to be the same functions of H^0 as μ and K are of H^i. Where Polder's[3] relations hold, it is sufficient to measure the quantities μ_1 and K_1 as functions of H^0 and state that the curves so obtained also represent the behavior of the intrinsic parameters, μ and K, as functions of H^i.

In a polycrystalline ferrite, however, it is hardly reasonable to expect Polder's equations to hold exactly, and one must use Eq. (1) to determine the intrinsic parameters precisely.

It will be observed that Eq. (1) is not a sensitive way to determine μ and K when $(\mu+2)^2-K^2$ is small. This is a region of great interest where $H^0 \approx \omega/\gamma$, $H^i \ll H^0$, where γ is the gyromagnetic ratio. Furthermore it is difficult to separate the imaginary parts of μ and K so that they may be related to the measured changes in the Q of the cavity. Thirdly, one must use spheres no more than 0.020 inch in diameter in order to obtain a uniform internal field. Such spheres produce very small effects at fields far from resonance.

Through the use of a disk all of these difficulties are avoided. At the end wall of a TE_{111} mode cylindrical cavity there are only transverse components of H, namely H_θ and H_r. If a very thin disk is placed against the end wall, we may state with good accuracy that $H_\theta{}^i = H_\theta{}^0$ and $H_r{}^i = H_r{}^0$ while $H_z{}^i = H_z{}^0 - 4\pi M$. Then the frequency shift is given by

$$2\delta\omega/\omega = (4t/\lambda_g{}^3)\lambda^2(\mu-1)R_1 \pm KR_2, \quad (3)$$

where R_1 and R_2 are constants of the geometry and t is the thickness of the disk. The free-space wavelength is λ and λ_g is the guide wavelength. Here μ and K are intrinsic properties of the medium which relate the true *internal* **H** to *internal* **B** and which are measured as functions of a known *internal* dc field: $H_z{}^0 - 4\pi M$.

In this relationship it is easy to treat $\delta\omega$ as complex and determine real and imaginary parts of μ and K.

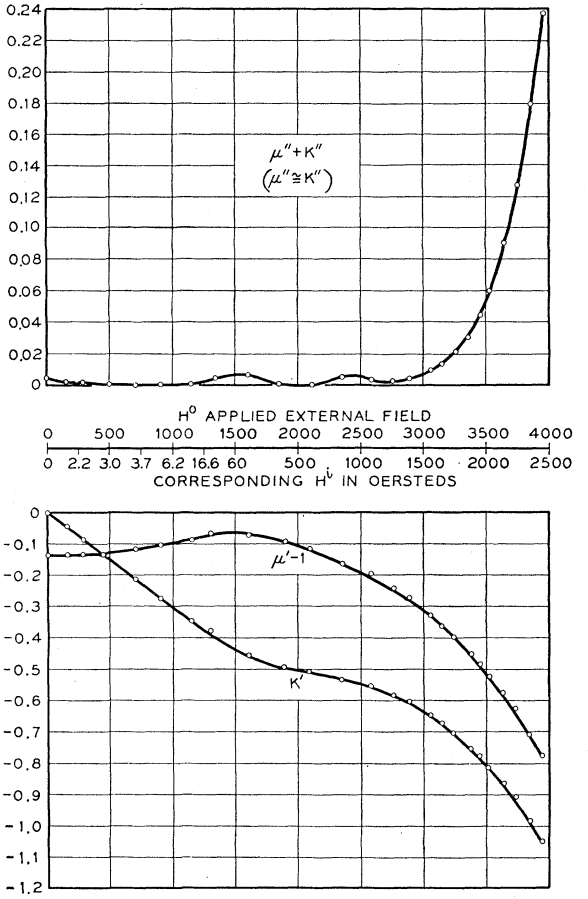

FIG. 1. Complex μ and K as functions of external and internal static fields. $\mu = \mu' - j\mu''$; $K = K' - jK''$. B.T.L. Ferrite No. 2089. $\epsilon = 8.7 - j(2\times10^{-4} \pm 2\times10^{-4})$.

Because of the relatively large volume of material it is possible to measure values of $(\mu''+K'')$ as small as 0.0004 if one can measure Q to within 2 percent. Since the thickness (order of 0.010 in.) is the only dimension over which the field is assumed constant there is no loss of validity if the disk diameter approaches the cavity diameter. To verify this several measurements were made in which diameter and thickness were varied, and good agreement was obtained as long as the ratio of diameter to thickness was very large. The only limitation thus far encountered is a difficulty in obtaining disks thin enough to permit measurements at ferromagnetic resonance where a thick disk absorbs so much power that the cavity resonance disappears.

In Fig. 1 we show a sample of data obtained in the low-field region. Both real and imaginary parts are

shown. These are plotted against the applied field and the corresponding values of internal field as determined from an experimental $B-H$ curve are shown on the auxiliary scale. The extra absorption peaks are repeatable and are being investigated in detail.

By placing the disk at the center of the cavity at the electric field maximum we obtain the real and imaginary dielectric constant of the same sample.

We should like to thank Dr. A. M. Clogston for his assistance in this investigation.

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Hollow Dislocations and Etch Pits

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Some time ago Frank[1] showed that dislocations having large Burgers vectors should be hollow. The present letter considers the conditions necessary to open up any dislocation (forming an etch pit) by placing the crystal in an undersaturated medium. The idea is simply to generalize Frank's analysis (limited to equilibrium conditions) to the general case of growth or evaporation. Let us consider a crystal containing a hollow dislocation of radius r and Burgers vector b. The crystal is *not* in equilibrium with the surrounding medium, and the decrease in free energy of the system by the formation of a unit volume of crystal (supposed perfect) is ΔG_v. If $\Delta G_v>0$, the crystal is growing; if $\Delta G_v<0$, the crystal is evaporating.

Then an increase by dr of the radius of the hollow will produce a change dG in the free energy of the system, per unit length of dislocation, equal to

$$dG=\Delta G_v 2\pi r dr+\gamma 2\pi dr-(\mu b^2/8\pi^2 r^2)2\pi r dr,$$

where γ is the crystal-medium surface energy, and μ the shear modulus. The value of r satisfying the condition $dG/dr=0$ will correspond to a steady state situation where the radius of the hollow remains constant, while the crystal grows or evaporates. This value of r is given by

$$r=\tfrac{1}{2}\rho_c\{[1+4(r_0/\rho_c)]^{\frac{1}{2}}-1\},$$

where $\rho_c=\gamma/\Delta G_v$ is the critical radius for two-dimensional nucleation on the surface of the crystal and $r_0=\mu b^2/8\pi^2\gamma$ is the radius of the hollow when the crystal is in equilibrium with the surroundings.

If $\rho_c>0$ ($\Delta G_v>0$), the hollow tends to close up as ρ_c decreases (ΔG_v increases). If $\rho_c<0$ ($\Delta G_v<0$), the hollow tends to open up giving a steady-state solution as long as $|\rho_c|$ is larger than the critical value $|\rho_c'|$ given by

$$\rho_c'=-4r_0.$$

For larger undersaturations the surface energy is not large enough to keep a constant radius for the hollow, and the etch pit is formed. If the surrounding medium is either vapor or dilute solution, $\Delta G_v=(kT/\Omega)\ln(p/p_0)$, where Ω is the molecular volume and p_0 the saturated pressure or concentration; the critical undersaturation ratio p_0/p_c is then given by

$$\ln(p_0/p_c)=2\pi^2\gamma^2\Omega/kT\mu b^2. \quad (1)$$

There is qualitative evidence for the critical opening up of a dislocation in the dissolution of CdI_2 crystals where the Burgers vectors are quite large (for instance, in the General Electric motion picture film). More quantitative experiments to test formula (1) would be worthwhile. Concerning the formation of etch pits in dislocations of small Burgers vectors, it is clear that this is only possible in a medium in which γ is considerably below the value corresponding to the free surface of a crystal.

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Ferromagnetic Resonance in Iron-Nickel Alloys*

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An anomalous sharp dip in the g value of iron-nickel alloys in the range of 30 to 50 percent nickel in colloidal suspensions has been reported by Bagguley,[1] the g value for 40 percent nickel falling to 2.01. Ferromagnetic resonance experiments have been made on disk-shaped bulk samples in an effort to verify this variation in g value with changing nickel concentration. Wavelengths of 6 mm, 1.2 cm, and 3 cm were used. Little or no variation in g value was observed in the four samples of varying nickel concentration investigated.

Disks 0.450 in. in diameter and about 0.010 in. thick, prepared from cold-rolled strip recrystallized at 1080°C for four hours, were polished with jewelers rouge, annealed in vacuum for two hours at 800°C, cooled slowly, and electropolished in a hot phosphoric acid-chromic acid solution. A small hole was drilled in the wall of a rectangular microwave cavity and the samples were clamped firmly to this wall. The 3-cm and 1.2-cm experiments were made using a reflection-type cavity forming one arm of a magic-T bridge. In the 6-mm experiments a crystal harmonic generator driven by a $2K33$, K-band klystron was used as a