Letters to the Editor

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Theory of the Formation of Powder Patterns on Ferromagnetic Crystals

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MAGNETIC powder patterns or "Bitter patterns" are sometimes formed on the surfaces of ferromagnetic crystals when a liquid suspension of fine ferromagnetic particles is placed on the crystal. Powder patterns are the most powderful tool available for the study of the nature of ferromagnetic domains,[1] yet there has not been an adequate discussion of the mechanism by which the powder particles collect at domain boundaries to form the lines which are observed under the microscope. It is frequently said that the colloid particles collect in the regions in which the maximum inhomogeneity in the local magnetic field occurs. This is an inadequate statement, and in particular fails to account for the enhancement of some lines when a uniform magnetic field is applied normal to the surface under examination, and the disappearance of other lines under the same conditions.

The particles in the suspension are small enough so that they remain indefinitely in suspension. The particle distribution is accordingly governed by the Boltzmann distribution law. The magnetic energy of a particle of effective susceptibility $\chi=(\mu-1)/4\pi$ in a field H is $-\frac{1}{2}\chi H^2V$, where V is the volume of the particle. In thermal equilibrium the density of particles is given by

$$p(H)=p(0)e^{\chi H^2V}/2^{kT}, \qquad (1)$$

where $p(0)$ is the density at a point for which $H=0$. It is seen that there will be a marked tendency for the particles to concentrate in regions in which H^2 is large.

On the surfaces of crystals there are strong local fields of diverse origin. The fields of greatest interest are caused by long narrow strips of poles formed by the intersection of Bloch walls with the crystal surface. Suppose that the poles produce a magnetic field $\mathbf{\Delta H}$ in their vicinity; we then apply from outside a uniform field $\mathbf{H}$. The particle density over the line of poles will be greater than that in other places by the factor

$$\exp[[2\mathbf{H}\cdot\mathbf{\Delta H}+(\Delta H)^2]\chi V/2kT].$$

When $\mathbf{H}$ is in the same direction as $\mathbf{\Delta H}$, the line is enhanced with respect to the density in the absence of the applied field; if $\mathbf{H}$ is opposite to $\mathbf{\Delta H}$, the line is weakened and may be made to disappear. The operation of this effect is beautifully illustrated by Fig. 17 in the paper by Williams, Bozorth, and Shockley.[1]

In the absence of an external field it is necessary that $(\Delta H)^2\chi V \gg 2kT$ for a well-defined line to collect. For magnetite spheres the effective susceptibility is essentially determined by the demagnetizing factor and we have $\chi\cong\frac{3}{4}\pi$. We require, for particles of volume 10^{-12} cc,

$$|\Delta H|\gg[2kT/\chi V]^{\frac{1}{2}}\cong[4\times10^{-13}/10^{-12}]^{\frac{1}{2}} \cong 0.6 \text{ oersted},$$

which may be expected to be exceeded near a Bloch wall.

If the particles in the suspension are small enough to behave as single domains,[2] that is, as small permanent magnets, then the distribution law will be

$$p(H)=p(0)[\sinh(\mu H/kT)]/(\mu H/kT), \qquad (2)$$

where μ is the magnetic moment of a particle. This relation is obtained by integrating the Boltzmann factor $\exp[\mu H\cos\theta/kT]$ over all solid angles. The effect of an applied field is exhibited in some cases by this density function, although in a less striking manner. In the colloidal suspensions employed in practice the particle size is relatively large, so that distribution law (1) is applicable. An account of other aspects of the theory will be found in reference 3. In the derivation of both distribution functions we have neglected field inhomogeneities over the volume of a single particle, the effects of mutual interactions among the particles, and the reorientation of spins in a wall under the action of the external magnetic field. These approximations are not likely to change the general nature of the results.

[1] Williams, Bozorth, and Shockley, Phys. Rev. **75**, 155 (1949); H. J. Williams and W. Shockley, Phys. Rev. **75**, 178 (1949).
[2] C. Kittel, Phys. Rev. **70**, 965 (1946).
[3] C. Kittel, Rev. Mod. Phys. **21**, 541 (1949).

Nuclear Moments of Mg^{25}

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THE Mg I lines 5184, 5173, and 5167A ($3s3p\,^3P^0_{2,1,0}-3s4s\,^3S_1$) and the Mg II resonance line 2796A ($3s\,^2S_{1/2}-3p\,^2P^0_{3/2}$) have been excited in an atomic beam light source and their hyperfine structures resolved with a Fabry-Perot etalon. The structures show that for Mg^{25} I=5/2 and the nuclear magnetic moment is negative and equal to -0.96 ± 0.07 nuclear magnetons.

The line 5167A ($3s3p\,^3P_0-3s4s\,^3S_1$) was studied with 21-, 54-, and 73-mm etalons. The interferometer plates were coated with evaporated silver[1] to give a reflectivity of 80 percent and a transmission of 17.5 percent in the green. The 21-mm etalon patterns showed no structure. The 54-mm patterns showed two weak components which are assigned to Mg^{25}, a strong component due to Mg^{24}, and indications of a component due to Mg^{26} very close to Mg^{24}. The separations of the Mg^{25} components relative to the Mg^{24} components are $+0.0303\pm0.0004$ and -0.0341 ± 0.0006 cm^{-1} where the positive sign indicates a higher wave number.

For all three lines the Mg^{24} and Mg^{26} components were resolved with a 73-mm etalon in which the silver films had a 90 percent reflectivity. The separations of the Mg^{26} component relative to the Mg^{24} component are -0.0138 ± 0.0003, -0.0122 ± 0.0015, and -0.0138 ± 0.0004 cm^{-1} for the lines 5167, 5173, and 5184A, respectively. As predicted by the specific mass effect, the isotope shifts in all three lines are equal within the assigned errors.

The resolution of the Mg^{24} and Mg^{26} components in 5167A permits an accurate determination of the center of gravity of the three components due to Mg^{25}, on the assumption that it is midway between the Mg^{24} and Mg^{26} components. Thus the interval rule can be used to determine the I value. The separations of the two Mg^{25} components, measured in the 54-mm pattern, from their center of gravity are -0.0272 and $+0.0372$ cm^{-1}. The ratio of these separations is 1.37 ± 0.07. This ratio should be 1.40 for I=5/2 and 1.29 for I=7/2. Thus the spin of Mg^{25} is 5/2 and the inverted splitting of $^3S_1$ shows that the magnetic moment is negative.

The over-all separation of the Mg^{25} components, 0.0644 ± 0.0010 cm^{-1}, is equal to $6A(^3S_1)$, where $A(^3S_1)$ is the h.f.s. interval factor. Thus $A(^3S_1)=0.0107$ cm^{-1}, and gives $\mu(Mg^{25})=-0.97\pm0.05$ n.m. by the method used for P IV by Crawford and Levinson.[2]

The line 2796A ($3s\,^2S_{1/2}-3p\,^2P_{3/2}$) was studied with 21-, 30-, and 50-mm etalons using aluminum coated plates with reflectivities of 80 percent. The 21-mm pattern showed a strong com-