# Microwave Absorption in Terbium at 10 GHz†

T. K. Wagner and J. L. Stanford
*Institute for Atomic Research and Department of Physics, Iowa State University, Ames, Iowa* 50010
(Received 17 November 1969)

Our recent experimental work on microwave absorption in Tb at 100 GHz indicated that the frozen-lattice model for incorporating the magnetoelastic effects was appropriate. This model, however, predicts that no resonant absorption should occur below ~ 230 K at 10 GHz, contrary to the observations of Bagguley and Liesegang. We have repeated their experiments, essentially agreeing with their results. We offer an alternative interpretation of the observations, which is not only consistent with the frozen-lattice model, but which we believe to be more consistent with present studies on the effects of sample thickness and polarization on the absorption. If our interpretation is correct, some conclusions concerning magnetoelastic effects in Tb that have recently been published will need revision.

## INTRODUCTION

Recently[1] we showed that the microwave absorption of Tb single crystals at 100 GHz could only be understood by taking into account magnetoelastic interactions according to the frozen-strain model, calculated by Cooper.[2] However, in this model, and with the magnetoelastic coefficient obtained from our data, no resonant absorption should be seen at 10 GHz at temperatures below about 230 K. Because this is contrary to the observations of Bagguley and Liesegang,[3] we felt it was desirable to repeat their experiments. We report here the results of these new experiments, essentially in agreement with the earlier work, but offer an alternative interpretation consistent with the frozen-lattice model.

## EXPERIMENT

Two crystals were used in this experiment. Their preparation was described in Ref. 1. Most of the work was done on the thinner disk, having 5.9 mm diam and 0.4 mm thickness with the $c$ axis normal to the disk.

The sample was cemented to a piece of paper which was then cemented to the end wall of a cylindrical cavity operating in the $TE_{111}$ mode at 9.78 GHz. An indentation in the wall of the cavity split the degeneracy of the modes, and the sample was aligned with a $b$ axis along the rf magnetic field of one of these modes. The dc magnetic field was oriented at right angles to this direction. The cavity was used in a reflection spectrometer employing a magic tee. The cavity was placed in an evacuated cryostat surrounded with liquid nitrogen. The sample was heated by a resistance wire wrapped around the cavity, and the temperature was monitored by a copper-constantan thermocouple attached near the bottom of the copper cavity. Most of the absorption data were taken in the form of the derivative of reflected power with respect to applied field obtained by field modulation (amplitude ~ 80 Oe $p$-$p$, at 77 Hz) and phase detection. In some cases the reflected power was recorded directly.

## RESULTS

Absorption maxima (zeros in the derivative) as a function of applied field were seen in the temperature range 175 to 270 K. The maxima are typically about 1 kOe in half-width, and are characterized by a sharp leading edge and a long tail. In the temperature range 270 K up to room temperature some very weak signals were observed, but were not considered reliable enough to plot. (Temperatures below 175 K were not readily attained with our 10-GHz apparatus.)

In the temperature range 222 to 227 K, the positive derivative peak (corresponding to the leading edge of the absorption peak) was split into two peaks. This temperature range coincides approximately with the antiferromagnetic-regime.

Changes in the absorption with field are seen in both senses of rf polarization, i.e., with microwave field perpendicular to, or parallel with, the dc field. Only in the perpendicular case, however, does the absorption have the shape of a resonant absorption. (See tracings A and B, Fig. 1.) At a fixed temperature, 208 K, the dc field was rotated in the plane of the sample at 10° intervals from one sense of polarization to the other. The difference (in arbitrary units) between the power absorbed when the rf and dc fields made an angle $\theta$ and the power absorbed when they were parallel, at a fixed field value of 2 kOe, satisfied fairly accurately a $\sin^2\theta$ dependence as would be expected of a resonance phenomenon.

A plot of the zero of the absorption derivative versus temperature is shown in Fig. 2. It has

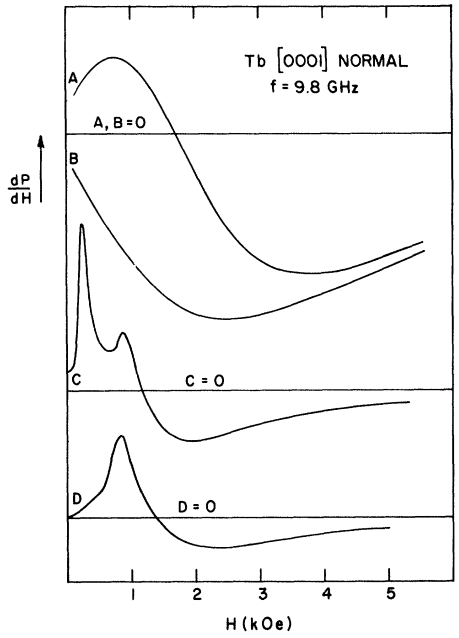


FIG. 1. Derivative of power absorption in Tb disk as a function of applied field for the thinner of the two samples studied (thickness = 0.4 mm). A: $T = 238$ K, $H_{rf} \perp H_{dc}$. B: $T = 238$ K, $H_{rf} \parallel H_{dc}$. C: $T = 226$ K, $H_{rf} \perp H_{dc}$. D: $T = 220$ K, $H_{rf} \perp H_{dc}$.

a minimum at about 228 K. (Points plotted are the average of up and down field sweeps.)

## INTERPRETATION

Many of our observations are in essential agreement with those of Bagguley and Liesegang. They apparently did not see the double positive peak in the derivative of the absorption in the antiferromagnetic regime. At 223 K we see a peak at about 160 Oe and another at about 870 Oe. At 226 K these have shifted to 230 and 830 Oe, respectively. The first could conceivably be ascribed to a transition from the spiral antiferromagnetic structure to a fan structure. (We are unaware of any previous report of a fan phase in Tb.) The second peak could be ascribed to a transition from the fan to the ferromagnetic phase. Since the peaks are seen in both senses of rf polarization, the contribution to the absorption is probably through the mechanism of changing the skin depth by a change in permeability.

If the frozen-lattice model is the correct one for including the magnetoelastic effects in Tb, and if the parameters which give the best fit to our 100-GHz data are appropriate here, then resonance should not be seen unless the temperature is above ~ 230 K.[1,2] Why do we see structure in the absorption at lower temperatures, and in particular why does it have a $\sin^2\theta$ dependance? We believe the basic structure to be related to the alignment of domains, since the temperature dependence below about 230 K is very similar to that observed by Rhyne and Legvold[4] for the onset of magnetostriction, which is related to domain alignment. This interpretation receives additional support from absorption data taken on the thicker sample (not shown on Fig. 2). In this case the structure below ~ 220 K occurred at higher-field values, but the high-temperature results were not appreciably changed. It can be shown that the true ferromagnetic resonance is not appreciably affected by the change in demagnetizing fields, whereas domain alignment is appreciably affected. The $\sin^2\theta$ polarization dependence of the absorption we attribute to off-resonance absorption appearing after domain alignment has taken effect. That such off-resonance absorption might occur is a consequence of the large natural linewidth of ferromagnetic resonance in terbium. In the present case the true resonant frequency is higher than the experimental frequency. We note that the same effect was observed in the 100-GHz experiment[1] at temperatures below about 160 K. Again, the true resonance was either nonexistent or occurred at a field below

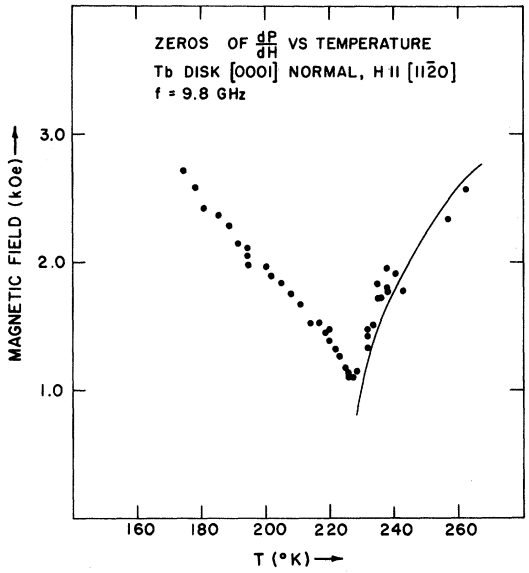


FIG. 2. Zeros of derivative of power absorption as a function of temperature for the thinnest Tb sample. Solid line calculated from the high-temperature limit of Eq. (2.11) in Ref. 2, i.e., $(\hbar\omega)^2 = g\mu_B H \{-2P_2 S\,(0.6m) + g\mu_B[H + (4\pi - N_x)M]\}$, where $M$ is the magnetization, $m$ is the reduced magnetization, and $N_x$ is the demagnetizing factor for a field in the plane of the disk. We have used the value $-2P_2S = 37.2$ K from Ref. 1.

the domain alignment field.

Cooper[2] has correctly pointed out that if the resonances reported by Bagguley and Liesegang in Tb are direct $k = 0$ spin-wave excitations, the frozen-lattice model cannot be valid at their experimental frequency. Marsh and Sievers[5] studied far-infrared absorption in Tb and concluded that the frozen-lattice model better explained their data. Our high-frequency microwave data[1] provided a definitive test: They could only be explained on the basis of the frozen-lattice model. (The free-lattice model could not even qualitiatively explain the experimental results.[1,2]) To understand the difference in behavior between the low-frequency microwave results of Bagguley and Liesegang and those of the above-mentioned far-infrared and high-frequency microwave regions, Marsh has proposed a two-sublattice model.[6] Brooks[7] has also discussed the possibility of a frequency-dependent mechanism which might allow the free-lattice model to be operative at low microwave frequencies. Our earlier high-frequency results,[1] together with the low-frequency investigation presented in this paper, provide a natural and satisfying resolution of the apparent discrepancy. Thus the conjectures related to the Tb problem made by the aforementioned authors [2,6,7] are no longer necessary.

ACKNOWLEDGMENTS

We wish to thank Professor R. G. Barnes of this laboratory for the loan of the 10-GHz components used in this experiment. We also acknowledge helpful discussions with Dr. B. R. Cooper.

†Work performed in the Ames Laboratory of the U.S. Atomic Energy Commission, Contribution No. 2654.

[1]T.K. Wagner and J.L. Stanford, Phys. Rev. 184, 505 (1969).

[2]B.R. Cooper, Phys. Rev. 169, 281 (1968).

[3]D.M.S. Bagguley and J. Liesegang, Phys. Letters 17, 96 (1965); J. Appl. Phys. 37, 1220 (1966); Proc. Roy. Soc. (London) A300, 497 (1967).

[4]J.J. Rhyne and S. Legvold, Phys. Rev. 138, A507 (1965).

[5]H.S. Marsh and A.J. Sievers, J. Appl. Phys. 40, 1563 (1969).

[6]H.S. Marsh, Ph.D. thesis, Cornell University, 1969 (unpublished).

[7]M.S.S. Brooks, Phys. Rev. (to be published).

PHYSICAL REVIEW B VOLUME 1, NUMBER 11 1 JUNE 1970

# Addendum to "Localized Correlations in Narrow Conduction Bands. I"

Joel A. Appelbaum
*Bell Telephone Laboratories, Murray Hill, New Jersey* 07974

David R. Penn*
*Brown University, Providence, Rhode Island* 02912

and

Philip E. Bloomfield*
*University of Pennsylvania, Philadelphia, Pennsylvania* 19104

(Received 19 December 1969)

The self-consistent equations derived by Appelbaum and Penn (AP) for a single strongly correlated impurity site in a narrow conduction band are solved using a rapidly converging density of states. This rectifies the convergence difficulties AP found when they used a Lorentzian density of states. We find that $n_0$, the total electron occupation number at the impurity site, is 0.497, compared to 0.4 found by AP. Results for the resistivity as a function of temperature are also presented.

Recently, Appelbaum and Penn[1] (AP) have treated the problem of localized correlations in a narrow conduction band by means of an equation-of-motion decoupling scheme. In the process of solving the resulting self-consistent equation for the local-correlated-site Green's function, they were forced to use a Lorentzian density of states

$$\eta(E) = (D/\pi)\, 1/(E^2 + D^2) \qquad (1)$$