velocity autocorrelation function of a dense one-component classical plasma.

We wish to thank J. P. Hansen for sending us his tabulated results for $S(q)$. We are thankful to the National Science Foundation and to Shang-keng Ma for support during the summer of 1974 when this work was initiated. One of us (H.G.) would like to acknowledge the support and hospitality of the Physics Department of Bar-Ilan University and to thank Daniel Lieberman for his help with the numerical calculations.

---

*Present address.

[1] J. P. Hansen, E. L. Pollock, and I. R. McDonald, Phys. Rev. Lett. 32, 277 (1974).

[2] J. P. Hansen, I. R. McDonald, and E. L. Pollack, Phys. Rev. A 11, 1025 (1975).

[3] We adopt the standard notation with e the charge, n the number density, N the number of particles, T the temperature, k_B Boltzmann's constant, m the mass, and $\beta = 1/k_B T$. Γ is related to the "plasma parameter" ϵ by $\Gamma = \epsilon^{2/3}/3^{1/3}$, where $\epsilon = \beta e^2/D$ and $D = (4\pi\eta\beta e^2)^{-1/2}$.

[4] G. Mazenko, Phys. Rev. A 7, 209 (1973).

[5] G. Mazenko, Phys. Rev. A 7, 222 (1973).

[6] G. Mazenko, Phys. Rev. A 9, 360 (1974).

[7] See, for example, D. Montomery and D. Tidman, *Plasma Kinetic Theory* (McGraw-Hill, New York, 1964).

[8] G. Mazenko, T. Y. C. Wei, and S. Yip, Phys. Rev. A 6, 1981 (1972).

[9] J. P. Hansen, Phys. Rev. A 8, 3096 (1973).

[10] See, for example, Ref. 5, Sect. VII.

[11] P. Vieillefosse and J. P. Hansen, Phys. Rev. A 12, 1106 (1975).

[12] We neglect $C_p - C_v$ compared to C_v. See Ref. 10.

Magnetic Resonance in Amorphous $TbFe_2$ and $GdFe_2$†

S. M. Bhagat* and D. K. Paul
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

(Received 14 July 1975)

We report measurements on the spin resonances in a-$TbFe_2$ and a-$GdFe_2$. A preliminary interpretation in terms of an oversimplified model involving clusters in a disordered material is also outlined.

Amorphous ferromagnetism has attracted considerable attention in recent years. For instance, a-$TbFe_2$ and a-$GdFe_2$ have been studied in great detail by Rhyne and co-workers using both neutron scattering[1] and static measurements.[2] Recently, Rhyne made available to us a few specimens of these materials. We have studied the spin resonances in a-$TbFe_2$ at several microwave frequencies between 9 and 31 GHz and at several temperatures between 77 and about 450 K. In a-$GdFe_2$ measurements have been made at several frequencies and $77 < T < 300$ K. The results are very anomalous and at present we can offer only rather rough explanations for some of the observations. The experiments were performed in conventional microwave spectrometers using setups described in earlier papers from this laboratory.[3] The samples were of millimeter size, chips or needles spark-cut from larger boules. However, one of the a-$TbFe_2$ samples was a sphere of diameter ~1 mm and one of the a-$GdFe_2$ specimens was a large parallelepiped ($5\times 3.5\times 1$ mm^3). The sample temperature was monitored by use of a copper-Constantan thermocouple affixed to the outside of the cavity. In a separate series of experiments using two thermocouples (one replacing the sample) we have checked that the sample temperature is within a degree of the thermocouple temperature.

Figure 1 is a typical recorder trace of the field derivative of the power absorption in a-$TbFe_2$ at 10.8 GHz and 300 K. Such a spectrum, i.e., one strong line (S_1) and three weak satellites (S_2 through S_4) on its high-field side, is essentially characteristic of all the samples studied. By repeated measurements the center of S_4 (i.e., H_4) was determined to about 100 Oe. H_4 varies roughly linearly with frequency (Fig. 2). However, *it is surprising that it is essentially independent of sample shape.* On the other hand the value of H_1 reflected the changes in the static demagnetizing field due to changes of size and shape. S_2 being very weak and lying rather close to S_1, its position (H_2) cannot be fixed without considerable analysis involving assumptions as to line shape, etc. However, in every case $H_2 > H_1$. At present, we have only rough measurements on H_3. Further, it should be noted that the intensity

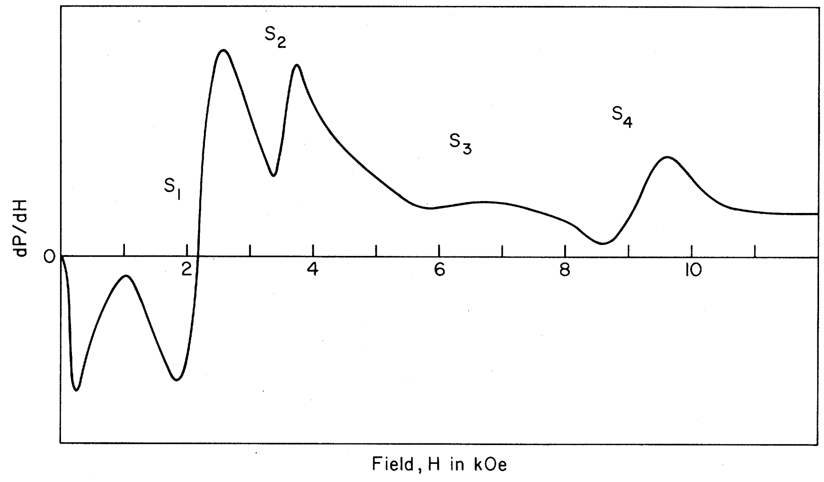

FIG. 1. Field derivative of the power absorption in a-TbFe$_2$ at 10.8 GHz and 300 K.

of the satellites is very sensitive to the location of the specimen in the cavity.

In a-GdFe$_2$ also we have observed a four-line spectrum. However, the S_1 line is much stronger and the satellites much weaker. Again H_4 values vary linearly with frequency (Fig. 2) and are independent of sample shape. Further, it is remarkable that the values of H_4 for a-TbFe$_2$ and a-GdFe$_2$ are very close to one another.

Next, we studied the temperature dependence of the resonances in a-TbFe$_2$ for $300 < T \lesssim 470$ K. First, it was found that the position of S_4 is *independent* of temperature. Next, the variation of H_1 at 9.6 GHz was measured and is shown in Fig. 3.

The effects of lowering the temperature on the spectrum of a-TbFe$_2$ can be summarized as follows: S_4 remains *completely unaltered* both as to position and as to intensity. S_1 first reduces in intensity and on further reduction of temperature (~ 200 K) splits up into several weak lines. S_2 does not alter its position but it appears to be sharper and also develops additional structure. No such anomalous behavior in S_1 is observed in a-GdFe$_2$. The line merely broadens and shifts to lower fields. In a-GdFe$_2$ also S_4 is entirely independent of temperature.

It seems reasonable to recall some of the properties[1,2] of a-TbFe$_2$ and a-GdFe$_2$. (1) Above technical saturation a-TbFe$_2$ exhibits a temperature-independent susceptibility down to about 150 K. It has been suggested that this is indicative of a loosely coupled system in which the Tb spins are kept from alignment by the presence of random local anisotropy fields. (2) Below 150 K a-TbFe$_2$ develops a "coercive" field which increases to rather large values (30 kOe) as T is lowered to 4 K. This is accompanied by the development of a remanence which also shows some time-dependent effects very similar to the magnetic aftereffects discussed in the literature.[4] (3) In a-TbFe$_2$ neutron scattering (magnetic) exhibits an increase of intensity at low angles which

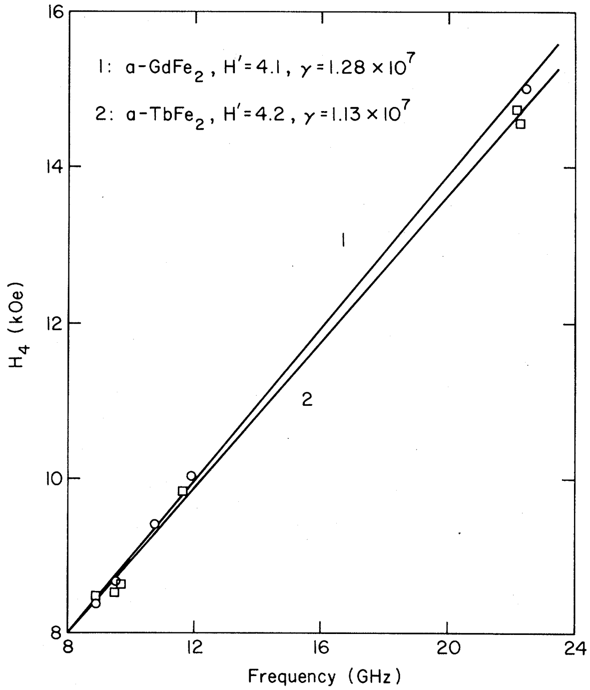

FIG. 2. H_4 as a function of frequency for a-TbFe$_2$ (□) and a-GdFe$_2$ (○) at 300 K. The line, i.e., $\omega/\gamma = H - H'$, is a least-squares fit to the data.

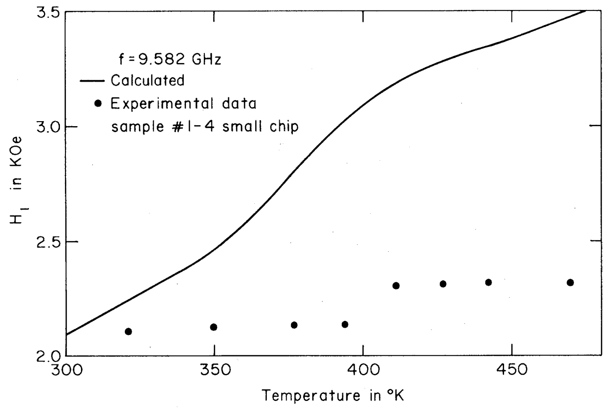

FIG. 3. The temperature dependence of H_1 in a-TbFe$_2$ for $300 < T \lesssim 470$ K. The full line was obtained by use of $g = 2.04$ and M values from Ref. 2.

is interpretated as being due to the presence of microdomains of about 30 Å diameter. Further, this increase is sensitive to the application of modest fields (1 kOe). (4) Both a-TbFe$_2$ and a-GdFe$_2$ have Curie temperatures which are about 40% of the corresponding Curie temperatures of the crystalline materials. This depression of the Curie point could be either due to fluctuation of exchange "fields"[5] or due to random variation of local anisotropy fields[6] (presumably weak or absent in a-GdFe$_2$ since Gd^{+++} is an S-state ion).

At present we do not have a model to account for all the surprising features exhibited by the resonances. As suggested by the earlier investigations[1,2] it seems reasonable to propose that these amorphous materials are composed of clusters of spins with the clusters themselves being rather loosely coupled to one another. Further, one can expect that the magnetization, exchange stiffness, and anisotropy vary randomly from cluster to cluster.

Consider first the strongest resonance, S_1. It is likely that there exists a large proportion of clusters whose magnetization is very close to the bulk magnetization. It is therefore reasonable to suggest that S_1 represents the ordinary ($k \sim 0$) ferromagnetic (ferrimagnetic) resonance involving such clusters. Indeed, at 300 K, the fields for S_1 obey the equation $\omega = \gamma[H(H + 4\pi M)]^{1/2}$ with g close to 2.1 and M equal to the measured saturation magnetization.[2] (In this calculation one must include the corrections to H_1 due to static demagnetizing fields.) However, as shown in Fig. 3, above 300 K, the position of S_1 does not vary with temperature in a manner consistent with a simple picture (full line in Fig. 3) in which the g value would be very nearly temperature independent. To account for the data one would have to make g strongly T dependent.

Next, consider the low-T behavior. One can understand it roughly if the S_1 $[k \sim 0]$ resonance at $T \geqslant 300$ K is being produced essentially by magnon hopping among clusters. If this hopping is thermally assisted one would expect that on lowering T the hopping will be less frequent and eventually the $k = 0$ line will disappear. This is presumably what happens in a-TbFe$_2$. We have already noted that this material develops a large coercive field (and time-dependent remanence) at low T which is presumably caused by the inability of the neighboring spin clusters to equilibrate. It is not too far-fetched to suggest that the disappearance of the $k = 0$ mode and the appearance of a T-dependent coercive field are both manifestations of the same basic process. In our experiments the effect appears at somewhat higher temperatures than in the static measurements because we are measuring "hysteresis losses" at very high frequencies (i.e., over very short time intervals). On the other hand, if the magnon hopping occurs with very small energy ($\ll kT$) one would not expect to see strong effects on lowering T. a-GdFe$_2$ probably falls into this category.

Finally consider S_4. This resonance presents the most surprising feature that it appears to be completely unaffected by sample shape. In other words, H_4 is not affected by the long-range dipolar (or demagnetizing) fields. Further, for several frequencies H_4 is very nearly the same for a-TbFe$_2$ and a-GdFe$_2$. We suggest that this resonance represents a magnon mode which is localized on clusters whose magnetization is very small; hence the linear dependence shown in Fig. 2. Further, since the resonance is entirely independent of T (and at the same fields in a-TbFe$_2$ and a-GdFe$_2$) it does not seem reasonable that the large (positive) H intercept in Fig. 2 is a consequence of anisotropy. We propose that it represents a contribution from an exchange energy (Dq^2) in which q^2 is negative, hence the localization. Such a picture clearly does not account for the baffling absence of demagnetization effects in H_4.

Perhaps the most dramatic demonstration of cluster resonances is the preliminary observation of a many-line spectrum in nonferromagnetic a-YFe$_2$. Further work is in progress and will be reported elsewhere.

We are deeply grateful to Dr. J. J. Rhyne for having made the samples available to us.

†Work supported in part by the National Science Foundation and the U. S. Office of Naval Research.

*Presently on sabbatical leave at Uppsala Universitet, Uppsala, Sweden.

[1] J. J. Rhyne, S. J. Pickart, and H. A. Alperin, *Magnetism and Magnetic Materials—1973*, edited by C. D. Graham, Jr., and J. J. Rhyne, AIP Conference Proceedings No. 18 (American Institute of Physics, New York, 1974), p. 563.

[2] J. J. Rhyne, J. H. Schelleng, and N. C. Koon, Phys. Rev. B 10, 4672 (1974).

[3] S. M. Bhagat, in *Techniques of Metals Research*, edited by R. F. Bunshah (Wiley, New York, 1973), Vol. 6, Pt. 2, Chap. VIII.

[4] S. Chikazumi and S. H. Charap, *Physics of Magnetism* (Wiley, New York, 1964), Chap. 15.

[5] A. I. Gubanov, Fiz. Tverd. Tela 2, 502 (1960) [Sov. Phys. Solid State 2, 468 (1960)].

[6] R. Harris, M. Plischke, and M. J. Zuckerman, Phys. Rev. Lett. 31, 160 (1973).

Photoemission Studies of Silver with Low-Energy (3 to 5 eV), Obliquely Incident Light

J. K. Sass, H. Laucht, and K. L. Kliewer*
Fritz-Haber-Institut, 1 Berlin 33, Germany

(Received 16 September 1975)

By use of the photoemission-into-electrolyte technique, the photoyields of silver have been measured for p- and s-polarized light in the energy range 3 to 5 eV with a wide range of incident angles. Pronounced structure, providing striking evidence for the validity of the nonlocal theory of the surface photoeffect, is obtained.

Vacuum photoemission experiments are limited to photon energies above the work function. The usual scheme for reducing the low-energy limit is to overlay the surface with cesium, the reduction of the work function resulting from the high polarizability of the cesium atoms. However, the extent to which the resulting photoemission is distorted by the cesium and thus no longer representative of the metal is unknown. An alternative is to study photoemission into an electrolyte[1]; the reduction of the work function occurs through the presence of an electrical double layer at the metal-electrolyte interface. The possibility that the electrolyte will affect the photocurrents sufficiently that they will be of limited utility for drawing conclusions about the metal must be faced. There is now evidence that such is not the case,[2] and we will present strong evidence to substantiate this view below. Indeed, the principal purpose of this note is to point up the effectiveness of this technique in solid-state investigations.

The low-energy limit on vacuum photoemission is unfortunate for silver. The occurrence of the sharply defined plasmon for energies above about 3.8 eV and suppression of the plasmon effects at about 4.0 eV due to transitions from the d bands take place below the work function. We have studied the photoemission into an electrolyte in the energy range from 3 to 5 eV. To include the possibility of observing manifestations of the surface photoeffect,[3-5] we have used polarized light with the apparatus of Ref. 2. The samples were thick (2500 Å) single-crystal films with (111) surfaces prepared by evaporation onto mica.

What would we then expect for the photoyields resulting from photons of energy $\hbar\omega$ incident at angle θ in the electrolyte? The simplest theoretical expressions for the yields, Y_p and Y_s, for p- and s-polarized light result from the isotropic-volume-excitation model.[6] In this case the yields for p and s light are given by

$$Y_{p,s}=A_{p,s}[\alpha\xi/(1+\alpha\xi)]P/2, \tag{1}$$

where α is the optical absorption coefficient, ξ the electron escape length (taken here for simplicity to be a function of ω), A_p (A_s) the absorptance for p (s) light, and P a function describing the escape of excited electrons through the surface.

The use of this model cannot be justified for the low energies of interest here. However, we can easily modify the expression for the p yield to improve significantly the physical content. Since the surface is (111), the normal passes through the L point of reciprocal space, in the neighborhood of which the threshold for interband transitions occurs at $\hbar\omega \sim 3.8$ eV.[7] This threshold involves transitions from the Fermi surface. Since the work function here is about 3 eV, those electrons excited at that L point associated with the surface will have energy and momentum sufficient to contribute to the photocurrent. Thus, it is the electric field component