

powers absorbed in the plasma at 100, 300, 500, and 800  $\mu\text{sec}$  are 83.5, 12, 4, and 1.3 milliwatts, respectively.

At this low pressure in neon the return to the original trace after removal of the microwave signal is relatively slow, probably caused by the poor thermal contact between the electron gas and the gas of the plasma. Note that since the loss of electrons by diffusion is not negligible here as it was in the high pressure case (Fig. 1), the intensity of the recombination light does not return to the value it had before the beginning of the microwave pulse.

It appears that the phenomenon here described will be applicable to the study of electron-positive ion recombination processes which result directly or indirectly in light emission. In addition, the quenching of afterglow by absorption of low level microwave signals seems to be a valuable new method of detection of electromagnetic energy.

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- <sup>1</sup> Goldstein, Anderson, and Clark, *Phys. Rev.* **90**, 151 (1953).  
<sup>2</sup> V. A. Bailey and D. F. Martyn, *Phil. Mag.* **18**, 369 (1934).  
<sup>3</sup> M. A. Biondi and S. C. Brown, *Phys. Rev.* **76**, 1697 (1949); Holt, Richardson, Howland, and McCline, *Phys. Rev.* **77**, 239 (1950).  
<sup>4</sup> RCA 931-A for the very near ultraviolet and the appropriate blue region of the visible portion of the spectrum and a 1P25 image converter for the red and near infrared portion of the spectrum.

## Superconducting Compounds of Nonsuperconducting Elements

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THE superconducting molybdenum, tungsten, and bismuth compounds indicate that the metals Mo, W, and Bi themselves are on the borderline of being superconductors.

Thus far the only superconducting compounds of definitely nonsuperconducting elements have been  $\text{CuS}^1$  and  $\text{CoSi}_2^2$  as such they seemed to be in a rather unique position.

The recent discovery of superconductivity in the (NiAs) and (MnP) crystal structures change this situation entirely. In the (NiAs) structure the following compounds of nonsuperconducting elements become superconducting:

$\text{PdSb} \sim 1.5^\circ\text{K}$ ,  
 $\text{PtSb} \sim 2.1^\circ\text{K}$ ,  
 $\text{PtBi} \sim 1.21^\circ\text{K}$ ,  
 $\text{PdTe} \sim 2.3^\circ\text{K}$ .

In the (MnP) structure it is

$\text{IrGe} \sim 4.7^\circ\text{K}$ .

PtBi cannot be considered a typical Bi compound, as  $\text{PtBi}_2$  should and does not become superconducting.<sup>3</sup>

The underlying working hypothesis will be detailed in a later publication.

- <sup>1</sup> W. Meissner, *Z. Physik* **58**, 570 (1930).  
<sup>2</sup> B. T. Matthias, *Phys. Rev.* **87**, 380 (1952).  
<sup>3</sup> N. Alekseyevsky, *J. Exptl. Theoret. Phys.* (U.S.S.R.) **20**, 863 (1950).

## Reversal of Spontaneous Magnetization as a Function of Temperature in $\text{LiFeCr}$ Spinels

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THE spontaneous magnetization of the ferromagnetic oxides having spinel structure<sup>1</sup> has been explained by Néel's hypothesis<sup>2</sup> of ferrimagnetism, or noncompensated antiferromagnetism. A preponderant exchange interaction between the magnetic moments on tetrahedral ( $8a$ )<sup>3</sup> and octahedral ( $16d$ )<sup>3</sup> sites, respectively, results in antiparallel alignment of these

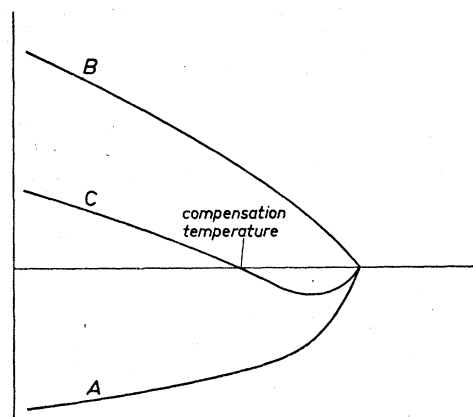


FIG. 1. A. Partial magnetization of tetrahedral sites vs temperature; B. partial magnetization of octahedral sites vs temperature; C. resulting spontaneous magnetization vs temperature. (After Néel, see reference 2.)

moments, and the spontaneous magnetization is thus the difference between the (unequal) partial magnetizations on tetrahedral and octahedral sites, respectively. This assumption has been amply verified by measurements of the saturation magnetization of various ferrites.<sup>4-6</sup>

The application of the neutron diffraction technique<sup>7</sup> has provided direct evidence for the correctness of Néel's hypothesis.

Néel pointed out<sup>2</sup> that the Weiss molecular fields for magnetic ions in the two crystallographic positions will be different because of the difference in numbers and spin orientations of the respective neighboring magnetic ions. Therefore, the curves giving the decrease of the two partial magnetizations with temperature will have different shapes. Thus Néel foresaw the possibility of the existence *inter alia* of a spontaneous magnetization that changes sign at a certain temperature (see Fig. 1).

We have investigated the series of mixed crystal spinels<sup>8</sup>  $\text{Li}_{0.5}^+\text{Fe}_{2.5-a}^{3+}\text{Cr}_a^{3+}\text{O}_4^{2-}$  between  $a=0$  and 2.0 and have found that this phenomenon occurs between  $a=1.0$  and 1.6.

The saturation magnetization of  $\text{Li}_{0.5}\text{Fe}_{1.25}\text{Cr}_{1.25}\text{O}_4$  vs temperature is shown in Fig. 2, curve I. In order to ascertain whether indeed the spontaneous magnetization changes sign, a rod of the material was saturated at a low temperature: the remanent magnetization was then measured in the absence of a magnetic field ( $\perp$  the earth's field) as a function of temperature. Curve II

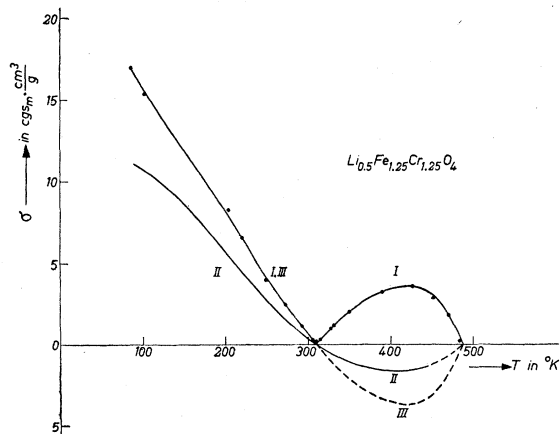


FIG. 2. I. Saturation magnetization of  $\text{Li}_{0.5}\text{Fe}_{1.25}\text{Cr}_{1.25}\text{O}_4$  vs temperature. The points given are measured at 8000 Oe. Points measured at 6000 and 4000 Oe show no greater deviations from the drawn curve; II. residual magnetization of a rod of this material (arbitrary scale); III. spontaneous magnetization.

shows that the remanent magnetization, and thus the spontaneous magnetization (curve III) is indeed reversed at about 38°C.

When a rod of this material is magnetized and suspended torsion-free in a small magnetic field ( $<H_c$ ), the turning of the rod over an angle of 180° on heating or cooling through the compensation temperature provides an illuminating demonstration of the existence of ferrimagnetism.

According to Néel's theory<sup>2</sup> this phenomenon could occur for spinels containing only one type of magnetic ions (e.g., Fe<sup>3+</sup>), when a certain relation (reference 1, p. 151) holds between the distribution of the magnetic ions among the tetrahedral and octahedral positions and the ratios between the tetr.-oct., tetr.-tetr. and oct.-oct. (indirect) exchange interactions.

As these ratios are fixed by the angles Me-O-Me,<sup>3</sup> and the distances Me-O (Me = magnetic ion) according to unknown laws,<sup>10</sup> it seems likely that for one type of magnetic ion only this relation can be fulfilled for a very narrow range of ionic distributions only.

For a material containing two types of magnetic ions Me<sub>i</sub> and Me<sub>ii</sub> there are, in addition, differences between the interactions Me<sub>i</sub>-Me<sub>i</sub>, Me<sub>i</sub>-Me<sub>ii</sub> and Me<sub>ii</sub>-Me<sub>ii</sub>, so that here a corresponding relation may be more easily fulfilled.

X-ray investigation of the above series of solid solutions<sup>11</sup> shows *inter alia* that with increasing Cr-content *a* an increasing proportion of Li ions occupies the tetrahedral position. This accounts for the fact that the low temperature saturation magnetization of Li<sub>0.5</sub>Fe<sub>1.25</sub>Cr<sub>1.25</sub>O<sub>4</sub> is unequal to zero, which value should have been expected for an arrangement [Fe]<sup>tetr</sup>[Li<sub>0.5</sub>Fe<sub>0.25</sub>Cr<sub>1.25</sub>]<sup>oct</sup>O<sub>4</sub>.

The magnetic investigation of the system Li<sub>0.5</sub>Fe<sub>2.5-a</sub>Cr<sub>a</sub>O<sub>4</sub> will be reported upon in the near future.<sup>12</sup> An interesting behavior of the *g* factor as a function of temperature was found by van Wieringen.<sup>13</sup>

<sup>1</sup> P. P. Ewald and C. Hermann, *Strukturberichte* (Akademische Verlagsgesellschaft, Leipzig, 1931), Vol. I, p. 350.

<sup>2</sup> L. Néel, *Ann. phys.* 3, 137 (1948).

<sup>3</sup> *International Tables for X-ray Crystallography* (Kynoch Press, Birmingham, England, 1952), Vol. I, p. 340.

<sup>4</sup> E. W. Gorter, *Nature* 165, 798 (1950); or *Compt. rend.* 230, 192 (1950).

<sup>5</sup> L. Néel, *Compt. rend.* 230, 190, 375 (1950).

<sup>6</sup> C. Guillaud *et al.*, *Compt. rend.* 229, 1133 (1949); 230, 1256, 1458 (1950); 232, 944 (1951).

<sup>7</sup> Shull, Wollan, and Strauser, *Phys. Rev.* 81, 483 (1951).

<sup>8</sup> For long-range order phenomena at the limiting compositions, see P. B. Braun, *Nature* 170, 1123 (1952) and reference 10.

<sup>9</sup> P. W. Anderson, *Phys. Rev.* 79, 350 (1950); E. W. Gorter, *J. phys. et radium* 12, 237 (1951).

<sup>10</sup> R. S. Weiss, *Ceramic Age* 59, 35 (1952), suggests an empirical formula for this relationship, which cannot, however, easily be tested because of the large possible error in the experimental oxygen parameter values. Theoretical background is still lacking.

<sup>11</sup> P. B. Braun, *Physica* (to be published).

<sup>12</sup> E. W. Gorter and J. A. Schulkes, *Physica* (to be published).

<sup>13</sup> J. S. van Wieringen, *Phys. Rev.* 89, 488 (1953).

## Anomalous Behavior of the *g* Factor of LiFeCr Spinels as a Function of Temperature

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IN the preceding letter<sup>1</sup> ferromagnetic LiFeCr spinels are described with a curious  $\sigma-T$  curve. For a certain range of values of *a* in the mixed crystal series Li<sub>0.5</sub>Fe<sub>2.5-a</sub>Cr<sub>a</sub>O<sub>4</sub>, the magnetization changes sign at a "compensation" temperature that depends on *a*. For Li<sub>0.5</sub>Fe<sub>1.25</sub>Cr<sub>1.25</sub>O<sub>4</sub> (*a* = 1.25), this compensation temperature is situated at 38°C. We measured the ferromagnetic resonance absorption of polycrystalline samples of Li<sub>0.5</sub>Fe<sub>1.25</sub>Cr<sub>1.25</sub>O<sub>4</sub> at 3.1-cm wavelength as a function of temperature. The samples were placed near the bottom of a TE111 resonant cavity. The cavity could be heated up by a filament or cooled down by a stream of cooled air. Two spheres of Li<sub>0.5</sub>Fe<sub>1.25</sub>Cr<sub>1.25</sub>O<sub>4</sub> of radii 0.5 and 0.2 mm, respectively, gave the same temperature dependence of *g*. Near the compensation temperature strong variations are found in the *g* factor (Fig. 1).

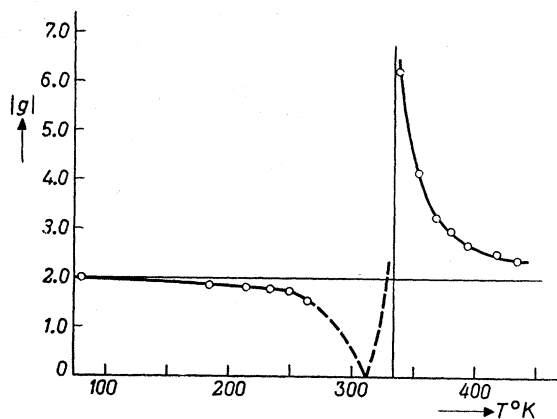


FIG. 1. *g* factor of Li<sub>0.5</sub>Cr<sub>1.25</sub>Fe<sub>1.25</sub>O<sub>4</sub> as a function of temperature. Dashed curve: approximate extrapolation making use of Kittel's *g*-factor formula (1).

Between 263 and 337°K the resonance absorption was too weak to be observed. This is the temperature region where the magnetic moment is very small.<sup>1</sup> Hence the resonance peak may be expected to have a small height here. Its height is still further reduced, because the half-width increases in the same temperature region.

The general behavior of the *g* vs *T* curve can be understood from Kittel's formula<sup>2</sup> for the spectroscopic *g* factor

$$g = \frac{2mc}{e} \frac{M_{\text{spin}} + M_{\text{orbit}}}{J_{\text{spin}}} \quad (1)$$

Here  $M_{\text{spin}}$  and  $M_{\text{orbit}}$  are the mean spin and orbital magnetic moments, respectively, and  $J_{\text{spin}}$  is the mean spin angular momentum averaged over the two sublattices. The total magnetic moment,  $M_{\text{spin}} + M_{\text{orbit}}$ , is shown in Fig. 2 of the preceding letter.<sup>1</sup> It changes sign at 38°C; hence *g* should be zero there. From a comparison of Eq. (1) and Fig. 1 it follows that  $J_{\text{spin}}$  goes through zero at about 60°C.

A sphere (radius 0.2 mm) of Li<sub>0.5</sub>FeCr<sub>1.5</sub>O<sub>4</sub> (*a* = 1.5) showed a similar resonance behavior.

The author wishes to thank Mr. Gorter and Mr. Schulkes who supplied the samples and Mr. Beljers and Mr. Van der Kint for their assistance during the measurements.

It is intended to publish a more detailed account in *Physica*.

<sup>1</sup> E. W. Gorter and J. A. Schulkes, preceding letter, *Phys. Rev.* 89, 487 (1953).

<sup>2</sup> C. Kittel, *Phys. Rev.* 76, 743 (1949).

## Semiconducting Intermetallic Compounds

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THE development of solid state electronic devices has been handicapped by the very small number of semiconducting materials that have been found suitable for practical application in spite of extensive investigations of the properties of the elements and of compounds of the elements of group six of the periodic table. It seems, however, that the existence of a number of semiconductors with promising properties has been largely overlooked, namely, the semiconducting intermetallic compounds. It was pointed out by Mott and Jones<sup>1</sup> that intermetallic compounds with the fluorspar structure, such as Mg<sub>2</sub>Sn, should be characterized by an unusually low conductivity, since the number of available states within the first Brillouin zone is just equal to the number of available valence electrons. This unusually low conductivity was first observed experimentally by Kurnakov and Stephanov.<sup>2</sup> More recently the semiconducting nature of Mg<sub>2</sub>Sn