# MAGNETORESISTANCE NEAR THE CURIE POINT OF TbZn SINGLE CRYSTALS

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*ABSTRACT* — Magnetoresistance studies of the intermetallic ferromagnetic TbZn compound have been performed for the first time, with accurate measurements of $\Delta\rho$ (T, H) and ( $d\rho/dT$ ) coefficients. The analysis of our results supports the theoretical predictions based on renormalization group calculations.

## 1 — INTRODUCTION

Previous studies of the critical behaviour of transport coefficients in TbZn ferromagnetic single crystals [1], [2] are now extended to include the effect of the magnetic field on the electrical resistivity ( $\rho$ ) near the Curie point of TbZn. Since the critical features are better displayed by the temperature derivative $d\rho/dT$, this quantity was measured directly as a function of temperature under constant values of the applied magnetic field ( $\mathbf{H}_a$ ).

TbZn has a cubic CsCl type structure in the paramagnetic phase but at the Curie point it suffers a tetragonal distortion caused by magnetoelastic effects in the ferromagnetic phase. The magnetization ( $\mathbf{M}$ ) is then directed along a quarternary axis; at low T, it changes to a binary axis.

The internal magnetic field ( $\mathbf{H}$ ) can act in several ways. By imposing a preferential direction to the ionic spins $\mathbf{S}_i$, the field reduces the magnitude of the fluctuations near $T_c$ and enhances the magnetization beyond its spontaneous zero field value. Also, multidomain structures below $T_c$ are gradually destroyed, the domains parallel (or closer in direction) to $\mathbf{H}_a$ growing at the expense of the domains magnetized in other directions. Several characteristic energies play a role here, their relative strengths just determining the extent of the magnetic field perturbations.

The initial readjustment of the domains is the easiest process, since no anisotropy energy differences exist between the symmetry-equivalent easy directions in the sample. In good crystals, and near $T_c$, we can assume a single domain situation inside the sample. If $\mathbf{H}_a$ is not along an easy direction, further orientational effects follow this initial stage, depending on the differences in the anisotropy energies between easy and hard magnetic directions. All these domains effects are not expected to be easily observable in simple electronic transport property measurements, due to the smallness of the electron wavelength ($\lambda \sim$ Å) when compared with the large size of the magnetic domains ($\sim 10^4$ Å) and of the domain Bloch walls ($\sim 10^2$-$10^3$ Å).

On the other hand, changes in the magnetization and in the spin fluctuations, which directly affect the order 'seen' by the electrons as they travel within a mean free path, are expected to produce observable effects in the electronic transport coefficients.

In a mean field description of the electrical resistivity without fluctuations one assumes $\rho$ to be a function of the magnetization components only ($M_i$). Since $\rho(M_i)$ must be an even function of M and $M \rightarrow 0$ as $T \rightarrow T_c$, one should have, to second order terms, in isotropic materials,

$$\rho / \rho_\infty = 1 + a \cdot M^2 \qquad (1)$$

with $\rho_\infty = \rho\ (T >> T_c)$. For localized spin systems it can be shown [3] that $a = -[S/(S+1)]\, M_0^{-2}$. Describing the changes in M produced by the field and temperature through the usual mean field expression

$$\sigma = B_S\ (3\,S/(S+1) \cdot \sigma/t + h/t) \qquad (2)$$

where $\sigma = M(T\ H)/M(0,0)$, $t = T/T_c$, $h = \mu_0 mH/(kT_c)$, m is the magnetic moment associated to each ion, and $B_S$ is the Brillouin function, one can derive the mean field behaviour of $\rho$ as a function of T and H. From such expression it results that the h-effects become negligible when $h << \sigma$ (or $H << M$).

The effect of the magnetic field on the fluctuations is far more complex; a thorough account of this problem can be found elsewhere [4]. Here we simply observe that the field effect in suppressing fluctuations will be maximum at $T_c$, where the difference in the free energies of the paramagnetic and ferromagnetic phases just vanishes. Also, the effect will be limited to a small range of temperatures ($\delta T$) close to $T_c$, imposed by the balance between the thermal energy $k\delta T$ and the magnetic energy per ion $\mu_0 m(H + M)$, so that $k\delta T \lesssim \mu_0 m(H + M)$. On the other hand the boundary between ferro and paramagnetism is not expected to be significantly altered (shift in the value of $T_c$), since we generally have $\mu_0 mH << kT_c$. Further comments on the role of fluctuations will be made in section 3.

## 2 — EXPERIMENTAL RESULTS

The single crystal used here ($1.2 \times 1.2 \times 12.9$ $mm^3$) had its long axis along a quaternary direction, the external magnetic field ($H_a$) and the electrical current being applied along it. The demagnetization factor (D) was below 0.1, so near $T_c$ ($M \rightarrow 0$) the internal field H becomes approximately equal to $H_a$, i.e. $H = H_a - DM \simeq H_a$. Far below $T_c$, the situation is quite different if $H_a$ is not sufficiently high, since M(T) rises towards an high saturation value, $M(0) = 22.5$ K0e in TbZn.

Fig. 1 shows the temperature dependence of $d\rho/dT$ for $H_a = 0$, 100, 700, 1200 and 2500 Oe.

Under zero field, $d\rho/dT$ exibits a sharp positive peak at the Curie temperature of TbZn, $T_c = 200 \pm 0.5$ K, and a monotonic decrease in the paramagnetic phase towards a constant background due to phonon scattering. This variation of $d\rho/dT$ above $T_c$ is, of course, due to short range correlation effects in the paramagnetic phase. For $H_a = 100$ Oe the $d\rho/dT$ curve in the ferromagnetic phase is practically the same as for $H_a = 0$, due to insufficient magnetic field to achieve penetration. However, in the paramagnetic phase the field effects are observed, producing an increase in $d\rho/dT$ values above the zero field curve.

For $H_a = 700$ Oe and above field penetration does occur in the ferromagnetic phase, originating a progressive rounding off in the experimental curves near $T_c$, and a systematic lowering

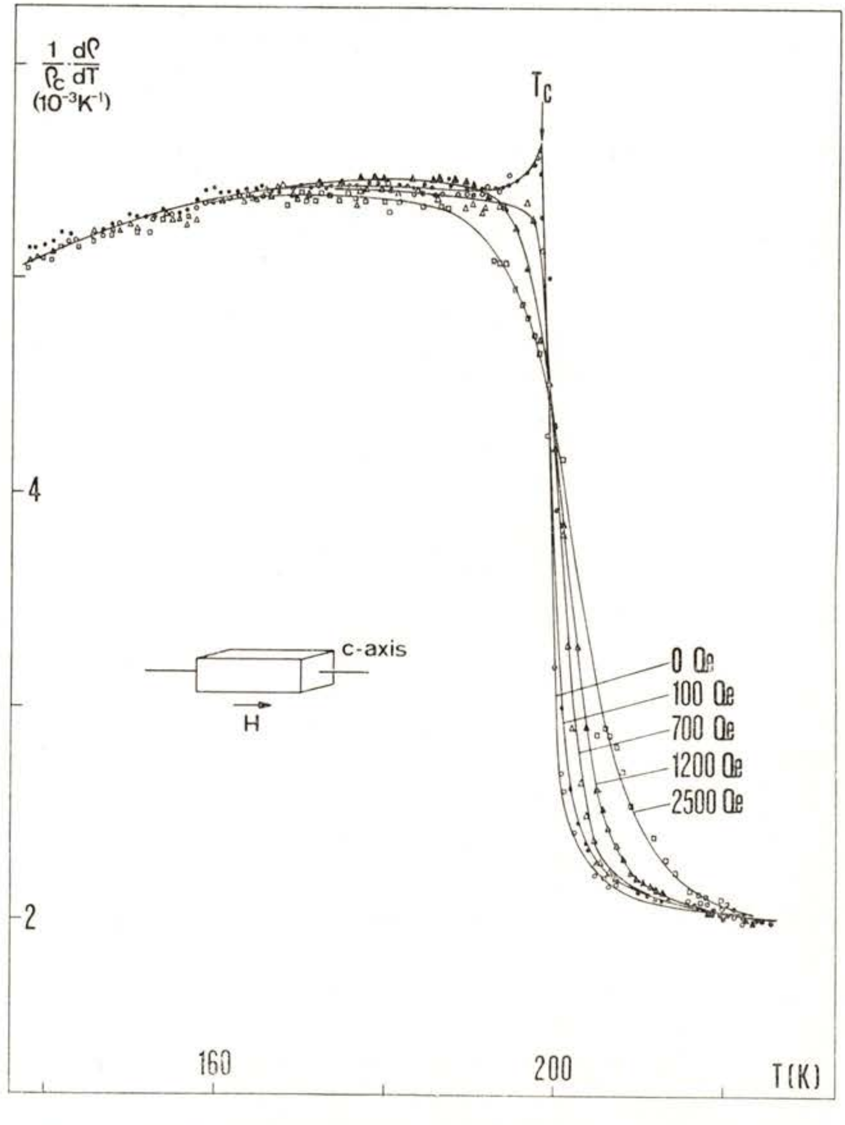


Fig. 1 — Critical behaviour of the normalized temperature derivative $(1/\rho_c)(d\rho/dT)$ in Gd, near the Curie point, at different values of the applied magnetic field: $H_a = 0$, 100, 700, 1200, 2500 Oe.

of $d\rho/dT$ at temperatures close (and below) $T_c$. For the moderate fields used here, the field effects in the ferromagnetic phase are restricted to a small temperature range ($\lesssim 30K$) below $T_c$. This is due to the fact that the magnetic energy of an ionic moment under $H_a$ becomes rapidly negligible when compared with the energy of the same moment under the increasing internal magnetization ($M(0) = 22.5$ KOe, whereas $H_a < 2.5$ KOe).

We have seen in section 1 that the effect of the magnetic field is expected to be maximum at $T_c$, where the critical fluctuations dominate the behaviour of the electrical resistivity. This is neatly evidenced by our results on $\Delta\rho$ (T, H), as shown in Fig. 2, for the normalized magnetoresistance $\Delta\rho/\rho = [\rho(T,H) - \rho(T,0)]/\rho(T_c\ 0)$ as a function of temperature. The magnetoresistance is always negative and indeed exibits a sharp maximum at $T_c$; also, it increases with the applied field, due to the progressive increase in magnetic order in the system. We should note that $\Delta\rho/\rho$ curves are less accurate than the $d\rho/dT$ ones, since the latter are obtained directly, whereas $\Delta\rho/\rho$ is obtained by a subsequent subtraction of the corresponding resistivities at several temperatures obtained in different experimental runs. For this reason, the following analysis will be based on the $d\rho/dT$ results.

## 3 — ANALYSIS OF EXPERIMENTAL RESULTS

Our $d\rho/dT$ results show that H has opposite effects on both sides near $T_c$: whereas $d\rho/dT$ is below the zero field curve for $T < T_c$, the reverse occurs above $T_c$. This can be qualitatively understood if one recalls that $d\rho/dT$ depends strongly on the magnetization derivative $|dM/dT|$, a quantity which is smaller than its zero field value for $T < T_c$, and higher as soon as $T > T_c$.

Let us separate the magnetoresistivity term ($\Delta\rho$) out of the total electrical resistivity:

$$\rho(T,H) = \rho(T,0) + \Delta\rho(T,H) \qquad (3)$$

In terms of the temperature derivatives we then get from (3):

$$(d\rho/dT)_H = (d\rho/dT)_0 + (d\Delta\rho/dT)_H \qquad (4)$$

The behaviour of the zero-field derivative $(d\rho/dT)_0$ in TbZn near $T_c$ has been previously studied in detail [1], leading above $T_c$ to a ln($T$-$T_c$) dependence in the immediate vicinity of $T_c$, and to a classical $(T\text{-}T_c)^{-1/2}$ dependence sufficiently away from the critical point. For this reason only the magnetoresistivity term

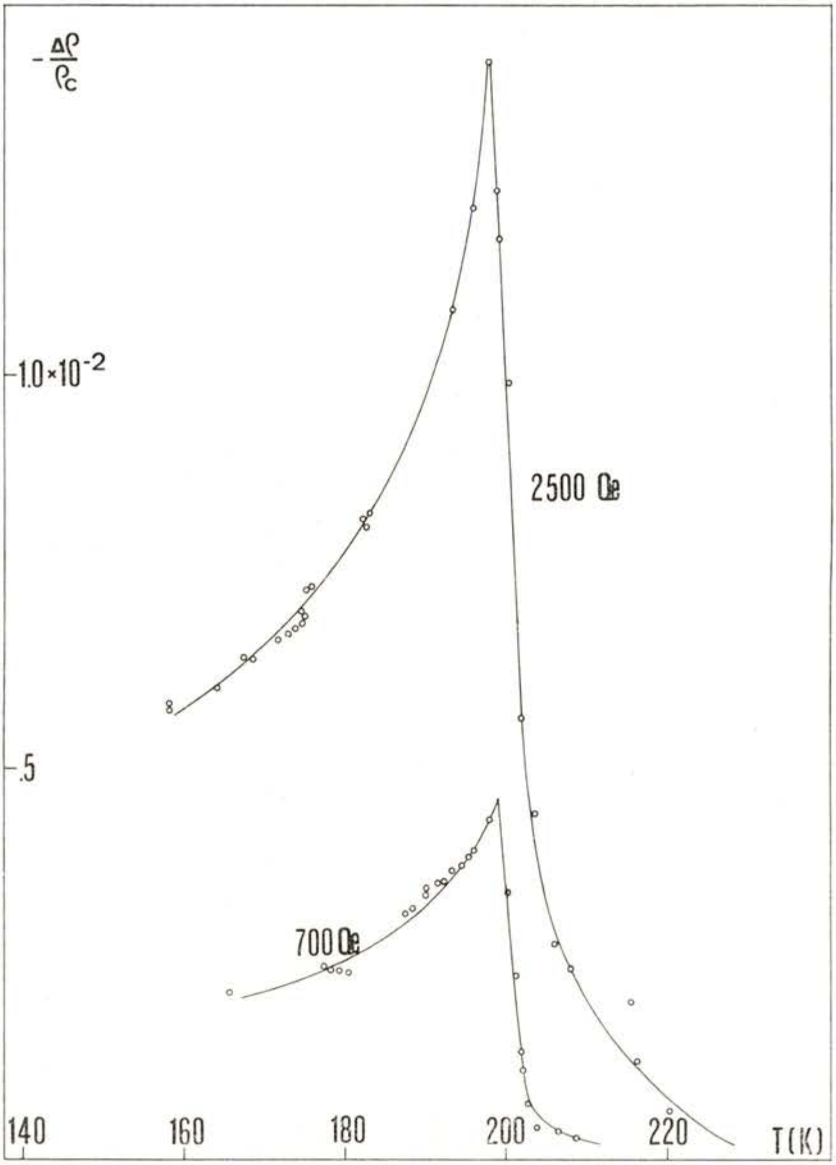


Fig. 2 — Critical behaviour of the normalized magnetoresistivity of Gd near the Curie point, at $H_a = 700$, 2500 Oe ; $\Delta\rho(T, H_a) = \rho(T, H_a) - \rho(T, 0)$.

will be considered. Renormalization group results lead to the following theoretical predictions (with $\varepsilon = (T-T_c)/T_c$) [4]:

$$\begin{array}{llcll} T > T_c & \text{(i)} & \varepsilon >> h & : & d(\Delta\rho)/dT \propto h^2/\varepsilon^{\gamma+2} \\ & \text{(ii)} & \varepsilon << h & : & d(\Delta\rho)/dT = 0 \\ T < T_c & \text{(iii)} & |\varepsilon| >> h & : & d(\Delta\rho)/dT \propto h/|\varepsilon|^{\alpha+\beta\delta} \\ & \text{(iv)} & |\varepsilon| << h & : & d(\Delta\rho)/dT = 0 \end{array} \qquad (5)$$

where $\alpha$, $\beta$, $\gamma$ and $\delta$ are the critical exponents for the specific heat, spontaneous magnetization, correlation length and critical isotherm respectively. For example, in mean field approximation ($\alpha = 0$, $\beta = 1/2$, $\gamma = 1$, $\delta = 3$) one gets for ($d\Delta\rho/dT$):

$$\text{(i) } h^2/\varepsilon^3 \;,\quad \text{(ii) } 0 \;,\quad \text{(iii) } h/|\varepsilon|^{3/2} \;,\quad \text{(iv) } 0.$$

In our case ($h = \mu_0 mH/kT_c \lesssim 0.001$) the temperature range $|\varepsilon| << h$ is not accessible with sufficient experimental data, and so only cases (i) and (iii) can be considered in detail.

The interesting check refers to the magnetic field dependence of $d(\Delta\rho)/dT$ ($h^2$ and $h$, cases i and iii respectively), because it should be independent of the particular values of $\alpha$, $\beta$, $\gamma$ and $\delta$.

As shown in Fig. 3, an $h^2$-dependence is indeed observed in our $d\rho/dT$ data above $T_c$ (case i), whereas an h-dependence is found

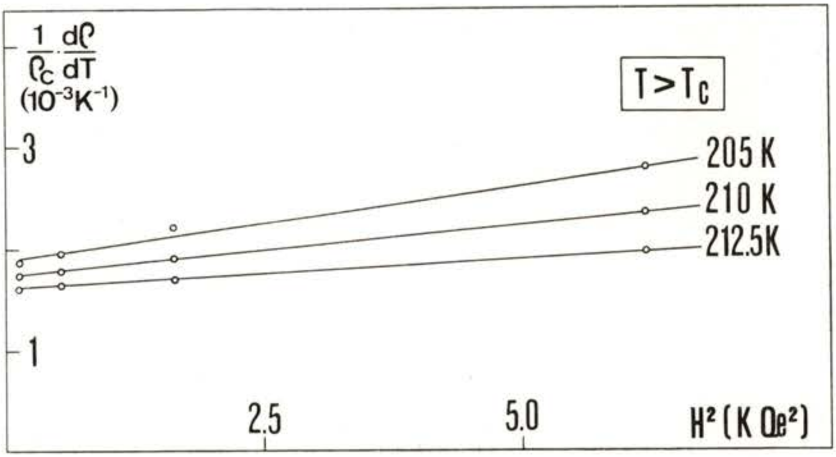


Fig. 3 — Above $T_c$, the normalized temperature derivative $(1/\rho_c)(d\rho/dT)$ follows a quadratic dependence on the magnetic field.

below $T_c$ (Fig. 4; case iii). We also found that the magnitude of the slopes in the corresponding plots always increases as T approaches $T_c$, as predicted by theory.

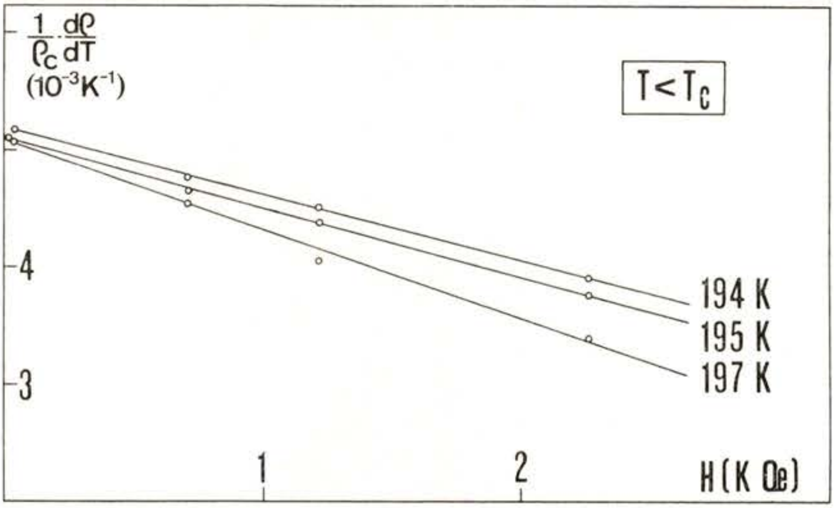


Fig. 4 — Below $T_c$, the normalized temperature derivative $(1/\rho_c)(d\rho/dT)$ obeys a linear dependence on the magnetic field.

As a final comment, let us add that, within a molecular field approximation, the results $d(\Delta\rho)/dT \propto h^2/\varepsilon^3$, $h/\varepsilon^{3/2}$, and $d(\Delta\rho)/dT = 0$ simply follow from expressions (1) and (2) in the limits corresponding to cases (i), (iii) and (ii+iv) respectively.

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