A phenomonological calculation of the effect of external magnetic fields on the Morin transition in hematite

by Robert William Gable

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Electrical Engineering
Montana State University

Abstract:
The effect of applied magnetic fields on the Morin transition of hematite (α-Fe2O3) has been investigated from a phenomenological point of view; all applied fields are directed in the (lll) plane. The calculation shows a temperature depression that is nearly proportional to the square of the applied field and a transition temperature which is close to the experimentally observed results.

Using a dipolar model only, the effect of certain impurities on the Morin transition has also been investigated and found to be inconsistent with experiment.

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A PHENOMONOLOGICAL CALCULATION OF THE EFFECT OF EXTERNAL MAGNETIC FIELDS ON THE MORIN TRANSITION IN HEMATITE

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ABSTRACT

The effect of applied magnetic fields on the Morin transition of hematite (α-Fe_2O_3) has been investigated from a phenomonological point of view; all applied fields are directed in the (111) plane. The calculation shows a temperature depression that is nearly proportional to the square of the applied field and a transition temperature which is close to the experimentally observed results.

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CHAPTER I

INTRODUCTION

In recent years a considerable amount of research has been devoted to studying the curious magnetic properties of hematite (α-Fe_2O_3) single crystals. The emphasis has been particularly intense since the discovery of neutron diffraction spectroscopy which is suitable to the investigation of antiferromagnetic materials. In fact, neutron diffraction methods produced the first experimental verification of Néel's original theory of antiferromagnetism.[1] He assumed the material was composed of two sublattices with equal magnetizations that are arranged in an antiparallel fashion, each sublattice being strongly coupled ferromagnetically within itself.

Hematite is the iron member of a group of antiferromagnetic sesquioxides all of which are isomophous with corundum, α-Al_2O_3. The most common are the oxides of Cr, Fe, Ti, and V. The respective antiferromagnetic structures differ only by lattice parameters and spin arrangement. In each case, the oxides have a trigonal unit cell containing four magnetic cations. For α-Fe_2O_3 the spins are directed in a +--+ order along the triaxial or c axis [111] as in Fig. 1a. The arrangement of the unit cells is such that all spins within any triaxial plane (111) are parallel, and adjacent planes contain oppositely directed spins as shown in Fig. 1b.

Since the actual distribution of spin states of any magnetic material is determined by a Boltzmann factor, it is evident that magnetic quantities will be strongly temperature dependent. The temperature dependency of the magnetic properties of hematite is particularly interesting and unique among the sesquioxides.

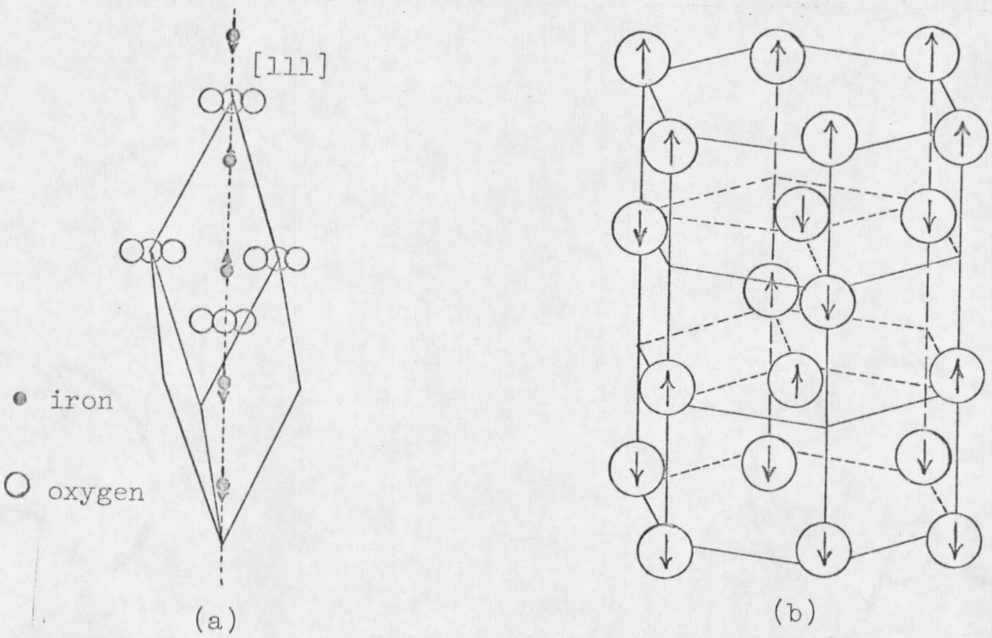

Fig. 1. (a) Trigonal cell of α-Fe_2O_3 showing spin arrangement of cation spin, (b) planar arrangement Fe ions.

For temperatures below a certain critical value, for the moment defined as T_m, the material is a pure antiferromagnet with spins aligned collinear with the c axis. In this antiferromagnetic phase, the magnetic susceptibilities $\chi_{\parallel}$ and $\chi_{\perp}$, for external fields applied parallel and perpendicular to the c axis respectively, behave according to the standard molecular field theory.

At the temperature T_m, about 260°K for pure hematite, there is a second-order phase transition and the spins rotate 90° into the triaxial plane (111) in such a manner that antiferromagnetism is still retained.* The effect of this rotation causes $\chi_{\parallel}$ to rise abruptly to the $\chi_{\perp}$ value,

*The actual situation is one of weak ferromagnetism. This will be explained later.

since the spin direction is now perpendicular to the c axis. On the other hand, $\chi_\perp$ would ideally stay constant since the spins are nearly free to rotate in the triaxial plane. The critical temperature, T_m, is often referred to as the Morin transition temperature after F. J. Morin[2] who originally reported the effect.

The cause of this phase transition has been the subject of discussion from the time of its discovery. One phenomenological approach to the effect shows that the spin-flip may be interpreted as a change of sign of the first-order crystalline anisotropy constant.[3,4] This is consistent with the definition, to first-order, of a uniaxial anisotropy energy of the form:

$$F = (K/2)\sin^2\alpha, \qquad 1.1$$

where α is the angle between the magnetic moment and the trigonal axis and K is the first-order anisotropy constant. The thermodynamic free energy, due to anisotropy, is then a minimum when $\alpha=0$ for $K>0$ and when $\alpha=\frac{\pi}{2}$ for $K<0$. From this idea, a phenomenological interpretation can be made by assuming that if the anisotropy constant is positive, the preferred or easy direction of the magnetic moment is collinear with the trigonal axis. Above T_m, however, the sign of K is negative and the spins lie in the triaxial plane.

The temperature range between T_m and the Néel temperature is complicated by an additional effect which is of interest. All of the spins are perpendicular to the c axis; but they are not directly antiparallel. Due to an anisotropic spin coupling the magnetic moments tend to be canted at a small angle with respect to each other. This results in a weak ferromagnetism since there is a net magnetic moment in the plane. The situation is