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Ferromagnetic resonance was measured in both a swept frequency mode of operation, in which the magnetic field was fixed, and a field swept mode, using field modulation techniques. Single-crystal spheres of 0.381, 0.305, and 0.483 mm in diameter were inserted in the waveguide and transmission was observed in the measurement. The g values for all the spheres averaged to 2.052 ± 0.011 and the uniaxial anisotropy field was 16.4 kOe. Our measurements show that the linewidth of barium ferrite is nearly independent of resonant frequency from 48 to 105 GHz. This is in disagreement with the Kasuya–LeCraw two-magnon–one-phonon mechanism, which would predict a linewidth linear with the resonant frequency. Previous measurements [J. Magn. Magn. Mater. **54-57**, 1141 (1986); IEEE Trans. Magn. **MAG-22**, 984 (1986)], however, show a strong temperature dependence, which rules out magnon scattering from static defects as the primary contributor to the intrinsic linewidth. These results are consistent with a single scattering process in which the uniform precession magnon is scattered into the continuum of magnons by time-dependent fluctuations of the trigonal symmetry ion between two equilibrium sites on either side of the mirror plane [J. Appl. Phys. **63**, 3350 (1988)]. This process differs from the usual two-magnon scattering in that the scattering mechanism is time dependent, and, therefore, the magnon frequency need not be conserved in the process.

I. INTRODUCTION

There has recently been a resurgence of interest in ferromagnetic resonance (FMR) linewidth measurements of barium ferrite. This interest has been sparked in part by the need for nonreciprocal microwave components operating at the millimeter wave frequencies. High-quality single crystals have been prepared by various laboratories. The FMR linewidth in single-crystal spheres of barium ferrite have been found¹ to be sufficiently narrow to warrant further investigation. The temperature dependence¹ of the FMR linewidth is linear from 77 to 300 K at a frequency of 56.1 GHz. There are a few measurements of the frequency dependence over a limited frequency range. We have measured the frequency dependence of the linewidth ($\Delta\omega$) over a range from 48 to 105 GHz (which is a much larger range than has been measured in the past). We believe that both the temperature and frequency dependence of $\Delta\omega$ are needed to estimate the various contributions to it.

II. EXPERIMENTAL RESULTS

The investigation of the FMR linewidth has been carried out for three highly polished barium ferrite spheres of diameters 0.381, 0.305, and 0.483 mm (which are the samples which were measured in Ref. 1). The linewidth was measured as a function of resonant frequency at room temperature over the frequency ranges 40–60 and 75–110 GHz. Each sample was sealed in a capillary tube and placed at the bottom of the waveguide (whose short dimension was in the horizontal direction) which in turn was placed in a static magnetic field (which is perpendicular to the rf field) of up to 20 kG. A detector was connected at the transmission end

of the waveguide. The experimental setup is shown schematically in Fig. 1. The transmitted power at or near the resonant field was normalized with respect to that at zero magnetic field. Several sample resonances for the 0.483 mm sample (which are typical of the resonances for all samples) are shown in Fig. 2. The quoted linewidths are the half-widths of the resonance absorption dips. The resonant frequency was found to be a linear function of the applied field H , displaying a g factor of 2.052 ± 0.011 which implies that we have been following the uniform mode or at least a single magnetostatic mode throughout the frequency range of our measurements. The measured linewidth should be the same in either case. In order to check our work, we have repeated the measurements using field modulation with lock-in detection of the output signal. In Fig. 3 the half-width obtained by both techniques is shown as a function of frequency. It appears to be independent of frequency, remaining at a value of about 80 MHz. Previous results^{1,2} imply a linear frequency dependence. At the present time we cannot resolve this apparent difference. The fact that the linewidths measured for the samples that we have studied are among the smallest

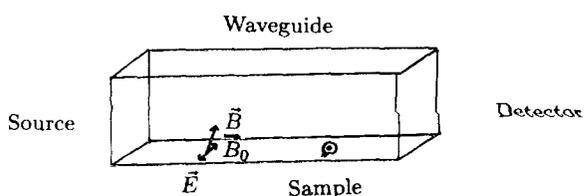


FIG. 1. This is a schematic sketch of the experimental setup.

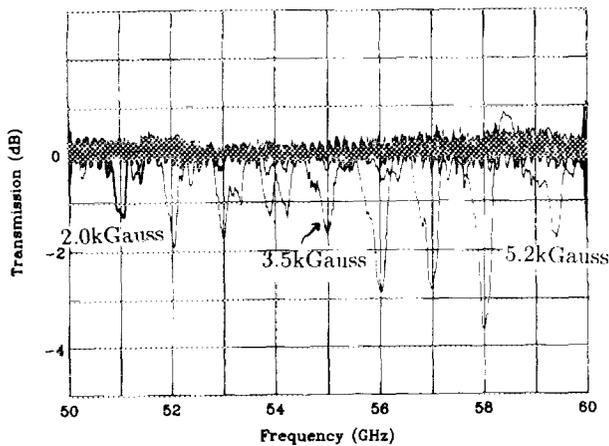


FIG. 2. Several absorption resonances are displayed as a function of frequency in the range 50–60 GHz. Each transmission minimum corresponds to a different value of the applied field (i.e., the spectra for different fields are superimposed on each other), where the minimum at 51 GHz corresponds to 2 kG, that at 55 GHz to 3.52 kG, and the minimum at 59.4 GHz corresponds to a field of 5.2 kG.

linewidths measured for barium ferrite, however, lends credence to our results.

III. DISCUSSIONS AND CONCLUSIONS

We have not applied any radiation corrections like those done in Ref. 2. If we had done so, however, they would only have amounted to a few percent because the absorbed power is only a few percent of the incident power. This procedure will be further justified in this section by solving the problem of scattering of electromagnetic radiation in the waveguide by a spherical sample inside the waveguide. The case of cylindrical samples of width small compared to the width of the waveguide but length comparable to the waveguide width has been considered in the past.³ In our case the sample is spherical and its radius is small compared to both the wavelength of the radiation (outside the sample) and the dimensions of the waveguide. This problem can be solved using the dipole approximation for radiation from a source

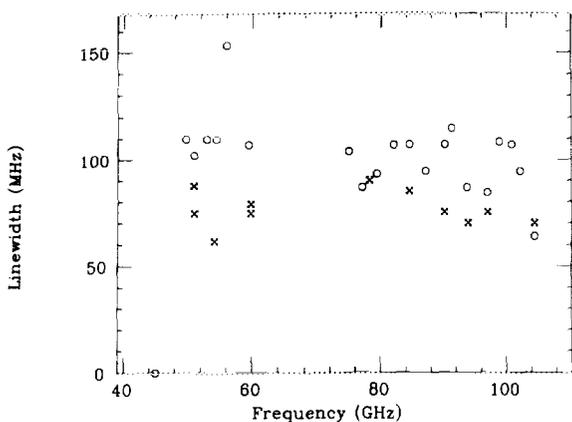


FIG. 3. The FMR linewidth (in MHz) is shown as a function of the resonant frequency (in GHz). The open circles are the results of direct measurement of the linewidth from the frequency swept spectra, and the x's represent the linewidths found from the field swept spectra by the field modulation technique.

of small dimensions inside of a waveguide.⁴ The radiation scattered by the sample is expanded in the waveguide as follows:

$$\mathbf{E} = \sum_{\lambda'} A_{\lambda'}^+ \mathbf{E}_{\lambda'}^+, \quad (1)$$

and similarly for \mathbf{H} , where the index λ' denotes the collection of indices which label the various waveguide modes and $\mathbf{E}_{\lambda'}^+$ and $\mathbf{H}_{\lambda'}^{\pm}$ signify these field modes, where the + and - signs signify a wave traveling to the right (the direction of the incident radiation) and the left, respectively. The expansion coefficient was shown in Ref. 4 to be given in the magnetic dipole approximation by

$$A_{\lambda'}^+ = -i(2\pi\omega/c)Z_{\lambda'} \mathbf{m} \cdot \mathbf{B}_{\lambda'}^+(\mathbf{r}_0), \quad (2)$$

where $Z_{\lambda'}$ is equal to $\omega/(ck)$ for the TE mode, \mathbf{m} is the dipole moment induced in the sample by the incident radiation field, and \mathbf{r}_0 is the location of the sample. The amount of radiation that gets past the sample, which is what is measured in our experiment, is given by

$$\begin{aligned} P &= P_{\text{abs}} + P_{\text{sc}} \\ &= -\frac{c}{8\pi} \int_S \text{Re}[(\mathbf{E}_i + \mathbf{E}_s) \times (\mathbf{H}_i^* + \mathbf{H}_s^*)] \cdot \hat{n} da \\ &\quad + \frac{c}{8\pi} \int_{S_L} \text{Re}(\mathbf{E}_s \times \mathbf{H}_s^*) \cdot \hat{n} da, \end{aligned} \quad (3)$$

where P_{abs} is the power absorbed by the sample, P_{sc} is the power scattered back by our sample, S is a closed surface surrounding the sample (consisting of the walls of the waveguide, a plane surface to the left of the sample perpendicular to the axis of the waveguide, and one to the right of the sample), S_L is the plane to the left of the sample, \mathbf{E}_i and \mathbf{H}_i are the incident fields, \mathbf{E}_s and \mathbf{H}_s are the scattered fields, and da and \hat{n} are the area element and unit vector normal to the area element, respectively.⁴ We will neglect the absorption of the walls in the remainder of our discussion. Since in our experiment we are in the lowest TE mode, we may take $\mathbf{E}_i = E_0 \mathbf{E}_{\lambda_0}^+$, and $\mathbf{E}_s = A_{\lambda_0}^+ \mathbf{E}_{\lambda_0}^+$ on the right of the sample and $\mathbf{E}_s = A_{\lambda_0}^- \mathbf{E}_{\lambda_0}^- e^{-2ikz}$ on the left, where E_0 is a real constant. The last two relations for \mathbf{E}_s hold because we have assumed that the plane surfaces to the left and right of the sample that we are integrating over are sufficiently far from the sample that the evanescent waves occurring the expansion of the field in waveguide modes are negligibly small, leaving the lowest TE mode (denoted by λ_0), the only propagating mode in the expansion. Then, following the discussion in Jackson's book⁴ we obtain, using $A_{\lambda_0}^{\pm}$ from Eq. (2),

$$\begin{aligned} P &= -0.5\omega E_0 H_0 H_{\lambda_0}(x_0, y_0) \text{Im } \chi \\ &\quad - (c/8\pi) (2\pi\omega/c)^2 Z_{\lambda_0}^2 E_0 H_0 |H_{\lambda_0}(x_0, y_0)|^2 \chi^2, \end{aligned} \quad (4)$$

where χ represents the response of \mathbf{m} to the incident electromagnetic field. If we take $\chi = \omega_m / (\omega_0 - \omega + i\Delta\omega)$, where ω_0 is the resonant frequency measured in the experiment, $\omega_m = 4\pi\gamma M$ (where M is the saturation magnetization of the sample in the applied static field), $\Delta\omega$ is the linewidth and $|\chi|^2 \propto \text{Im } \chi$, we find that P is proportional to $\text{Im } \chi$. In

other words, our experiment measures the susceptibility directly. The relationship between this susceptibility, which measures the response of the sample magnetization to the incident electromagnetic field, to the permeability of the sample is shown on p. 198 of Ref. 4 to be given by $\chi = 4\pi a^2(\mu - 1)/(\mu + 2)$, where μ is the permeability and a is the radius of the sample. If we write $\mu = 1 + 4\pi\chi'$, where $\chi' = \omega_m/(\omega'_0 - \omega + \Delta\omega')$, we find by substituting for μ in the above expression for χ that $\omega_0 = \omega'_0 + \omega_m/3$ and $\Delta\omega = \Delta\omega'$. In other words, the linewidth measured in our experiment is exactly equal to the linewidth of the substance being measured without any further corrections. Although in the present discussion, we have treated μ as if it were isotropic when it is known to be anisotropic, because all components of the permeability tensor have a resonance at the same resonant frequency and with the same linewidth our main conclusion should still hold. As a check on this result, we have also calculated the transmission of plane waves in free-space passing through an infinite planar sample of thickness small compared to a wavelength in free-space. Again, no change was found in the width of the dip in the transmitted power at resonance, as the resonant frequency is varied (although the depth of the dips did vary), implying that it is not necessary to make a correction of the linewidth for the variation of the skin depth with frequency and the consequent variation of the coupling of the electromagnetic field to the sample.

Now let us discuss the experimental results in terms of microscopic models. Reference 1 shows that the intrinsic linewidth of barium ferrite is nearly linear in temperature over a wide range of temperature, which is consistent with the Kasuya-LeCraw mechanism, but our results for the same samples show that it is nearly independent of frequency over a wide range of frequency, which is not consistent with this mechanism.⁵ It is known, however, that the trigonal site Fe ions are positionally disordered,⁶ and, in fact, this disorder fluctuates with time at a rate that increases with temperature,⁶ consistent with a model in which these ions lie in a double well potential, with a hopping rate between the wells increasing with increasing temperature. This picture was first suggested by Tsantes and Silber.⁷ The model that we will discuss consists of ions moving back and forth periodically (but not necessarily harmonically) between the wells. This leads to a scattering of the uniform magnon into another magnon of frequency differing from its frequency by the fluctuation frequency of the trigonal site ions. Since the magnon density of states increases with increasing frequen-

cy, and since the fluctuation frequency increases with temperature, this model predicts a linewidth that increases with temperature. Lowest-order time-dependent perturbation theory⁸ predicts a linewidth given by

$$\Delta\omega = \frac{2\pi}{\hbar} \sum_{n,\pm} |V_n|^2 \int d^3k \delta[\omega_u \pm n\omega_1 - \omega(\mathbf{k})], \quad (5)$$

where V_n is the time Fourier transform of the time-dependent potential of the fluctuating ion, ω_u is the uniform magnon frequency, ω_1 is the fluctuation frequency of the ion, and $\omega(\mathbf{k})$ is the frequency of a magnon of wave vector \mathbf{k} , which for a spherical sample, if $\omega_u \gg \omega_m$, is given by⁵

$$\omega(\mathbf{k}) \approx Dk^2 + \omega_u - \frac{1}{2}\omega_m + 0.5\omega_m(1 - x^2),$$

where x is the cosine of the angle between \mathbf{k} and the magnetization direction. On substituting this approximate expression into Eq. (5), it is obvious that the contribution to the linewidth due to the present mechanism will be independent of ω_u . The dependence of the linewidth on ω_1 was calculated and found to be an increasing function, as expected. Since we expect ω_1 to be thermally activated, this is consistent with a linewidth that increases with increasing temperature.

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¹ L. M. Silber, E. Tsantes, and W. D. Wilber, *J. Magn. Magn. Mater.* **54-57**, 1141 (1986); L. M. Silber and W. D. Wilber, *IEEE Trans. Magn.* **MAG-22**, 984 (1986).

² M. Labeyrie, M. C. Mage, and J. P. Ganne, *J. Appl. Phys.* **64**, 5825 (1988); M. Labeyrie, J. C. Mage, W. Simonet, J. M. Desvignes, and H. Le Gall, *IEEE Trans. Magn.* **MAG-20**, 1224 (1984); M. Labeyrie, J. C. Mage, and T. M. Robinson, *IEEE Trans. Magn.* **MAG-22**, 976 (1986); P. Roschmann, M. Lemke, W. Tolksdorf, and F. Welz, *Mater. Res. Bull.* **19**, 385 (1984).

³ J. Schwinger and D. S. Saxon, *Discontinuities in Waveguides* (Gordon and Breach, New York, 1968).

⁴ J. D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1962), p. 407.

⁵ M. Sparks, *Ferromagnetic Relaxation Theory* (McGraw-Hill, New York, 1964).

⁶ E. Kreber, U. Gonser, A. Trautwein, and F. Harris, *J. Phys. Chem. Solids* **36**, 263 (1975); A. Collomb, P. Wolfers, and X. Obradors, *J. Magn. Magn. Mater.* **62**, 57 (1986); X. Obradors, A. Collomb, M. Pernet, D. Samaras, and J. C. Jourbert, *J. Solid State Chem.* **56**, 171 (1985); Y. Xu, G. L. Yang, D. P. Chu, and H. R. Zhai, *J. Magn. Magn. Mater.* **31-24**, 815 (1983); W. D. Townes, J. H. Fang, and A. J. Perrotta, *Z. Kristallogr.* **125**, 437 (1967).

⁷ E. Tsantes and L. M. Silber, *J. Appl. Phys.* **63**, 3350 (1988).

⁸ A. Messiah, *Quantum Mechanics* (Wiley, New York, 1958).