CHARACTERIZATION OF LUNAR FERROMAGNETIC PHASES BY THE EFFECTIVE LINEWIDTH METHOD*

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SUMMARY

The effective linewidth technique, first developed to study the physics of microwave relaxation in ferrites, has been successfully applied to lunar matter. Effective linewidth measurements have been made on two selected samples containing disperse spherical metallic iron particles below 40 μm in diam. The data were obtained for fields from 7 to 12 kOe and a temperature range 125 - 300 K. The effective linewidth was field independent and temperature independent at 650 - 750 Oe. The high field tails of the ferromagnetic resonance absorption were highly Lorentzian. From the relatively large and temperature independent high field effective linewidths, it appears that (1) the metallic iron phases in lunar soil are rather impure, (2) the impurities are passive, in that there is no evidence for a temperature peak process, and (3) these samples contain no appreciable magnetite.

I. INTRODUCTION

The magnetic properties of lunar matter have attracted considerable attention, and the nature of the specific magnetic constituents has been the subject of much controversy. Tsay and Live[1] have made a case for the presence of metallic iron, based on ferromagnetic resonance data (FMR). Griscom et al.[2] have noted that the resonance losses at low temperature increase much more rapidly than expected for metallic iron, and associate their data with a "magnetite like" second phase.

The ganeral technique employed in such work has been to observe the FMR absorption derivative profile on a given sample at different temperatures, and analyze the data to infer the nature of the magnetic phases. At best, such an analysis involves quantitative measurements of the derivative of a complicated response. The absorption reflects the superposition of narrow and broad resonances, as well as loss at low field.

A quantitative technique developed to study microwave relaxation in ferrites offers several advantages over conventional FMR methods for the characterization of lunar matter. The technique, termed "effective linewidth", involves the measurement of the absolute complex microwave susceptibility at high fields.[3] This susceptibility is characteristic of the intrinsic relaxation of the magnetic phases contributing to the response. This is true even when inhomogeneities broaden the resonance line and increase the apparent FMR losses. With this technique, therefore, intrinsic relaxation can be measured in spite of complications which broaden the resonance.[4]

This paper reports the first application of this technique to the study of lunar ferromagnetic phases. The essentials of the method and sample considerations are presented in Section II. The experimental results are discussed in Section III.

II. EXPERIMENTAL TECHNIQUE AND SAMPLE CONSIDERATIONS

The method is based on the uniform mode susceptibility at high field,[5]

$$\chi = \chi' + i\chi'', \tag{1}$$

$$\chi' = (\omega_m/\omega)\left[1/(\omega_o - \omega) + 1/(\omega_o + \omega)\right], \tag{2}$$

$$\chi'' = (\omega_m/\omega)\left[1/(\omega_o - \omega)^2 + 1/(\omega_o + \omega)^2\right]\eta, \tag{3}$$

$$\omega_m = 4\pi M_o, \tag{4}$$

$$\omega_o = \gamma H_o. \tag{5}$$

Here, $4\pi M_o$ is the saturation induction of the magnetic phase, γ is the gyromagnetic ratio, taken as positive, H_o is the applied external field, and ω is the microwave frequency in rad/sec. Equations (2) and (3) are valid for spherical magnetic particles with uniform microwave excitation. It has been assumed that the microwave relaxation rate η is sufficiently small that its contribution to the resonance denominators in Eqs.(2) and (3) can be neglected. These equations, therefore, are not valid for fields near FMR.

At 10 GHz, ω/γ is about 3.5 kOe. If the effective linewidth,

$$\Delta H_{eff} = 2\eta/\gamma, \tag{6}$$

is less than 1 kOe, Eqs.(2) and (3) are adequate for fields above about 7 kOe. Note that the effective linewidth simply expresses the relaxation rate in linewidth units. The conventional FMR linewidth is the average over the resonance line,

$$\Delta H = 2\langle\eta\rangle_{res}/\gamma. \tag{7}$$

For FMR lines which are inhomogeneously broadened, one would expect ΔH to be larger than the high field ΔH_{eff}.

From standard microwave perturbation

Manuscript received March 6, 1977.

* Supported by the National Aeronautics and Space Administration, Grant NSG 9037.

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0018-9464/78/0900-0880$00.75 ©1978 IEEE

theory, one can relate the above susceptibility components to the microwave cavity parameters,[6]

$$\chi' = -2C\,(\omega-\omega_\infty)/\omega\,, \qquad (8)$$

$$\chi'' = C(1/Q - 1/Q_\infty)\,. \qquad (9)$$

Here, C is a cavity calibration coefficient related to the cavity dimensions and sample volume. The ω_∞ and Q_∞ parameters refer to the cavity frequency and quality factor Q extrapolated to infinite field.

In previous applications of the technique to ferrite materials, perturbation theory was used to evaluate C, and high field data on cavity Q and frequency were used to determine the effective linewidth. For lunar samples, this procedure is not appropriate for two reasons. First, the lunar material, in the form of a sieved powder, is contained in an evacuated sealed quartz tube which must be inserted into the high Q cavity. The cavity loading due to the quartz and the large volume of the lunar material needed to get adequate sensitivity combine to introduce substantial errors into the perturbation theory analysis. Second, the exact volume of the magnetic phase is not known, and this causes further calibration problems.

An alternative procedure was developed for lunar sample analysis. It is based on the realization that χ' at high field depends only on the intrinsic material parameters γ and $4\pi M_0$ and the experimental parameters and H_0. Equation (2) can therefore be used to calculate ' explicitly. This value can then be combined with the frequency data to obtain an empirical cavity calibration parameter C from Eq.(8). Once C is determined, Eqs.(9), (3), and (6) can be used to obtain χ'', η, and ΔH_{eff} from the Q data. This new procedure depends on perturbation theory only to justify the relations between χ' and ω, and between χ'' and Q. It is superior to the old procedure, since it does not depend on perturbation theory for the actual numerical calibration.

The cavity Q and frequency at each field point from 7 to 12 kOe, in steps of 500 Oe, were measured using the transmission cavity feedback technique described in ref. 3. The system was modified to allow for direct frequency measurement and low temperature operation.[7] The infinite field cavity parameters ω_∞ and $1/Q_\infty$ were determined by plotting the measured ω and 1/Q versus the square bracket term (SBT) of Eq.(2) and of Eq.(3), respectively. These terms go to zero as the field H_0 goes to infinity. The appropriate extrapolations yield ω_∞ and $1/Q_\infty$. Note that the field dependence of χ'', as contained in the SBT of Eq.(3), corresponds to a Lorentzian line. Therefore, a linear dependence of the measured 1/Q on the SBT of Eq.(3) means that the high field tail of the FMR absorption is Lorentzian and that ΔH_{eff} is independent of field.

The samples were carefully selected for this initial exploratory application of the effective linewidth method to lunar matter, in order to avoid problems concerning identity of the magnetic phases, particle size and shape complications, and sensitivity limitations. The available data on the two samples are listed in Table I. These samples were selected because of their reasonably narrow FMR lines, the absence of secondary FMR peaks in the spectra, and well characterized microstructural and magnetic properties.[8] The soil samples were sieved to obtain the restricted range of particle sizes listed in the table. The magnetic phase consisted of spherical particle metallic iron. All linewidths refer to half-power linewidths.[9]

TABLE I
Data on Lunar Magnetic Samples

NASA Code	10084,85	65701,13
weight	213 mg	130 mg
particle size	20 - 45μ	below 45μ
FMR linewidth at 9 GHz	1454 Oe	963 Oe
Fitted, intrinsic linewidth	670 Oe	600 Oe
Wt. % Fe	1.13 %	0.63 %

III. EFFECTIVE LINEWIDTH RESULTS

Figure 1 shows the dependence of 1/Q on the SBT of Eq.(3) for the 213 mg sample at room temperature. The extrapolation to "$1/H^2$" = 0 corresponds to $1/Q_\infty$. It is to be noted that all data points fall on a straight line. This means that the high field tail of the FMR line is Lorentzian and is characterized by a constant effective linewidth. Similar results were obtained for the 130 mg sample. It is seen that the effective linewidth method represents, among other things, a simple way to analyze FMR lineshapes.

The complete analysis was performed for the two samples as a function of field and temperature from 129 to 300 K. The average high field effective linewidth for the 213 mg sample as a function of temperature is shown in Fig. 2. It is seen that the high field ΔH_{eff} for this sample is temperature independent at a value of 650-700 Oe. For the 130 mg sample, the high field ΔH_{eff} was also temperature independent at 650-750 Oe. The error is larger because of the smaller amount of material. These values are to be compared with the FMR linewidths given in Table I. The measured linewidths of 1454 and 963 Oe are larger than the high field ΔH_{eff} because of inhomogeneous broadening. The crystalline anisotropy of the randomly oriented disperse crystallites increases the FMR linewidth by 500-1000 Oe. The quantitative superposition of individual FMR lines for an ensemble of randomly oriented noninteracting single crystal spheres yielded the "fitted intrinsic linewidth" value in the table. These fitted values are in good agreement with the ΔH_{eff} results, which represent a much more direct measurement of the intrinsic linewidth.

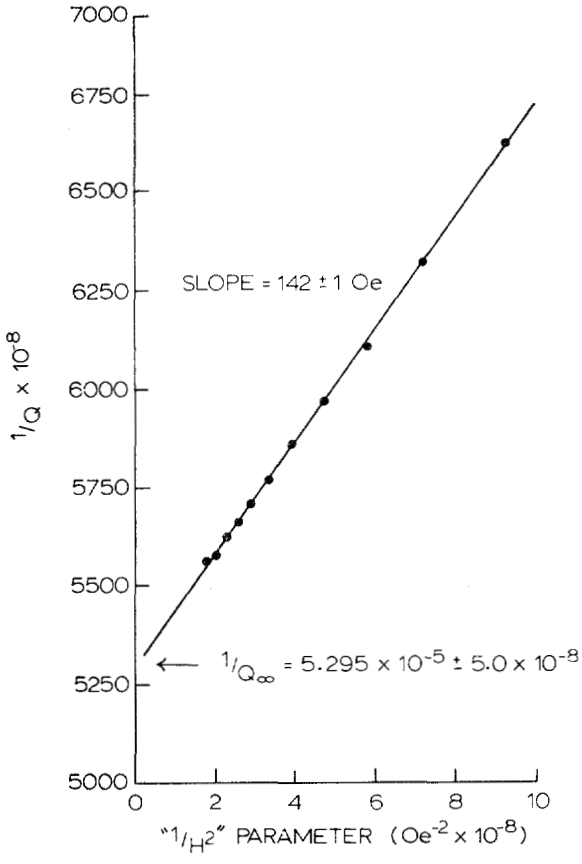

Fig. 1. Inverse Q as a function of the square bracket term of Eq.(3) for the 213 mg lunar sample at 9.9 GHz and 300 K.

The relatively large temperature independent high field effective linewidth suggests that the elemental iron particles in these soils are rather impure. Iron single crystals can exhibit much narrower FMR lines, with ΔH values of 50 Oe or lower.[10] The fact that the high field ΔH_{eff} does not increase at low temperature indicates that temperature peak processes are not involved. This appears, therefore, to rule out the presence of active impurities such as the fast relaxers as well as any appreciable magnetite content.

ACKNOWLEDGEMENTS

The authors are indebted to Ira Goldberg and Bob Housley for stimulating discussions and generous assistance with sample preparations, and to Ron Kaelberer for the development of the effective linewidth system used for the measurements.

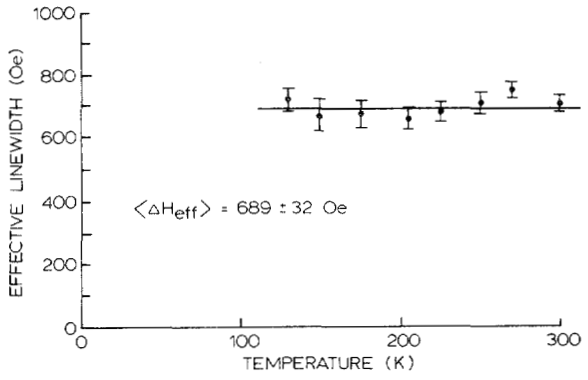

Fig. 2. Average high field effective linewidth at 9.9 GHz as a function of temperature for the 213 mg lunar sample.

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