difficult to analyze the intensities in terms of order-disorder transformations. However, after comparing the intensities of fundamental and superlattice lines of different specimens one is led to the conclusion that the spikes might well be surrounded by disordered regions. The observations made during and after annealing of the specimens can also be understood on the basis of this model. The spikes with the quasi-liquid configuration transform to the normal solid configuration below room temperature. This can be deduced from the shape and the intensity of the x-ray lines.

Experiments are in progress to verify and extend the present observations. The detailed results of this work will be published shortly.

We want to express our gratitude to Professor J. S. Koehler, Professor F. Seitz, and Dr. A. H. Kahn for many valuable discussions, and to Professor W. K. Jentschke, Professor J. S. Allen, and Dr. P. Stähelin of the Illinois cyclotron for their kind cooperation.

[1] H. Welker, Z. Naturforsch. **7a**, 744 (1952).

[2] See, for a recent survey of radiation damage: F. Seitz and J. S. Koehler, in *Solid State Physics* (Academic Press Inc., New York, 1956), Vol. 2, p. 307.

Ferrimagnetic Resonance in Yttrium Iron Garnet

J. F. DILLON, JR.

Bell Telephone Laboratories, Incorporated, Murray Hill, New Jersey

(Received November 21, 1956)

THE discovery of ferrimagnetism in yttrium iron and rare earth iron garnets was recently announced by Bertaut and Forrat.[1] It was discovered independently, though somewhat later, by Geller and Gilleo[2] of these Laboratories. The garnets constitute a whole new class of magnetic oxides of cubic symmetry which are structurally completely distinct from the now familiar ferrites. A study of ferrimagnetic resonance in one of these compounds has been made possible by Nielsen's[3] success in the growth of almost exactly stoichiometric single crystals of yttrium-iron garnet $[Y_3Fe_2(FeO_4)_3]$. The experimental specimens used were polished spheres of various sizes from 0.005 in. to 0.020 in. Some of these same spheres were used in the single-crystal structural analysis described in reference 2.

Two frequencies were used in these experiments, 9300 and 24 000 Mc/sec. Data were taken at various temperatures in the range from 2.85° to about 540°K. Transmission cavities were used in both cases. At the lower frequency, a rectangular cavity operating in the TE_{102} mode was used, while at 24 000 Mc/sec a cylindrical TE_{013} cavity was used. Temperatures different from that of the room were reached by using techniques in which the specimen and its mounting rod were cooled or heated rather than the entire cavity. In the
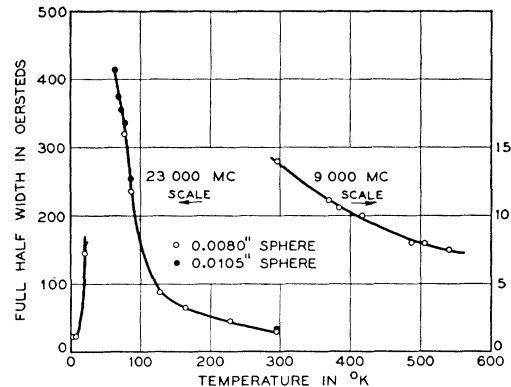

FIG. 1. Plot of line width with the steady field along [100] against absolute temperature. Note the scale change in the vertical coordinate near 300°K. Line width is defined as the field interval between points of $\frac{1}{2}(\mu'')_{max}$. The 295°K line widths of 13 oe at 9300 Mc/sec and 31 at 24 000 Mc/sec indicate a frequency dependence of line width.

spectrometer used in these experiments, a klystron was sawtooth-modulated so as to sweep across an entire mode. The transmission cavity containing the specimen sphere acted as a filter passing only radiation near its natural frequency. The relative power absorbed by the sample was obtained from the variation in the height of the cavity transmission characteristic with magnetic field. Semiautomatic data recording schemes were used at both frequencies.

Shape and width of the resonance lines.—At every temperature, it was found that the line width was a function of crystallographic direction. Figure 1 shows the line width data for the steady field parallel to [100].
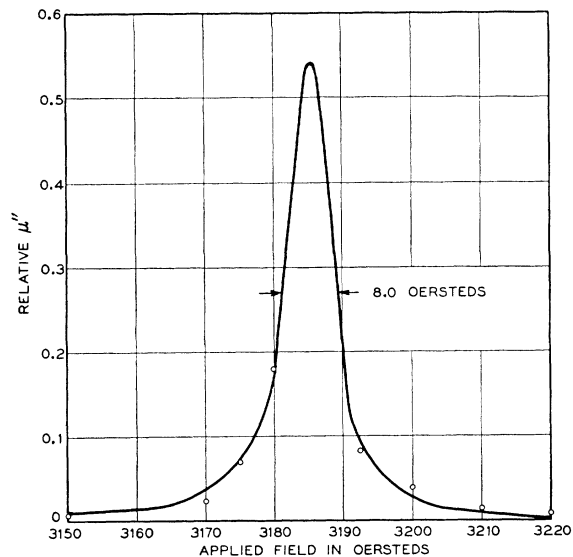

FIG. 2. Line shape taken at 540°K with the steady field along [100]. Curves for the other crystal directions are not shown since they so closely overlap. At this temperature the first-order anisotropy constant $K_1/M_s = 2.27$ oersteds. The circled points are those of the Lorentzian curve $y = 5.4\{1 + [(x-3185.5)/4]^2\}^{-1}$.

It was along this direction that the narrowest line was found in every case. Figure 2 shows a resonance line observed at 540°K.[4] It is only 8.0 oersteds wide. It does not differ from a Lorentzian shape by more than the experimental error. Aside from the very narrow lines at higher temperatures, the most striking feature of the plot in Fig. 1 is the peak which lies between 20° and 65°K. For the case of the steady field along [100], line widths measured at 4.2° and 2.85°K are essentially the same.[5] However, the line widths with the field along other directions are still decreasing with temperature at 2.85°.

Magnetocrystalline anisotropy.—The field required for resonance varied with crystal direction. Values of the constants describing the anisotropy energy surface may be deduced from the fields for resonance measured in an appropriate number of crystal directions. Relations for doing this when first- and second-order terms suffice are collected as a footnote in the paper by Dillon *et al.*[6] If some higher order term in the anisotropy appears, that set of relations is incomplete. Except for data at the very lowest temperatures, K_1/M_s and K_2/M_s were were sufficient to express the observed fields. The coefficient K_1/M_s is plotted in Fig. 3 over the temperature range from 20° to above 500°K. No values of K_2/M_s were obtained in this range which were greater than the error in their determination. At the lowest temperature a much more complex behavior was found.
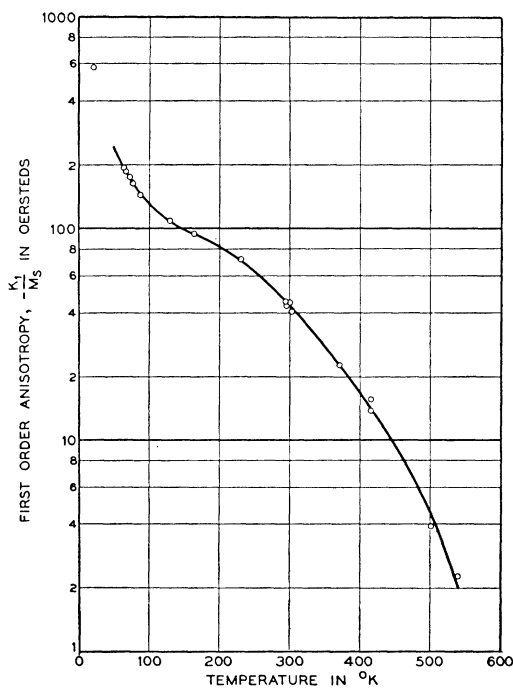

FIG. 3. Variation with temperature of the first-order anisotropy constant K_1/M_s. Values are plotted only for those temperatures at which K_1/M_s described the variation of field for resonance with angle. At 4.2° and below, the coefficients of higher order terms become appreciable.

The crystal still appeared to have cubic symmetry, but the anisotropy surface was rather more convoluted than before. The principal directions are all hard direction at helium temperatures, and the easy directions are near but not exactly coincident with [112] and [221]. This remark applies to directions accessible in a (110) plane. Examination of a crystal mounted to rotate about [111] shows that [123] or a direction very close to it is an even easier direction. The field for resonance in different directions at 4.2° extends over a range of almost exactly 3000 oersteds. Measurements at nearby temperatures show that these values are still changing with temperature. The terms necessary for the expression of this anisotropy and the values of the coefficients will be discussed in a later paper.

Spectroscopic splitting factor.—In the temperature region in which the usual first- and second-order anisotropy terms describe the variation of field for resonance with direction, we may deduce a value of g from the relations in reference 6. The value for g obtained in this way is somewhat arbitrary since it depends upon the form of the terms chosen to express the anisotropy. At room temperature the value $g=2.005\pm0.002$ was obtained at both frequencies for the 0.008-in. sphere, with a slightly lower value for larger spheres. Values of g between 2.002 and 2.009 were obtained for the 0.008-in. sphere in the temperature range from 100° to 540°. Below 100° the values rose with decreasing temperature to 2.040 at 65° and 2.035 at 20.5°. However, this is just the range where higher order terms may be entering the description of the energy surface.

The author wishes to thank J. W. Nielsen for the single crystals, and S. Geller for orienting some of the samples. He is also indebted to A. M. Clogston for helpful discussions and S. Geschwind for many discussions as well as the use of the high-frequency spectrometer.

[1] F. Bertaut and F. Forrat, Compt. rend. 242, 382 (1956).
[2] S. Geller and M. A. Gilleo, Acta Cryst. (to be published).
[3] J. W. Nielsen (unpublished).
[4] F. B. Humphrey has determined the Curie point of these crystals to be 550°K.
[5] At helium temperatures, a discontinuous change in the adsorption takes place above a certain power level. The results quoted here stem from data taken at power levels below that threshold. While nonlinear effects in ferromagnetic resonance are well known, the threshold power level in this case is so low as to merit special interest. These data will be given more fully in forthcoming papers.
[6] Dillon, Geschwind, and Jaccarino, Phys. Rev. 100, 750 (1955).

Electron Spin Relaxation Times in Gadolinium Ethyl Sulfate

G. FEHER AND H. E. D. SCOVIL

Bell Telephone Laboratories, Murray Hill, New Jersey

THE recent proposal by Bloembergen[1] to utilize a paramagnetic salt to amplify or produce micro-