ΦΥΣΙΚΗ.— **Magnetoresistance of Magnetite after application of various magnetic fields,** *by D. Kostopoulos - J. Grammatikakis* *. Ἀνεκοινώθη ὑπὸ τοῦ Ἀκαδημαϊκοῦ κ. Κ. Ἀλεξοπούλου.

ABSTRACT

The state of magnetite at low temperature is disturbed by a magnetic field (H_{dis}) even below the transition point at 120 K. This effect is examined at 78 K from measurements of the transversal magneto-resistance with a working field H_w in a variety of directions. Two methods were applied. In the first, the H_{dis}, H_w and the field H_{tr} during the transition, were static. Moreover the H_{dis} in some cases was applied in one direction but in other cases successively in two directions. In the second method the H_{tr} was static but the H_w was rotating.

In this case the disturbance was found to be due to the working fields of all preceeding measurements.

1. INTRODUCTION

It has long been known that the application of a magnetic field during the cooling of magnetite through the transition point (120 K) produces a number of pronounced effects. Their interpretation is respect to crystalline superstructure, magnetic structure and orientation of the quasi-orthorhombic c-axis is not yet securely established [1]. Also the arrangement of divalent and trivalent ions in the lattice and the mechanism of the electrical conductivity are strongly disputed. Subsequently it was found that the state could be disturbed also at temperatures below the transition point. Bickford [2] showed that a field at 15 kG can produce switching of the quasi-orthorhombic c-axis at temperatures between 90 K and the transition point. Calhoun [3] found that the field necessary for switching increased as the temperature is lowered.

Bonstrom, Morrish and Watt [4] managed to untwine the a- and b-axes in the temperature range between 80 and 90 K by applying a magnetic field in a suitable direction. Vittoratos, Baranov and Meincke [5]

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* ΔΗΜ. ΚΩΣΤΟΠΟΥΛΟΥ - ΙΩΑΝ. ΓΡΑΜΜΑΤΙΚΑΚΗ, **Μαγνητοαντίστασῃ τοῦ Μαγνητίτου ὑπὸ τὴν ἐπίδρασιν διαφόρων μαγνητικῶν πεδίων.**

found that the switching effects are not established immediately; the relaxation time increases as the temperature is lowered.

In a recent paper [6] we described the influence of such «disturbing fields» at 78 K on the magnetoresistence MR. The measurements were made after cooling through the transition point under the influence of a «transition field» H_{tr}, then applying a «disturbing field» H_{dis} at 78 K and finally measuring MR with a working field H_w. Various directions were chosen for each of these fields. It was found that the disturbing field could considerably influence the MR so that the magnetic prehistory of a specimen should be carefully scrutinized if there will be any hope of explaining the dependence of MR on the crystallographic or the magnetic state. In the present paper the measurements of Ref. 6 are extended to a variety of crystallographic directions. In some cases two consecutive disturbing fields were applied before starting the MR measurements.

2. EXPERIMENTAL

The specimen and the experimental arrangment are the same as in Ref. 6. The crystallographic indices used are those of the initially cubic crystal. The working field is always perpendicular to the current direction [110] thus giving the transversal MR. In all experiments H_{dis} was chosen equal to 11 kG. Two different sequences of operations were followed during the measurements. For reasons of convenience they will be designated a) as static and b) as rotating sequence.

3. STATIC SEQUENCE

Each curve of this category has been taken after a single cooling through the transition point under a field H_{tr} and then applying a disturbing field towards a single or two consecutive directions. Finally MR is measured for a certain weak working field H_w thus obtaining one point of the curve. Before measuring the next point with a somewhat larger value of H_w the specimen is demagnetized. In this way a curve is obtained for working fields up to 11 kG. Before another curve is taken, corresponding to another H_{tr}, the specimen was heated up to room temperature.

3.1. Working field parallel to the $[1\bar{1}1]$ direction.

3.1.1. $H_{tr} // [001]$, $H^{a}_{dis} // [001]$, $H^{b}_{dis} // [1\bar{1}0]$, $H_{w} // [1\bar{1}1]$.

Curves **a** to **g** of Fig. 1 show the MR as a function of $H_w // [1\bar{1}1]$ for transition fields $H_{tr} // [001]$ of various strengths. As for the disturbing field it was first applied in the same direction $[00\bar{1}]$ as the transition field and then after sometime in the $[1\bar{1}0]$ direction. During the applica-

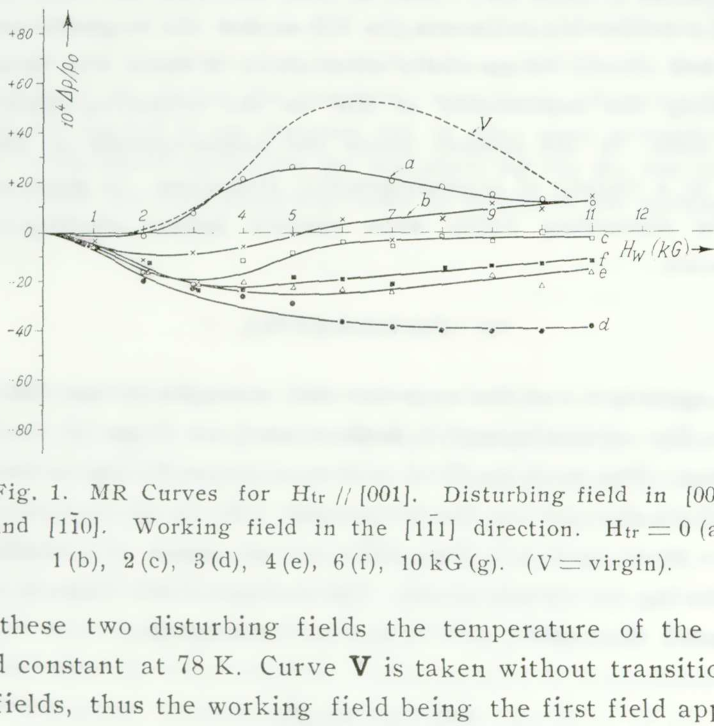

Fig. 1. MR Curves for $H_{tr} // [001]$. Disturbing field in [001] and $[1\bar{1}0]$. Working field in the $[1\bar{1}1]$ direction. $H_{tr} = 0$ (a), 1 (b), 2 (c), 3 (d), 4 (e), 6 (f), 10 kG (g). (V = virgin).

tion of these two disturbing fields the temperature of the specimen remained constant at 78 K. Curve **V** is taken without transition or disturbing fields, thus the working field being the first field applied. We describe this state as «virgin».

Curve **a** is also taken without a transition field ($H_{tr} = 0$) but we remind that two disturbing fields have been applied. The difference between **a** and **V** is solely due to the influence of the disturbing fields.

3.1.2. $H_{tr} // [1\bar{1}0]$, $H^{a}_{dis} // [1\bar{1}0]$, $H^{b}_{dis} // [001]$, $H_{w} // [1\bar{1}1]$.

Curves **a** to **f** of Fig. 2 show the MR as a function of $H_w // [1\bar{1}1]$ for various values of a transition field parallel to the $[1\bar{1}0]$ direction and for two successive disturbing fields $H^{a}_{dis} // [1\bar{1}0]$ and $H^{b}_{dis} // [001]$. Curve **V** represents the virgin material.

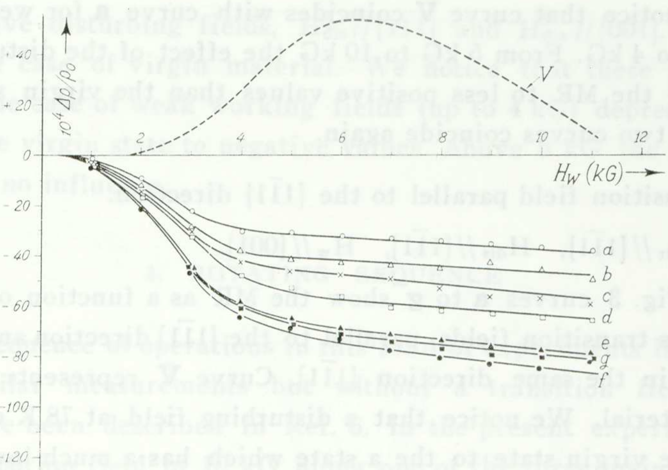

Fig. 2. MR Curves for H_{tr} // [1$\bar{1}$0]. Disturbing field in [1$\bar{1}$0] and [001]. Working field in the [1$\bar{1}$1] direction $H_{tr} = 0$ (a), 2 (b), 3 (c), 6 (d), 8 (e), 10 kG (f). (V = virgin).

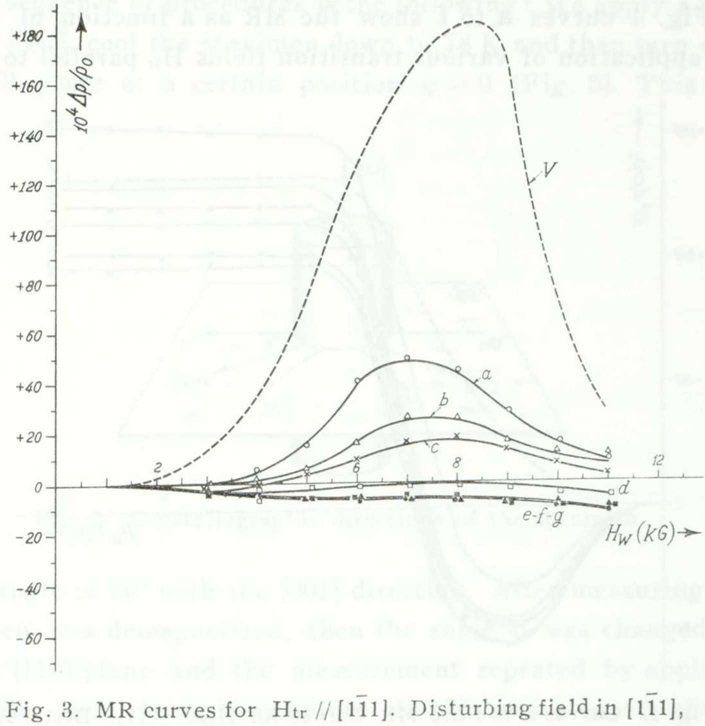

Fig. 3. MR curves for H_{tr} // [1$\bar{1}$1]. Disturbing field in [1$\bar{1}$1], Working field in [001] direction $H_{tr} = 0$ (a), 1 (b), 2 (c), 3 (d), 4 (e), 6 (f), 10 kG (g). V = virgin).

We notice that curve **V** coincides with curve **a** for weak working fields up to 4 kG. From 5 kG to 10 kG the effect of the disturbing field is to bring the MR to less positive values than the virgin state but at 11 kG the two curves coincide again.

3.2. Transition field parallel to the $[1\bar{1}1]$ direction.

3.2.1. $H_{tr} // [1\bar{1}1]$, $H_{dis} // [1\bar{1}1]$, $H_w // [001]$.

In Fig. 3 curves **a** to **g** show the MR as a function of $H_w // [001]$ for various transition fields, parallel to the $[1\bar{1}1]$ direction and a disturbing field in the same direction $[1\bar{1}1]$. Curve **V** represents the case of virgin material. We notice that a disturbing field at 78 K changes the MR of the virgin state to the a state which has a much lower positive value. Anyway, we see that at high working fields we again tend to have a coincidence of the **V** and **a** curves.

3.2.2. $H_{tr} // [1\bar{1}1]$, $H^a_{dis} // [1\bar{1}1]$, $H^b_{dis} // [001]$, $H_w // [110]$.

In Fig. 4 curves **a** to **f** show the MR as a function of $H_w // [110]$ after the application of various transition fields H_{tr} parallel to $[1\bar{1}1]$ and

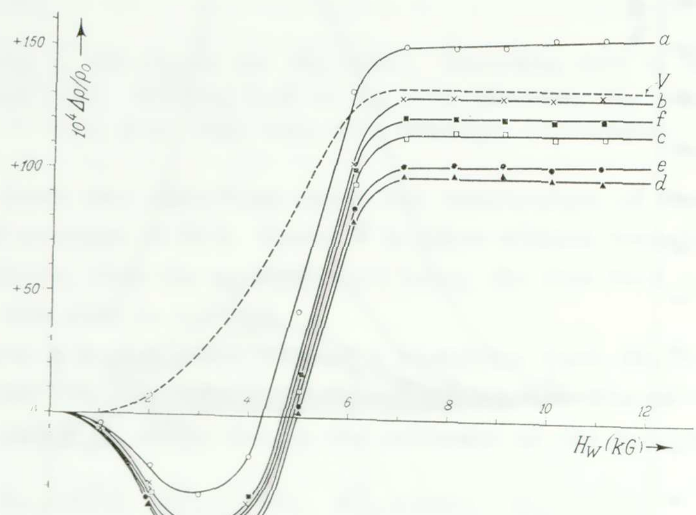

Fig. 4. Curves a to f are MR Curves for $H_{tr} // [1\bar{1}1]$. Disturbing field in $[1\bar{1}1]$ and $[001]$. Working field in the $[1\bar{1}0]$ direction $H_{tr} = 0$ (a), 2 (b), 3 (c), 4 (d), 6 (e)r 10 kG (f), (V = virgin).

two succesive disturbing fields, $H^a_{dis}//[1\bar{1}1]$ and $H^b_{dis}//[001]$. Curve **V** reflects the case of virgin material. We notice that these disturbing fields in the case of weak working fields (up to 4 kG) depress the MR curve of the virgin state to negative values. Above 5 kG the disturbing fields have no influence.

4. ROTATING SEQUENCE

The sequence of operations in this kind of experiments is described below. Similar measurements but without a transition field during cooling have been described in Ref. 6. In the present experiments we apply a transition field of 10 kG along one of the three main crystallographic directions.

4.1. Transition field parallel to [001] direction.

The sequence of procedures is the following: We apply a transition field $H_{tr}//[001]$, cool the specimen down to 78 K and then turn on a field in the (110) plane at a certain position $\varphi = 0$ (Fig. 5). This direction

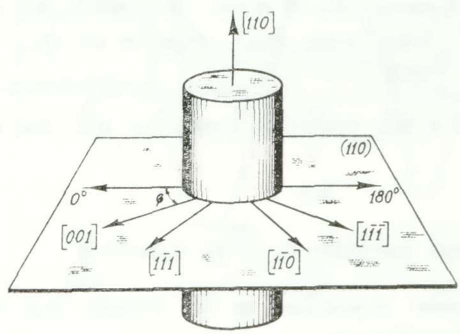

Fig. 5. Crystallographic directions of the specimen.

makes an angle of 30° with the [001] direction. After measuring the MR the specimen was demagnetized, then the angle φ was changed slightly within the (110) plane and the measurement repeated by applying the same working field strength as before. In this way a curve of constant working field was obtained. After each curve was taken the specimen was heated to room temperature so that the next curve was in no way influenced by the precedent handling. The procedure was then repeated with another value of H_w. The results are given in Fig. 6. The comparison with Fig. 5 of Ref. 6 shows a very strong influence of the transi-

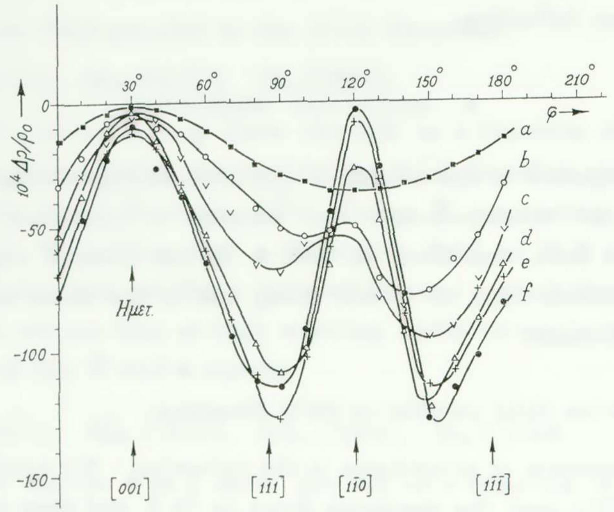

Fig. 6. MR Curves for various working fields within the (110) plane. $H_{tr} = 10$ kG, H_{tr} //[001] $H_w = 2$ (a), 3 (b), 4 (c), 6 (d), 8 (e), 10 kG (f).

tion field; it gives a big negative term to MR for all directions φ of the working field.

4.2. Transition field parallel to [1$\bar{1}$0] direction.

This experiment is similar to the former but the transition field 10 kG is applied in [1$\bar{1}$0] direction.

The results are seem in Fig. 7. A working field increases the positive terms of MR in all those azimouths that are close to the [001] direction.

For azimouths near the [1$\bar{1}$0] directions, which we remind is the direction of H_{tr}, the influence of the working field is weaker.

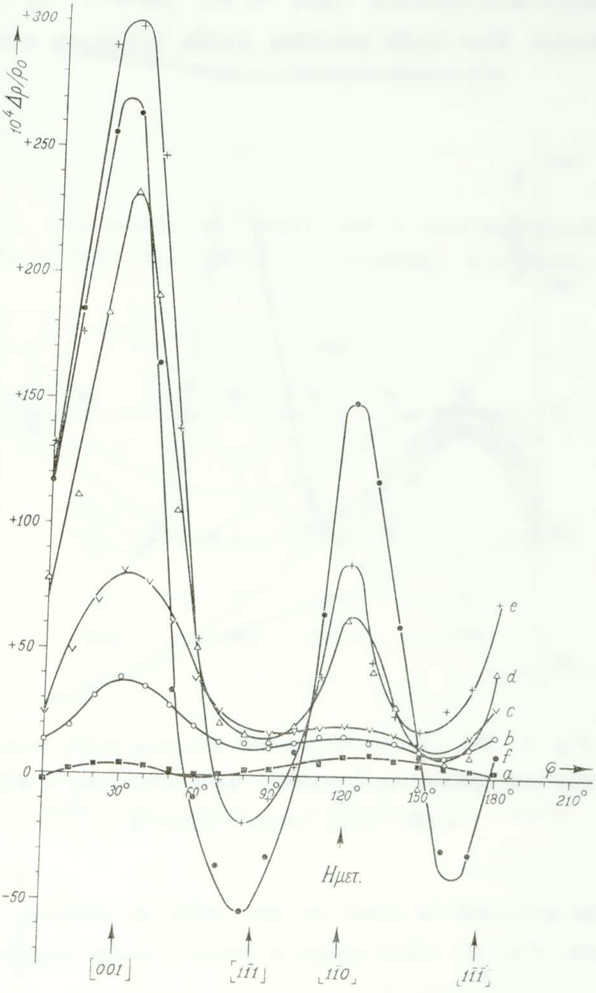

Fig. 7. MR Curves for various working field within the (110) plane. $H_{tr} = 10$ kG, H_{tr} // [1$\bar{1}$0]. $H_w = 2$ (a), 3 (b), 4 (c), 6 (d), 8 (e), 10 kG (f).

4.3. Transition field parallel to [1$\bar{1}$1] direction.

If we apply a transition field 10 kG parallel to [1$\bar{1}$1] direction (Fig. 8) we notice that large working fields influence strongly the MR

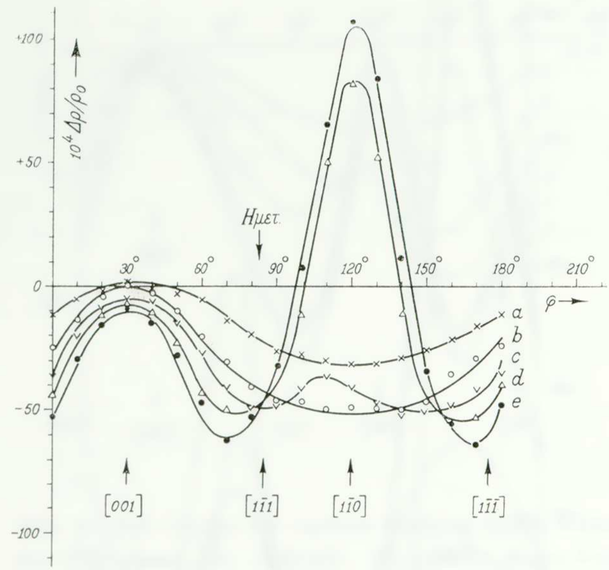

Fig. 8. MR Curves for various working fields within the (110) plane. $H_{tr} = 10$ kG, H_{tr} // [1$\bar{1}$1]. $H_w = 2$ (a), 3 (b), 4 (c), 6 (d) 10 kG (f).

only when the azimuth is close to the [1$\bar{1}$0] direction; it produces an increase of MR. For all other cases it gives a weak negative term.

5. COMPARISON OF THE STATIC AND THE ROTATING SEQUENCE

The influence of a disturbing field preceeding the actual measurement of the MR can be clearly seen in Figs. 9-11 where the MR curves obtained from the rotating sequence are compared to the corresponding curves of the static sequence.

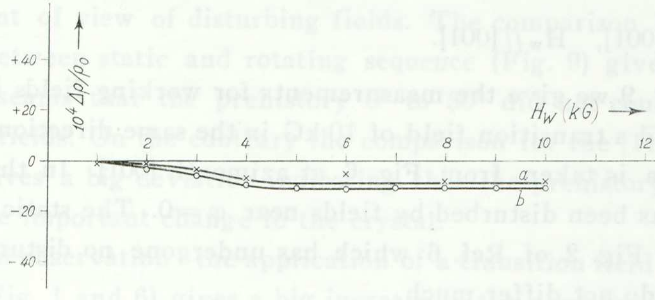

Fig. 9. Comparison of a static and a rotating sequence H_{tr} // [001], H_w // [001]. a = rotating, b = static.

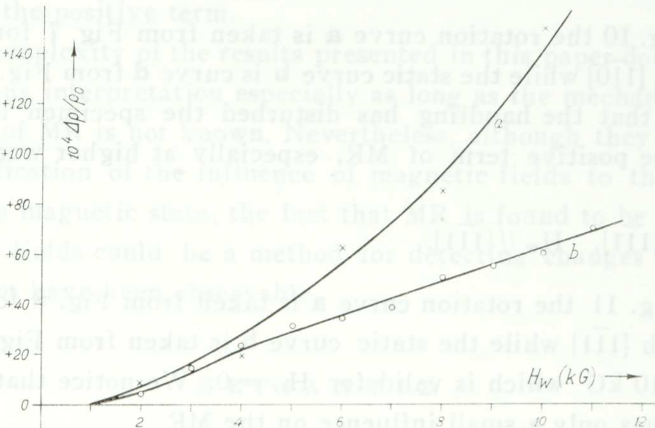

Fig. 10. Comparison of a static and a rotating sequence. H_{tr} // [1$\bar{1}$0], H_w // [110] a = rotating, b = static.

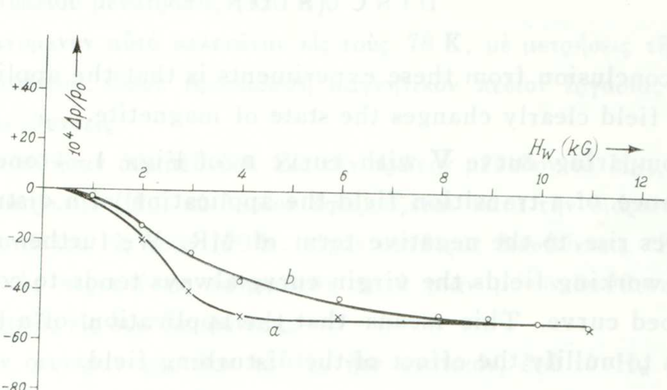

Fig. 11. Comparison of a static and a rotating sequence. H_{tr} // [1$\bar{1}$1], H_w // [I11], a = rotating, b = Static.

5.1. H_{tr} // [001], H_w // [001].

In Fig. 9 we give the measurements for working fields in the [001] direction and a transition field of 10 kG in the same direction. The rotation curve a is taken from Fig. 6 at azimouth [001]. In this case the specimen has been disturbed by fields near $\varphi = 0$. The static curve **b** is curve **c** of Fig. 2 of Ref. 6 which has undergone no disturbance. The two curves do not differ much.

5.2. H_{tr} // $[1\bar{1}0]$, H_w // $[1\bar{1}0]$.

In Fig. 10 the rotation curve **a** is taken from Fig. 7 for H_{tr} // $[1\bar{1}0]$ at azimouth $[1\bar{1}0]$ while the static curve **b** is curve **d** from Fig. 2 of Ref. 6. We notice that the handling has disturbed the specimen in a way to increase the positive term of MR, especially at higher working fields.

5.3. H_{tr} // $[1\bar{1}1]$, H_w // $[1\bar{1}1]$.

In Fig. 11 the rotation curve **a** is taken from Fig. 8 for H_{tr} // $[1\bar{1}1]$ at azimouth $[1\bar{1}1]$ while the static curve **b** is taken from Fig. 3 of Ref. 7 for $H_{tr} = 10$ kG which is valid for $H_{tr} = 0$. We notice that the disturbing field has only a small influence on the MR.

DISCUSION

The conclusion from these experiments is that the application of **a** disturbing field clearly changes the state of magnetite.

By comparing curve **V** with curve **a** of Figs. 1 - 4 one finds that in the absence of a transition field the application of a disturbing field always gives rise to the negative term of MR. We further remark that for strong working fields the virgin curve always tends to coincide with the disturbed curve. This means that the application of a big working field tends to nullify the effect of the disturbing field.

In the rotation sequence the influence of a disturbing field is more complicated. This is because the measurement of MR itself effectively acts as a disturbing field so that each point has a different prehistory from a point of view of disturbing fields. The comparison in the [001] direction between static and rotating sequence (Fig. 9) gives the same result ; it seams that the prehistory 0^0 to 30^0 did not contain drastic disturbing fields. On the contrary the comparison for the [110] direction (Fig. 10) gives a big deviation indicating that the prehistory must have caused some important change to the crystal.

A final observation : the application of a transition field in the [001] direction (Fig. 1 and 6) gives a big increase to the negative term of MR for all directions of the working field while the applications of a transition field in the [110] directions (Fig. 2 and 7) generally gives an increase of the positive term.

The complexity of the results presented in this paper does not allow at present any interpretation especially as long as the mechanism for the production of MR is not known. Nevertheless, although they do not and to the clarification of the influence of magnetic fields to the crystallographic resp magnetic state, the fact that MR is found to be very sensitive to such fields could be a method for detecting changes that would otherwise not have been observable.

ΠΕΡΙΛΗΨΙΣ

Ἡ κατάστασις τοῦ μαγνητίτου εἰς χαμηλὰς θερμοκρασίας διαταράσσεται ἀπὸ ἕνα μαγνητικὸν πεδίον (H_{dis}), ἔστω καὶ ἐὰν ἡ θερμοκρασία αὐτοῦ εἶναι κατωτέρα τοῦ σημείου μετατροπῆς (120 K).

Τὸ φαινόμενον αὐτὸ μελετᾶται εἰς τοὺς 78 K, μὲ μετρήσεις τῆς ἐγκαρσίας μαγνητοαντιστάσεως, ἀφοῦ ἐφαρμοσθῇ μαγνητικὸν πεδίον ἐργασίας (H_w) κατὰ διαφόρους διευθύνσεις.

Ἐφηρμόσθησαν δύο μέθοδοι. Εἰς τὴν πρώτην μέθοδον τὸ H_{ds}, τὸ H_w καὶ τὸ πεδίον μετατροπῆς (H_{tr}) τὸ ὁποῖον ἐφαρμόζεται κατὰ τὴν διάρκειαν τῆς ψύξεως τοῦ κρυστάλλου εἰς τοὺς 120 K, εἶχαν σταθερὰς διευθύνσεις. Ἐπιπλέον τὸ H_{dis} εἰς μερικὰς περιπτώσεις ἐφηρμόσθη κατὰ μίαν μόνον διεύθυνσιν, ἐνῶ εἰς ἄλλας, διαδοχικῶς εἰς δύο διευθύνσεις.

Εἰς τὴν δευτέραν μέθοδον τὸ H_{tr} ἦτο στατικόν, ἐνῶ τὸ H_w ἐφηρμόζετο διαδοχικῶς εἰς διαφόρους διευθύνσεις.

Εἰς αὐτὴν τὴν περίπτωσιν εὑρέθη ὅτι ἡ διαταραχὴ τὴν ὁποίαν ὑφίσταται τὸ ὑλικὸν προέρχεται ἀπὸ ὅλα τὰ ἐφαρμοσθέντα προηγουμένως πεδία ἐργασίας.

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