Low-temperature electrical resistance and magnetoresistance of disordered $Cu_{72}Y_{28}$

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For two differently prepared disordered samples of $Cu_{72}Y_{28}$ we have measured the temperature dependence of the electrical resistance, $\rho(T)$, in the region 1–25 K and the low-field magnetoresistance, $\rho(B)$, at a few different temperatures up to 13 K in fields below 1.8 T. The inelastic scattering time, τ_i, is determined for both samples from $\rho(T)$ as well as from $\rho(B)$. These different estimates agree satisfactorily, within an order of magnitude in the worst case at 1 K. The temperature dependence of τ_i is found to be strong with an average exponent of -3 to -4 in the temperature range up to 20 K.

I. INTRODUCTION

It is by now well established that weak localization and interaction effects can be observed in the low-temperature transport properties of three-dimensional disordered samples such as glassy metals.[1] The more informative investigations have been made on nonsuperconducting alloys where the analysis is not further complicated by superconducting fluctuations. Some such studies include Cu-Ti alloys,[2–6] Y-Al alloys,[7,8] Cu-Y alloys,[9,10] Lu-based samples,[9,11] and a Mg-Cu sample.[9]

The overall picture of these results is that the electrical resistance at low temperatures is described by a contribution $-\sqrt{T}$ from interaction effects while the magnetoresistance is dominated by weak localization. However, there are a number of open questions and contradictions regarding the details. For instance, Olivier *et al.*[8] concluded that theory only gave a semiquantitative description of the magnetoresistance of $Y_{60}Al_{40}$ and $Y_{80}Al_{20}$ while Poon *et al.*[7] found large differences between theory and experiments for $Y_{75}Al_{25}$. The magnetoresistance in[11] $Lu_{75}Pd_{25}$ up to at least 2 T (at 0.7 K) could be described by the Fukuyama-Hoshino theory[12] provided the magnitude predicted by theory was multiplied by the arbitrary factor 1.2. Bieri *et al.*[9,13] used an adjustable prefactor in the expression for the magnetoresistance given by Altshuler *et al.*[14] to fit the magnetoresistance up to about 6 T for several different metallic glasses.

A number of authors[3,6,8,9,11] have argued that the inelastic scattering rate τ_i^{-1} should be proportional to T^2. In Ref. 11 such a relation is supported by the experiments down to 0.7 K, while in Refs. 9 and 13 there are deviations below 5–10 K in the direction of a weaker temperature dependence approaching $T^{-1/2}$ at the lowest temperatures. In contrast, Howson and coworkers[5] found a stronger temperature dependence of τ_i^{-1} in CuTi glasses below about 10 K and in a Cu-Y alloy[10] we found $\tau_i^{-1} \sim T^{3.6}$ as an average value for the temperature range 1.7–12 K. Also, the results for the spin-orbit scattering time in one alloy system differ considerably between different investigators.[5,6]

Different properties of different alloy systems may explain some of these different results. However, it is not clear how the results are system dependent or what is the influence of different ways of analyzing the data or using different formulations of the theory. In addition, for experiments on metastable materials, there is also the possibility that the observed properties depend on structural differences between different samples of similar chemical composition.

Since to some extent the same parameters are used to describe the electrical resistance and the magnetoresistance, it is clearly useful to analyze such experimental results together. In a recent note[10] we determined τ_i for a sample of disordered $Cu_{72}Y_{28}$ from the magnetoresistance and showed that this result and interaction effects could accurately describe the observed resistivity up to 20 K.

The different values of τ_i in metallic glasses mentioned above raises the question how reproducible such results are. In this paper we have investigated two samples of disordered $Cu_{72}Y_{28}$ prepared and stored in different ways. The analysis of Ref. 10 is generalized and τ_i and its temperature dependence are determined for each sample both from the temperature dependence of the resistivity and from the magnetoresistance. In this way we obtain four independent estimates of τ_i for this alloy. These results are compared and discussed.

II. EXPERIMENTAL DETAILS

A. Sample characterization

Starting materials were Cu and Y of 99.9 wt. % nominal purity from Johnson and Matthey. Appropriate quantities were repeatedly arc-melted on a water-cooled copper hearth under reduced pressure of Ar gas. Sample no. 1 of $Cu_{72}Y_{28}$ was melt-spun in a nitrogen-enriched atmosphere obtained by allowing liquid nitrogen to boil off from below the melt-spinning wheel prior to melting. There was no observable discoloring of the surface of the sample in this process indicating that oxides did not form. This sample was stored in air at room

temperature for a few months before the resistance measurements, and then again for a further period of about one year before the magnetoresistance measurements. At this time the surface had become somewhat yellowish by oxide formation.

Sample no. 2 of the same composition was melt-spun in He gas and stored in air in a refrigerator at about $-4\,^{\circ}\mathrm{C}$. This sample retained its metallic shiny surface throughout our observation period of about 20 months. In this case the measurements of the resistance as a function of temperature and magnetic field were made in succession within a few weeks. Both samples were found to be x-ray amorphous.

B. The experiments

The experimental technique was conventional. The electrical resistance was measured by a dc four-probe technique. In a separate cryostat the magnetic field was applied perpendicularly to the current in the plane of the ribbon. The magnet, of NMR type, had a high field homogeneity of at least 10^{-4} and reached a field strength of 1.8 T. Temperatures down to 1.7 K were obtained in pumped He baths and read from calibrated carbon resistors.

The resistivity, ρ, at room temperature was obtained by estimating the cross-sectional area with a micrometer. Therefore it is accurate only to about 15%. The result was $\rho = 110\ \mu\Omega\,\mathrm{cm}$.

III. ELECTRICAL RESISTANCE

The electrical resistance as a function of temperature for our two samples is displayed in Fig. 1. ρ_0 is a constant value close to the minimum of ρ, which has been subtracted from the measured data to display more clearly the temperature dependence.

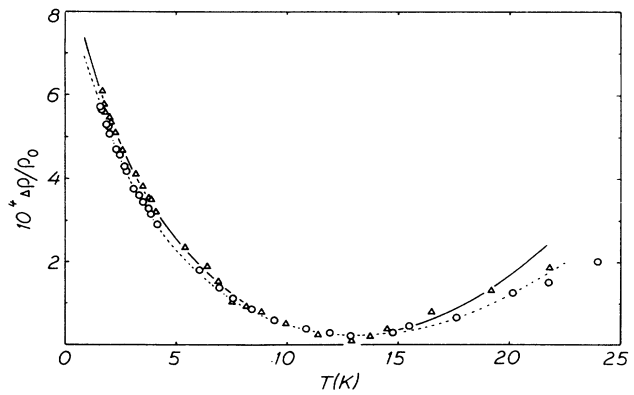

FIG. 1. The temperature dependence of the resistivity for disordered $Cu_{72}Y_{28}$. ○: sample no. 1; △: sample no. 2. The dashed curve is a fit of the measured data for sample no. 1 to Eq. (6), the solid curve is a similar fit for sample no. 2. The value of ρ_0 is arbitrary for each sample.

According to Ref. 12 the contribution to the conductivity from weak localization including spin-orbit scattering is

$$\Delta\sigma = -\Delta\rho/\rho^2 = A(3\sqrt{1+t} - \sqrt{t}\,)\ , \tag{1}$$

with

$$A = \frac{e^2}{2\pi^2\hbar}(D\tau_{\mathrm{SO}})^{-1/2} \tag{2}$$

and

$$t = \tau_{\mathrm{so}}/4\tau_i\ . \tag{3}$$

D is the diffusion coefficient and τ_{SO} the spin-orbit scattering time. In the limit $\tau_i \gg \tau_{\mathrm{SO}}$, which is satisfied below 20 K for the present alloys, the temperature-dependent part of these equations reduces to

$$\frac{\Delta\rho}{\rho} = 0.62\times 10^{-5} D^{-1/2}\rho\tau_i^{-1/2}\ , \tag{4}$$

with D in cm^2/s and ρ in $\Omega\,\mathrm{cm}$. We assume that in the temperature range of interest τ_i can be described by a single average power law

$$\tau_i = \tau_0 T^{-p}\ . \tag{5}$$

Besides this contribution we also expect a term $-\sqrt{T}$ from interaction effects. Therefore the observed resistance is fitted to an expression of the form

$$R = R_0(1 + B\sqrt{T} + CT^{p/2})\ , \tag{6}$$

and the coefficients and p are used as fitting parameters.

The results of these analyses for the data below $T^{\max} = 20$ K are summarized in Table I. We investigated whether these coefficients were sensitive to the choice of $T^{\max}$ and fitted various subsets of the data with $T^{\max}$ down to 13 K. For sample no. 1 the result in Table I was found to be well defined. For sample no. 2 however, although B was stable, p varied within 10% and C by a factor of 2. This sensitivity can be traced to the larger scatter of these data and the flexibility of the last term of Eq. (6) with two adjustable parameters.

To evaluate τ_i from Eqs. (4) and (5) one also needs the diffusion coefficient or the density of states $N(0)$ and the relation

$$\rho^{-1} = e^2 D N(0)\ . \tag{7}$$

We have not found any specific-heat results for Cu-Y alloys. Guided by some calculations for Y-rich glasses,[15] however, one can assume $N(0) = 0.7$ states/eV atom leading to $D = 1.3\ \mathrm{cm}^2/\mathrm{s}$ with an uncertainty of 30%.

With these assumptions one then obtains for sample no. 1

$$\tau_i = 2.6\times 10^{-9} T^{-3}\ , \tag{8}$$

TABLE I. Fit of resistivity data to Eq. (6).

Sample	$10^4 B$	$10^6 C$	$p/2$	10^6 (Rel. rms)
1	−4.58	11.72	1.5	5
2	−4.22	3.10	1.9	9

and sample no. 2

$$\tau_i = 3.7\times 10^{-8} T^{-3.8} . \tag{9}$$

The less accurate fit for sample no. 2 leads to larger uncertainty in τ_i. The result for this sample should be within the limits $2.4\times 10^{-8} T^{-3.6}$ and $1.3\times 10^{-7} T^{-4.2}$.

Equations (8) and (9) are shown by the dashed and solid lines, respectively, in Fig. 2 and the uncertainty for sample no. 2 is illustrated by an error bar at 2 K. It is seen from Fig. 2 that any difference in τ_i between the two samples is rather small in the temperature region above 10 K. At low temperatures this discrepancy is progressively worse and amounts to an order of magnitude difference at 1 K. Such a trend may be expected from Eq. (6) since the last term is important only at higher temperatures and the low-temperature behavior is dominated by the $\sqrt{T}$ term.

The coefficient B in Eq. (6) which is similar in both samples, is of the order of magnitude observed in a number of metal glasses[16,17] and expected from theory.[1] With

$$\frac{\Delta\rho}{\rho} = -\frac{e^2}{4\pi^2\hbar}\frac{1.3}{\sqrt{2}}\left(\tfrac{4}{3}-\tfrac{3}{2}\tilde{F}_\sigma\right)\left[\frac{k_B}{\hbar D}\right]^{1/2}\rho\sqrt{T} \tag{10}$$

from Ref. 1 the parenthesis containing the factor $\tilde{F}_\sigma$ is about 2 leading to an unphysical negative value of $\tilde{F}_\sigma$. However, the correct definition of $\tilde{F}_\sigma$ is a difficult problem with a number of different suggestions.[1,18] If we use instead an expression from Ref. 3 based on the work by Altshuler and Aronov,[18] assuming $T_c \approx 0$ and the electron-phonon interaction $\lambda \approx 0.2$, the factor within parenthesis in Eq. (10) should be replaced by $2(\frac{4}{3}-2F+0.4)$. Thus from this estimate small and positive values of F are obtained for both samples. At present we cannot obtain a quantitative estimate of F. Besides the question of the correct expression for the coefficient of the $\sqrt{T}$ term, the uncertainty of λ as well as the large experimental errors in ρ and D contribute to this difficulty.

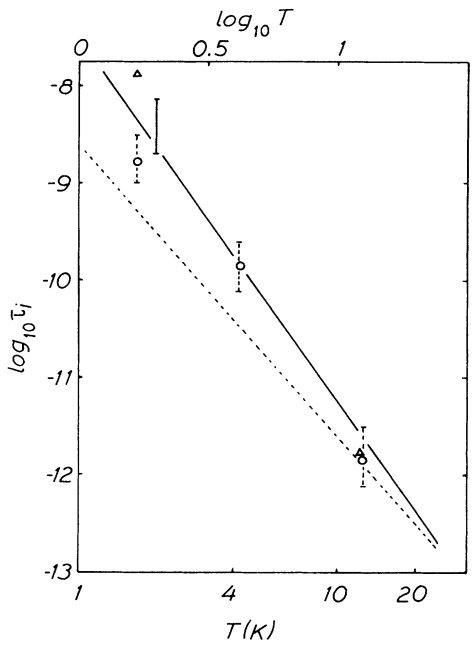

FIG. 2. The temperature dependence of the inelastic scattering time τ_i. Dashed line: from $\rho(T)$ of sample no. 1; solid line: from $\rho(T)$ of sample no. 2; ○: from $\rho(B)$ of sample no. 1; △: from $\rho(B)$ of sample no. 2. The dashed bars are estimates of the error from the fit to the magnetoresistance of sample no. 1. The solid bar is an error estimate at 2 K of Eq. (9).

IV. MAGNETORESISTANCE

Results from the magnetoresistance measurements are shown in Fig. 3. They were analyzed with the Fukuyama-Hoshino theory[12] which gives the following expression for the additional resistance in magnetic field:

$$\Delta\rho = \rho(B,T)-\rho(0,T) = -A\rho^2\left\{\sqrt{h}\,F\left[\frac{1+t}{h}\right]+0.5\left[\frac{h}{1-\gamma}\right]^{1/2}\left[F\left[\frac{t_+}{h}\right]-F\left[\frac{t_-}{h}\right]\right]\right.$$
$$\left.-\frac{1}{\sqrt{1-\gamma}}(\sqrt{t_-}-\sqrt{t_+})+(\sqrt{t}-\sqrt{t+1})\right\} . \tag{11}$$

A and t are defined in Eqs. (2) and (3). With the magnetic field B in tesla and D in cm^2/s

$$h = 1.52\times 10^{11} DB\tau_{SO} , \tag{12}$$

$$\gamma = \left[\frac{0.58}{D}\right]^2 h^2 , \tag{13}$$

$$t_\pm = t+0.5(1\pm\sqrt{1-\gamma}) , \tag{14}$$

and

$$F(x) = \sum_{N=0}^{\infty}\left[2\sqrt{N+1+x}-2\sqrt{N+x}-\frac{1}{\sqrt{N+x+\frac{1}{2}}}\right] . \tag{15}$$

τ_i and τ_{SO} are fitting parameters. In the present case, however, with small applied magnetic fields and strong spin-orbit scattering, we cannot determine τ_{SO} accurately and the result $\tau_{SO} = 10^{-13}$ s, is accurate only within about a factor of 5. The curves in Fig. 3 were obtained with this value of τ_{SO} and values of τ_i which depend

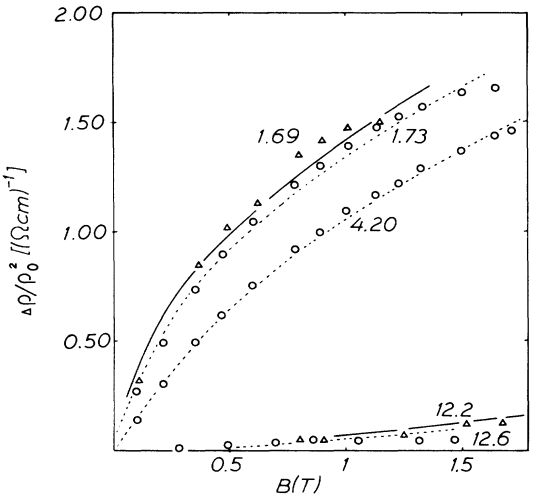

FIG. 3. The magnetoresistance at the indicated temperatures (in K). ○: sample no. 1; △: sample no. 2. The curves are fits to Eq. (11). Dashed curves: sample no. 1, solid curves: sample no. 2.

strongly on temperature. These results for τ_i are shown in Fig. 2.

For sample no. 1, experimental errors and the uncertainty in the value of D mentioned above lead to the indicated error bars in Fig. 2. For sample no. 2, in addition, there are clear deviations between the observed data and the fitted curve at 1.7 K in Fig. 3 and the error of τ_i at this point may be even larger.

The results for τ_i from magnetoresistance are consistent with those from $\rho(T)$ as seen in Fig. 2. Experimental results from two independent sources thus support the order of magnitude of τ_i and a fairly strong temperature dependence with an exponent in the range -3 to -4.

V. DISCUSSION

The results for $\rho(T)$ as well as $\rho(B)$ suggest small differences between the two samples. However, we have no clue as to the physical origin of such differences. Possible small concentration differences between the samples or different short-range structure due to differences in cooling conditions or differences in relaxation during storing may be some possibilities.

On the other hand, Fig. 2 gives results for τ_i of disordered $Cu_{72}Y_{28}$ which illustrate the level of accuracy obtained with standard procedures. We have used two samples of nominally the same chemical composition, where the crucial parameters defining any difference are not known. Furthermore, we have measured the resistance with an accuracy of order 10 ppm and obtained fairly but not completely successful fits to the magnetoresistance. This leads to values for τ_i for the two samples within a factor of 2 at 10 K and within an order of magnitude at 1.7 K. These results are strengthened by the consistent independent estimates of τ_i.

Disordered $Cu_{72}Y_{28}$ may represent a rather unusual metallic glass with respect to its low-temperature transport properties. In particular, two circumstances serve to facilitate the present analysis. (i) The measured magnetoresistance can be accounted for by the Fukuyama-Hoshino[11] theory. In contrast, the magnetoresistance in many metal glasses is larger than consistent with this theory as discussed above. (ii) The spin-orbit scattering is rather strong in Cu-Y. This implies that the temperature below which $\tau_i \gg \tau_{SO}$ is as high as 20 K and the simplifying approximation of Eq. (4) is useful over a large range of temperatures. In Cu-Ti, for instance, this condition is not obeyed and Eq. (1) must be used. In this case the observed $\rho(T)$ may be more complicated with a maximum as well as a minimum at low temperatures and the analysis is more difficult.[2–6,19]

Therefore disordered $Cu_{72}Y_{28}$ can be regarded as a simple model case where some prominent features of the theory are clearly displayed. In particular, the low-temperature minimum of the resistivity is seen to arise from a combination of interaction and weak localization effects. The inelastic scattering time can be determined at the level illustrated in Fig. 2, which includes some possible variation between different samples and results from the temperature dependence of resistivity as well as from magnetoresistance. The temperature dependence of τ_i is strong with a variation over more than 4 orders of magnitude from 1 to 20 K.

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[1]P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985).
[2]M. A. Howson and D. Greig, J. Phys. F **13**, L155 (1983).
[3]B. J. Hickey, D. Greig, and M. A. Howson, J. Phys. F **16**, L13 (1986).
[4]M. A. Howson and D. Greig, J. Phys. F **16**, 989 (1986).
[5]M. A. Howson, B. J. Hickey, and C. Shearwood, J. Phys. F **16**, L175 (1986).
[6]A. Schulte and G. Fritsch, J. Phys. F **16**, L55 (1986).
[7]S. J. Poon, E. J. Cotts, and K. M. Wong, Solid State Commun. **52**, 519 (1984).
[8]M. Olivier, J. O. Strom-Olsen, Z. Altounian, R. W. Cochrane, and M. Trudeau, Phys. Rev. B **33**, 2799 (1986).
[9]J. B. Bieri, A. Fert, and G. Creuzet, in *Localization and Transport in Impure Metals,* edited by L. Sceweitzer and B. Kramer (Physikalisch Technische Bundesanstalt, Braunschweig, 1984), p. 94.
[10]Y. F. Li and Ö. Rapp, Z. Phys. Chem. (to be published).

[11]S. J. Poon, K. M. Wong, and A. J. Drehman, Phys. Rev. B **31**, 1668 (1985).
[12]H. Fukuyama and K. Hoshino, J. Phys. Soc. Jpn. **50**, 2131 (1981).
[13]J. B. Bieri, A. Fert G. Creuzet, and A. Schul, J. Phys. F **16**, 2099 (1986).
[14]B. L. Altshuler, A. G. Aronov, A. I. Larkin, and D. E. Khmelnitskii, Zh. Eksp. Teor. Fiz. **81**, 768 (1981) [Sov. Phys. —JETP **54**, 411 (1981)].
[15]M. Tenhover, D. Lukco, and W. L. Johnson, J. Non. Cryst. Solids **61&62**, 1049 (1982).
[16]Ö. Rapp, S. M. Bhagat, and H. Gudmundsson, Solid State Commun. **42**, 741 (1982).
[17]R. W. Cochrane and J. O. Strom-Olsen, Phys. Rev. B **29**, 1088 (1984).
[18]B. L. Altshuler and A. G. Aronov, in *Electron-Electron Interactions in Disordered Systems,* edited by A. L. Efros and M. Pollak (North-Holland, Amsterdam, 1985), p. 1.
[19]P. Lindqvist and Ö. Rapp (unpublished).