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Quantum corrections to the electronic transport properties of the 'free-electron' metallic glass MgZn

A Schulte†, P Löbl‡, F Küß‡ and E Lüscher‡§

† Department of Physics and Center for Research in Electro-Optics and Lasers, University of Central Florida, Orlando, FL 32816, USA
‡ Physik Department, TU München, D-8046 Garching, Federal Republic of Germany

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Abstract. The conductivity and the Hall effect of three-dimensional Mg_xZn_{100-x} glasses are studied as a function of magnetic field ($0 \leqslant B \leqslant 6$ Tesla), temperature ($1.5 < T < 100$ K) and concentration ($x = 67, 72$ and 77). The magnetoconductivity $\Delta\sigma(T, B)$ provides evidence for quantum corrections to the Boltzmann equation. It is in quantitative agreement with perturbation theories, when contributions due to quantum interference, electron–electron interaction and superconducting fluctuations are taken into account. The spin–orbit scattering field increases with the Zn concentration from 0.086 Tesla ($Mg_{77}Zn_{23}$) to 0.13 Tesla ($Mg_{67}Zn_{33}$). The temperature and concentration dependence of the Hall coefficient are also consistent with the nearly-free-electron model when quantum corrections are included.

1. Introduction

Quantum mechanical coherence effects form the basis for understanding the electronic properties of metals. For a long time very pure single crystals have been considered the ideal systems to investigate these phenomena in detail [1]. More recently, however, it was realized that quantum effects are crucial for the electronic transport in disordered or 'dirty' metals as well [2, 3]. Because there is a high density of defects, the elastic scattering time at low temperatures becomes small when compared with the phase coherence time of the electronic wavefunction. In that range interference processes of the elastically scattered electrons turn out to be significant. They can be probed by measuring the magnetic field- and the temperature-dependence of the transport coefficients. Experiments on two-dimensional films of disordered simple metals [2, 4] established the contribution of quantum corrections to the conductivity and the Hall effect. In three-dimensional systems the experimental verification is more tedious because the length scale is different and leading order divergencies are absent. Here, most of the evidence for quantum corrections comes from high-resistivity, transition metal-based glasses [5].

MgZn has been termed a simple metallic glass and is frequently being used as a model for amorphous and quasi-crystalline phases [6]. This alloy has no relevant d-electrons at the Fermi energy and there is a wealth of experimental and theoretical information on the atomic and electronic structure. The electrical resistivity

§ Deceased.

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($\rho \approx 50\ \mu\Omega$ cm) has been calculated from first principles [7,8] and found to agree remarkably well with the nearly-free-electron model.

We study the low-temperature conductivity $\sigma(T,B)$ and the Hall effect for several Mg concentrations [9]. The measured magnetoconductivity is accounted for by quantum corrections and superconducting fluctuations. Within our experimental error of $\approx 0.5\%$ we cannot resolve a correction to the Hall constant due to the Coulomb anomaly as in transition metal-based glasses. This finding is in agreement with the screening constant for the electron–electron interaction calculated from the nearly-free-electron model.

2. Experimental details

MgZn alloys (starting materials Mg:4N and Zn:6N) were melted several times in closed graphite containers (Ringsdorf EK50, Fe content < 5 ppm) with RF heating under protective Argon atmosphere. Amorphous ribbons were prepared by melt-spinning (speed $\approx$ 3000 rpm, diameter of the copper wheel = 27 cm) in He atmosphere ($\approx$ 300 mbar). After fabrication the metallic glasses were stored in liquid nitrogen to avoid crystallization. Angle-dispersive x-ray scattering showed only amorphous rings.

Inductively coupled plasma analysis (resolution 500 ppm) gave no indications for Fe impurities. From tests with a SQUID susceptometer we estimate the amount of magnetic impurities to be less than 10 ppm. We rule out a Kondo effect due to residual magnetic impurities, since we observe no non-linearities in the magnetic field dependence of the Hall resistivity. We have verified from the Hall effect, the low-temperature conductivity and the magnetic-field dependence that $Mg_{70}Zn_{30}$ containing 5000 ppm Mn exhibits a Kondo effect.

To characterize the samples further we measure the temperature dependence of the conductivity (relative error $< 10^{-5}$) in the range 1.5–300 K, and the Hall effect as well. In addition, measurements of the crystallization behaviour and of structural relaxation [10] near the glass transition have been carried out on samples from the same ribbons. Our results of the crystallization behaviour agree well with literature data [11]. We find an activation energy for crystallization of about 1.8 eV in the case of $Mg_{67}Zn_{33}$. Before crystallization sets in we observe an increase of the resistivity during isothermal annealing, in agreement with other authors [12]. This increase can be correlated with an increase of the first peak in the structure factor [12] during the relaxation process.

The samples had typical dimensions of $8 \times 2 \times 0.03$ mm^3. Electrical contacts were made by pressing Cu wires (0.2 mm in diameter) into taps cut into the specimens with a diamond slitting saw. This arrangement formed the inner part of a 'sandwich' consisting of a sapphire plate, a thin sheet of mica or Teflon and a Cu plate which was clamped to a Cu block. Using pressure contacts, as opposed to soldering the leads, has the advantage that the samples are not exposed to higher temperatures which can cause partial crystallization. During the experiments slow cooling and heating rates ($\approx$ 30 K h^{-1}) had to be employed to avoid stresses on the samples.

The resistance was measured with a standard four-wire DC technique with a precision better than 10^{-5}. The current density was kept below 5 A cm^{-2} for the resistance and below 250 A cm^{-2} for the Hall effect measurements to avoid sample heating. Voltages in the nanovolt range were detected with a galvanometer amplifier connected to an integrating microvoltmeter. To ensure long-term stability the amplifiers and the standard resistors for monitoring the amplification factor were contained in copper boxes, which were temperature stabilized to 0.2 K. Noise levels were below 3 nV at an integration time of 0.5 s. A further reduction in noise could easily be achieved by averaging over longer times (10 s), since the data aquisition including switching of the current direction was handled by computer. A superconducting magnet ($0 \leqslant B \leqslant 6$ Tesla) provided the magnetic field B penetrating the sample perpendicular to the ribbon plane. The field settings were measured with a calibrated Hall probe. The errors in the temperature determination of the sample, which was performed with the aid of a calibrated carbon glass or a Pt resistor (above 40 K), were smaller than 0.1 K. The stability of the temperature as achieved by control was better than 10^{-2}.

3. Results and discussion

3.1. Temperature dependence of the conductivity

The resistance normalized to its value at 4.2 K is shown as a function of temperature in figure 1. The resistivities at room temperature and other characteristics of the samples are summarized in table 1. In all cases, the resistivity ρ is in the region 50 $\mu\Omega$ cm, that is $k_F l \approx 17$. The Fermi wavevector $k_F = 1.42$ A^{-1} and the electronic mean free path l are obtained from the nearly-free-electron (NFE) model. The temperature coefficient at room temperature $\alpha = \rho^{-1}\partial\rho/\partial T$ shows a negative sign, the magnitude of α being about 10^{-4}. First the resistance is increasing with decreasing temperature, then the temperature coefficient becomes positive before again turning negative at the lowest temperatures. The maximum at about 40 to 60 K and the minimum around 10 K have been observed before and agree with literature data [13].

A detailed and systematic calculation of the resistivity on the basis of the generalized Faber–Ziman theory has been performed by Hafner [7]. It turns out that the Debye–Waller term provides a negative contribution to the temperature coefficient of resistivity (TCR) near the peaks in the partial structure factors, while the electron–phonon term invariably produces a positive contribution to the temperature coefficient of resistivity. At high temperatures the negative contribution to the TCR from the

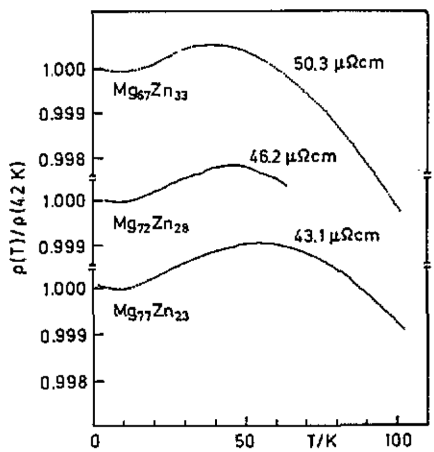

Figure 1. The resistance of amorphous MgZn normalized to its value at 4.2 K as a function of temperature. The resistivities at 4.2 K are indicated.

Table 1. Material parameters of Mg_xZn_{100-x}.

	$Mg_{77}Zn_{23}$	$Mg_{72}Zn_{28}$	$Mg_{67}Zn_{33}$
ρ ($\mu\Omega$ cm)	43.1	46.2	50.3
R_H (10^{-11} m^3 A^{-1} s^{-1})	-6.15 ± 0.6	-6.9	-6.45
R_H (10^{-11} m^3 A^{-1} s^{-1})[a]	-6.97 ± 0.3	-6.15	-5.81
d (g cm^{-3})[a]	2.65 ± 0.06	2.92	3.13
$N(E_F)$ (eV^{-1} at^{-1})[b]	0.4	0.39	0.38
D (10^{-4} m^2 s^{-1})	7.74	7.12	6.52
$B_n\tau_n$ ($10^{-13} T$ s)[c]	2.12	2.30	2.52
$\tilde{F}$	0.52	0.51	0.51
B_{so} (Tesla)	0.086	0.10	0.127

[a] Reference [13].
[b] Conductivity assuming the NFE model.
[c] $B_n\tau_n = (\hbar/e)(4/D) = 1.64 \times 10^{-16}\ D^{-1}$ (m^2 s^{-1}).

quasi-elastic mechanisms dominates. The maxima and minima at lower temperatures are well reproduced by Hafner's calculation too. Briefly, they are the result of an interplay between defect scattering by the static disorder, which is temperature-dependent through the Debye–Waller factor and the inelastic electron–phonon scattering which depends on the details of the vibrational spectrum.

3.2. Hall effect

The magnetic field dependence of the Hall resistivity ρ_H at 4.2 K is shown in figure 2 for $Mg_{67}Zn_{33}$ and for the Kondo alloy $Mg_{70}Zn_{30}$ doped with 0.5% Mn. In the Kondo alloy ρ_H is a non-linear function of the magnetic field. On the other hand the linearity in the MgZn alloys indicates the absence of a Kondo effect. The error in the absolute value is about 10% due to the uncertainty in the sample thickness. The Hall coefficients R_H are summarized in table 1. They are in agreement with the data of Matsuda and Mizutani measured at temperatures above 77 K [13]. For isotropic materials the Hall constant R_H is given by $R_H = 1/(ne)$. With $R_H = -6.5 \times 10^{-11}$ m^3 A^{-1} s^{-1} ($Mg_{67}Zn_{33}$) one gets for the electron density $n = 0.096$ Å^{-3}. This is in good agreement with measurement of the Fermi wavevector by positron annihilation which results in $n = 0.0967$ Å^{-3} [14]. Also the (bare) electronic density of states [15] is free-electron-like.

The measured Hall constant, normalized to its value at 77 K, is shown as a function of temperature in figure 3. One may raise the question of whether there is a temperature dependence of R_H due to electron–electron interaction effects in the particle–hole channel. Such corrections have been observed consistently in the conductivity and the Hall effect of two- [16, 17] and three-dimensional [18–20] disordered conductors as predicted by Altshuler *et al* [21]. The diffusion correction to the temperature dependence of the Hall constant is given by [21, 22]

$$\frac{\delta R_H(T)}{R_H(0)} = \frac{R_H(0) - R_H(T)}{R_H(0)} = 1.3 L_{00}\rho(0)\left(\frac{4}{3} - \frac{3}{2}\tilde{F}\right)\left(\frac{k_B}{2\hbar D}\right)^{1/2} T^{1/2} \tag{1}$$

where $L_{00} = e^2/2\pi^2\hbar = 1.233 \times 10^{-5}\ \Omega^{-1}$ denotes a universal conductance. In general the sign of the correction depends on that of the interaction constant $\tilde{F}$ and thus may be arbitrary. The correction due to the electron–electron interaction is not only determined by the screening parameter, but also by the magnitude of ρ. δR_H becomes larger with increasing resistivity and decreasing diffusion coefficient. Compared to the transition metal glasses the conductivity and the diffusion constant of MgZn are larger by factors of roughly 4 and 10, respectively. Thus the estimated correction to R_H is about a factor of 12 smaller than, for instance, in CuTi and CuZr. Using the data in table 1 ($\tilde{F} \approx 0.5$) and $T = 100$ K we obtain from equation (1) $\delta R_H(100 \text{ K})/R_H(0 \text{ K}) \approx 5 \times 10^{-4}$ for MgZn. The temperature dependence due to the electron–electron interaction is extremely weak and within the experimental error (figure 3).

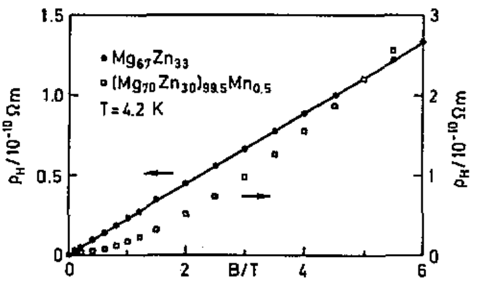

Figure 2. Magnetic-field dependence of the Hall resistivity for amorphous $Mg_{67}Zn_{33}$ and amorphous $Mg_{70}Zn_{30}$ containing 5000 ppm Mn at 4.2 K.

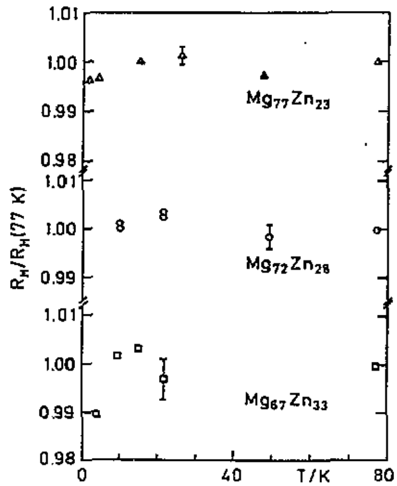

Figure 3. The Hall constant R_H of MgZn glasses normalized to its value at 77 K as a function of temperature.

3.3. Quantum correction and superconducting fluctuation contributions to the conductivity

The measured magnetoconductivity $\sigma(B) - \sigma(B = 0) = \Delta\sigma(B)$ is only of the order 10^{-5} to 10^{-4} when compared with σ, but it displays a pronounced structure (figure 4). At higher fields and at high temperatures $-\Delta\sigma$ is negative. At low fields $-\Delta\sigma$ exhibits a small positive maximum, which decreases with decreasing Zn concentration and disappears with increasing temperature. As in two dimensions, quantum corrections including spin–orbit scattering [23] are the essential origin of this feature. For vanishing spin–orbit scattering the 'weak localization' of the scattered electrons is reduced and the conductivity increases with the magnetic field. Dominating spin–orbit scattering changes the sign of the magnetoconductivity.

It was noted [9] that the quantum interference contribution cannot describe the measurements over the full magnetic field and temperature range. To decide whether this is due to the limited validity of the theoretical expressions or due to additional contributions we consider first the high-temperature–low-field limit

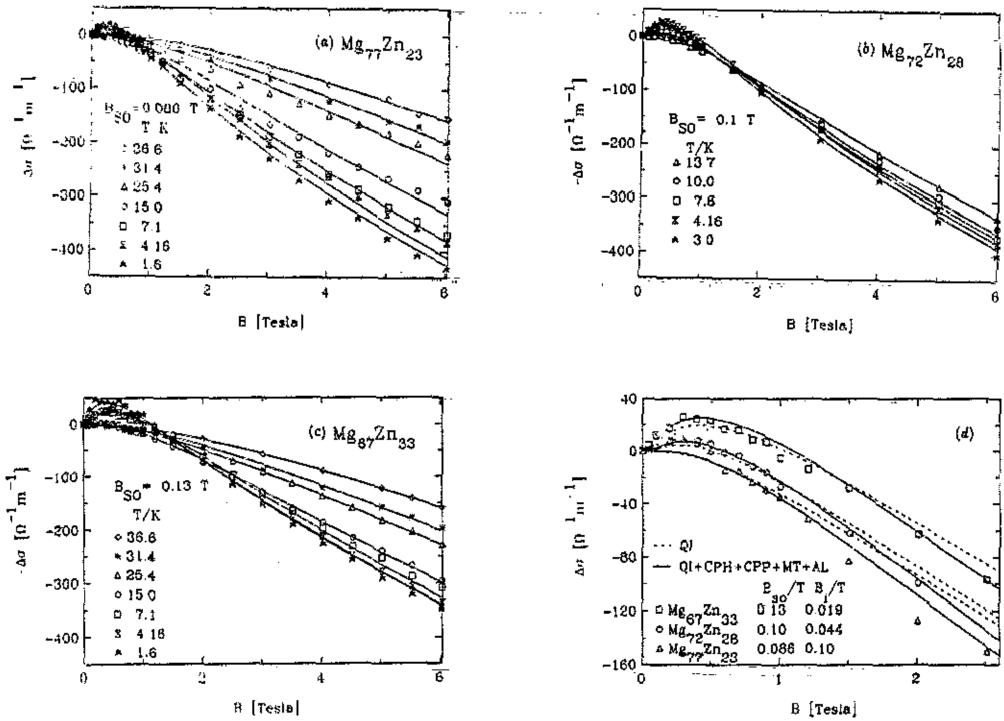

Figure 4. Change in the conductivity $-\Delta\sigma$ versus magnetic field B for (*a*) $Mg_{77}Zn_{23}$, (*b*) $Mg_{72}Zn_{28}$, and (*c*) $Mg_{67}Zn_{33}$. Results for various temperatures as indicated are given. The full curves are fits of the sum of contributions due to quantum interference, electron–electron interaction and superconducting fluctuations to the data as explained in the text. (*d*) Comparison of the three alloys at 7 K for $B/T < 0.4$ T K^{-1}. Full curves: all contributions; broken curves: quantum interference only. About 20 Ω^{-1} m^{-1} in $\Delta\sigma$ correspond to a measured change in resistance $\Delta R/R$ of 10^{-5}.

($B/T < 0.4$ Tesla K^{-1}). The simplest assumption is that the total magnetoconductivity is given by the quantum interference term alone. Since for MgZn the electronic diffusivity is large ($\geqslant 5\times 10^{-4}$ m^2 s^{-1}), we can neglect the Zeeman effect on the quantum interference [24]. Quantum interference then yields the following contribution to the magnetoconductivity [24, 25].

$$\Delta\sigma_{\mathrm{QI}}(B) = L_{00}\left(\frac{e}{\hbar}\right)^{1/2} B^{1/2}\left[\frac{3}{2}f_3\left(\frac{B}{B_{\mathrm{i}}+\frac{4}{3}B_{\mathrm{so}}}\right)-\frac{1}{2}f_3\left(\frac{B}{B_{\mathrm{i}}}\right)\right] \qquad (2)$$

where $f_3(x)$ is a function given by Kawabata [25].

The only free parameters are the characteristic fields for inelastic and spin–orbit scattering, B_i and B_{so}. The fields B_n are defined with respect to the scattering times τ_n via

$$\tau_n^{-1} = \frac{4eD}{\hbar} B_n \tag{3}$$

where D denotes the diffusion coefficient.

B_{so} and B_i are determined by a least-squares fit of equation (2) to the data performed simultaneously at all temperatures. B_{so} is even more restricted, because it must be the same for all temperatures. This procedure gives a rather good description of the magnetoconductivity for temperatures higher than about 4 K. The spin–orbit fields are 0.067, 0.088 and 0.12 Tesla for $Mg_{77}Zn_{23}$, $Mg_{72}Zn_{28}$ and $Mg_{67}Zn_{33}$, respectively. The temperature dependence of the inelastic field B_i can be described by a power law $B_i = 3.03 \times 10^{-4}\ T^{2.16}$ for all three concentrations: At the lower temperatures the experimental values have a tendency to fall above the line given by the power law.

However, since $Mg_{70}Zn_{30}$ is superconducting below 0.11 K [15] contributions of superconducting fluctuations [26] to the conductivity may not be negligible. In addition the effective electron coupling constant affects the orbital part of the Coulomb interaction in the particle–particle channel. These contributions are rather substantial as we will show in the following.

Electron–electron interaction effects in disordered metals have been reviewed by Altshuler and Aronov [3]. The contribution to magnetoconductivity in the particle–hole channel associated with spin effects is [3, 27]

$$\Delta\sigma_{\mathrm{CPH}}(B) = -L_{00}\ \frac{\tilde{F}}{2}\left(\frac{k_{\mathrm{B}}T}{2\hbar D}\right)^{1/2} g_3\left(\frac{2\mu_{\mathrm{B}}B}{k_{\mathrm{B}}T}\right) \tag{4}$$

where μ_{B} denotes the Bohr magneton and the function g_3 is given in [3, 27].

The magnetic field dependence of the particle–particle channel is dominated by the orbital part. The result of calculations performed by Fukuyama [28] and Altshuler and co-worlers [3, 29] is

$$\Delta\sigma_{\mathrm{CPP}}(B) = L_{00}\left(\frac{e}{\hbar}\right)^{1/2} [-g(T,B)] B^{1/2}\phi_3(B/B_{\mathrm{T}}) \tag{5}$$

with $B_{\mathrm{T}} = \pi k_{\mathrm{B}}T/2eD$. The function $\phi_3(x)$ is defined as an integral in the literature [3, 29]. The electon coupling g in a superconductor is given by [3]

$$-\frac{1}{g(T,B)} = \ln\frac{T^*}{T_{\mathrm{C}}} \qquad \text{with} \quad T^* = \max\left(T, \frac{4DeB}{k_{\mathrm{B}}}\right). \tag{6}$$

The magnetic-field dependence due to the Maki–Thompson contribution [30, 31] of superconducting fluctuations may be expressed as [32–34]

$$\Delta\sigma_{\mathrm{MT}}(B,T) = -L_{00}\left(\frac{e}{\hbar}\right)^{1/2} B^{1/2}\beta(-g(T,B)) f_3(B/B_i). \tag{7}$$

β is a function tabulated by Larkin [33] in the limit of small applied fields and long-phase coherence times. If the B-dependence of g is neglected, the Maki–Larkin term has the same field dependence as the quantum interference effects with the opposite sign and a coefficient $\beta(T)$ diverging at T_C.

The contribution of superconducting fluctuations from virtual Cooper pairs (Aslamasov–Larkin term [35]) was calculated by Usadel [36] and Mikeska and Schmidt [37]. The temperature dependence in a transverse magnetic field is

$$\Delta\sigma_{AL}(B,T) = \pi L_{00}\left(\frac{e}{\hbar}\right)^{1/2} B_T^{1/2}\Phi(B/B_T, T/T_C) \tag{8}$$

where $\Phi(B/B_T, T/T_C)$ is a function defined in [36] and [37].

To start with, the contributions due to the electron–electron interaction (CPH and CPP) and superconducting fluctuations (AL) were calculated and then subtracted from the measured data. All necessary parameters are determined from the NFE model (D, $\tilde{F}$) or are known from experiments (T_C = 0.11 K [15]). The electronic diffusion constant D is calculated from the measured resistivity and the calculated non-renormalized density of states $N(E_F)$ in the nearly-free-electron model ($\rho^{-1} = e^2 N(E_F)D$). The remaining contributions are due to quantum interference and superconducting fluctuations described by the Maki–Thompson diagram. Now B_i and B_{so} are determined from simultaneous fits to these two contributions at all temperatures.

Figures 4 and 5 show that this procedure results in excellent agreement between experiment and theory. The sum of all the contributions (QI, CPH, CPP, MT, AL) reproduces the measured data rather well. This holds over the whole range of temperatures and magnetic fields. This outcome is somewhat surprising since it is not clear from the beginning which diagrams describing corrections to the Boltzmann conductivity are important. In addition, at low temperatures the quantum interference contribution is not the only one. We have relied on the same contributions which have proven to be relevant (because of divergencies) in the two-dimensional case [4, 38]. Obviously, a more stringent test would be to extend the experiments to higher fields. Close to the superconducting transition temperature, we expect discrepancies, because some of the approximations are no longer valid.

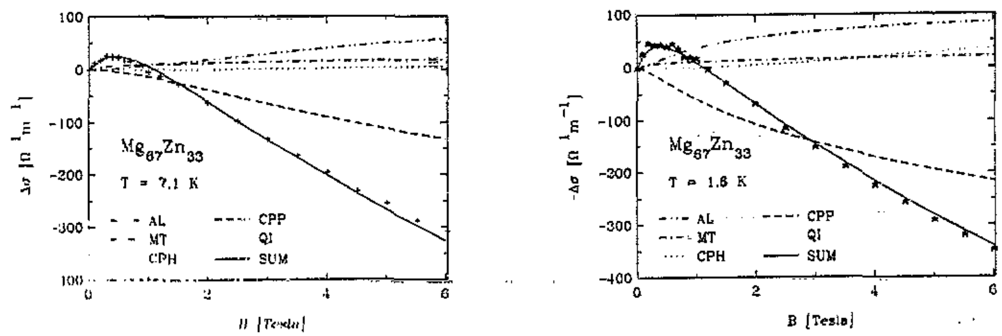

Figure 5. Change in conductivity $-\Delta\sigma$ for $Mg_{67}Zn_{33}$ at 7.1 and 1.6 K. The symbols denote the experimental results, the full curve is the sum of corrections due to quantum interference, Coulomb interaction and superconducting fluctuations.

In analogy to other amorphous superconducting alloys, a concentration dependence of T_C is to be expected. For instance, in the metallic glass Cu_xZr_{1-x}, T_C is increasing linearly with the Zr concentration [39]. When we keep the transition temperature as a free parameter in the least squares fits of $\Delta\sigma$, the lowest T_C is obtained for $Mg_{77}Zn_{23}$ and the highest for $Mg_{67}Zn_{33}$.

The temperature dependence of the inelastic fields can be described by a power law $B_i = B_{i0}T^p$ (figure 6) with an exponent p around 1.7. This finding is similar to those in two-dimensional systems [4]. Also in other metallic glasses [40–42] experimental data do not support a saturation of the temperature dependence of $B_i(T)$, at least above 1 K. According to Bergmann [43] for dominant electron–phonon scattering $p \approx 4$ is expected, whereas more recent calculations [44] predict $p = 3$. For electron–elecron scattering p should be about 1.5, which is somewhat smaller than the observed effect.

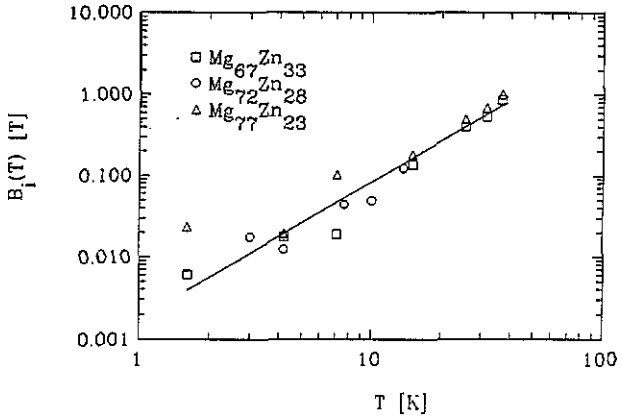

Figure 6. Results for the temperature dependence of the inelastic fields $B_i(T)$ in a log–log representation. The full curve is given by a power law with an exponent of 1.68.

The spin–orbit scattering, B_{so}, increases with the concentration of the element having the higher atomic number. The result for MgZn is close to that for Cu (B_{so} = 0.11 T) determined from two-dimensional films [43]. It remains a challenge for theory to account for the concentration dependence in detail.

Bieri *et al* [45] find that the quantum interference contribution alone gives a quantitative description for the magnetoconductivity of $Mg_{80}Cu_{20}$ for temperatures between 1.2 and 10 K in magnetic fields up to 10 Tesla. These authors obtain a spin–orbit field $B_{so} = 0.04$ Tesla. On the other hand, Richter *et al* [46] conclude from measurements on $Mg_{70}Cu_{30}$ and $Mg_{70}Zn_{30}$ doped with varying levels of Ag and Au that the theories of quantum corrections to the conductivity cannot explain the observed magnetoresistance over the full range of field. When only quantum interference is taken into account, $B_{so} = 0.075$ T is obtained for $Mg_{70}Zn_{30}$, in [46]. A similar analysis was presented in [9] yielding $B_{so} = 0.08$ T for $Mg_{72}Zn_{28}$ (about 3% uncertainty in concentration). Since both sets of measurements give essentially the same results it is unlikely that the samples contain different amounts of magnetic impurities. In these analyses the AL contribution due to superconducting fluctuations has been neglected. However, figures 4 and 5 demonstrate that the Aslamasov–Larkin term can be quite significant, essentially because of the large diffusion constant, as compared with transition metal-based glasses. Neglecting the influence of superconducting fluctuations even at higher temperatures modifies the magnitude of B_{so} and the temperature dependence of B_i as well. If the analysis is restricted to the quantum interference term, B_i has a tendency to saturate at low temperatures. However, this deviation from a power law is less significant when the superconducting fluctuations are included. In two-dimensional disordered Mg films it was found [47] that neglecting the spin–orbit coupling ($B_{so} = 0.005\,47$ T), induces a non-linear bebaviour of $\log B_i(T)$ as a function of $\log T$ with decreasing temperature.

The corrections to the Boltzmann conductivity can cause a contribution $\delta\sigma(T)$ to the temperature dependence without a magnetic field. Figure 7 shows the conductivity between 1.5 and 25 K for the three MgZn glasses. Below about 4 K the temperature dependence of σ is practically the same for all three alloys. Using the parameters determined from the magnetoconductivity of $Mg_{67}Zn_{33}$ we have calculated the corrections $\delta\sigma(T)$ due to quantum interference, electron–electron interaction and superconducting fluctuations.

The contributions due to quantum interference $\delta\sigma_{QI}$ [24] and electron–electron interaction $\delta\sigma_C$ [2, 3, 22] are taken from the literature as follows:

$$\delta\sigma_{QI}(T) = L_{00}\left(\frac{e}{\hbar}\right)^{1/2} B_{so}^{1/2}\left[3\left(\frac{4}{3}+\frac{B_i}{B_{so}}\right)^{1/2} - \left(\frac{B_i}{B_{so}}\right)^{1/2}\right] \tag{9}$$

and

$$\delta\sigma_{CPH}(T) + \delta\sigma_{CPP}(T) = L_{00}\left[0.46\left(\frac{4}{3}-\frac{3}{2}\tilde{F}\right) + \frac{0.915}{\ln\frac{T_C}{T}}\right]\left(\frac{k_B T}{\hbar D}\right)^{1/2}. \tag{10}$$

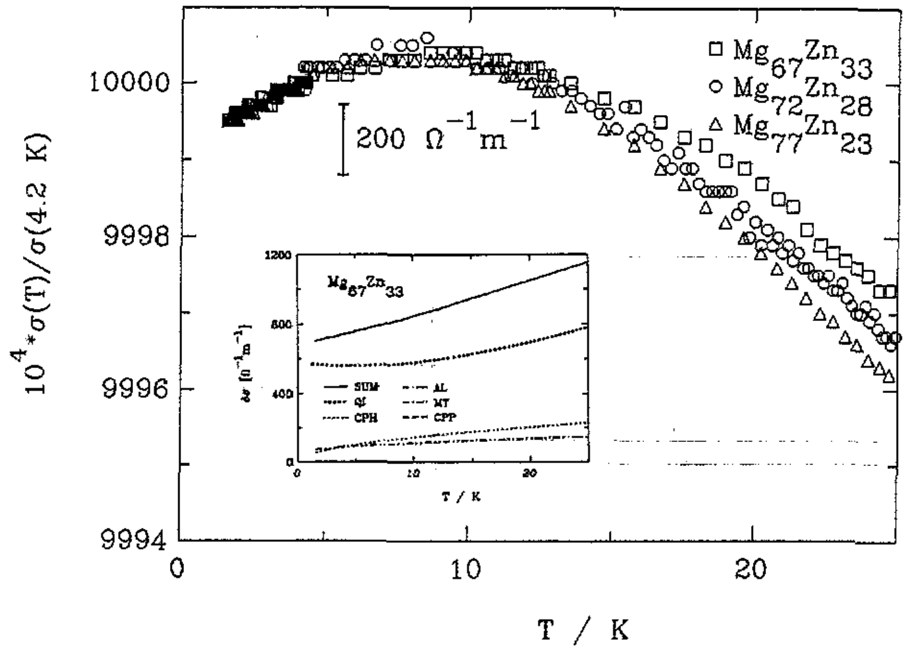

Figure 7. Temperature dependence of the conductivity for amorphous MgZn without a magnetic field, normalized to the value at 4.2 K. Inset: Decomposition into contributions due to quantum corrections (QI: quantum interference, CPH, CPP: Coulomb interaction) and superconducting fluctuations (MT, AL) calculated with the parameters obtained from the magnetoconductivity for $Mg_{67}Zn_{33}$. Full curve: sum of theoretical contributions for QI, CPH, CPP, MT and AL.

The temperature dependence of the paraconductivity due to superconducting fluctuations can be approximated by [30, 31, 35]

$$\delta\sigma_{\mathrm{AL}}(T) + \delta\sigma_{\mathrm{MT}}(T) = \frac{[1+4\alpha]e^2}{32\hbar\xi_{\mathrm{GL}}(0)}\left(\frac{T-T_{\mathrm{C}}}{T_{\mathrm{C}}}\right)^{-1/2}. \tag{11}$$

Here, $\xi_{\mathrm{GL}}(0) = 0.783\sqrt{\hbar D/k_{\mathrm{B}}T_{\mathrm{C}}}$ is the coherence length in the dirty limit case. α denotes the pair-breaking parameter which is related to the inelastic scattering rate [32] via $\alpha = \hbar/8k_{\mathrm{B}}T\tau_{\mathrm{i}}$.

It can be seen from figure 7 that the Coulomb correction accounts at least partially for the decrease in conductivity below about 4 K, although in this particular metallic glass the correction is small. According to the *ab initio* calculations by Hafner [7] an essential contribution is due to the phonon part of the dynamic structure factor, which also explains the maximum of σ around 10 K.

4. Summary and Conclusions

We have presented conductivity and Hall-effect measurements as a function of magnetic field, temperature and concentrations in three-dimensional MgZn glasses. In this simple system perturbation theories for quantum interference give a good quantitative description of the experimental results. However, it is important to take contributions due to superconducting fluctuations and the Coulomb interaction in the particle–particle channel into account, even at temperatures higher than 50 T_{C}. The temperature dependence of the inelastic scattering rate can be approximated by a power law with an exponent of about 1.7. The values of the spin–orbit scattering rates increase with atomic number. The characteristic fields are comparable to those determined in two-dimensional disordered films of similar metals [4]. These findings are also consistent with the temperature dependence of the conductivity and the Hall effect. Our results give further evidence that the NFE model is a good description of MgZn and that these alloys are model systems to test transport theories for three-dimensional disordered conductors.

Acknowledgments

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