Quantum corrections to transport properties of icosahedral Al-Cu-Fe in extended regimes

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Studies of quantum corrections to the transport properties of icosahedral Al-Cu-Fe (i-AlCuFe) have been made in extended regimes. The magnetoresistance, $\Delta\rho(B,T)$, was measured and analyzed up to 12 T and ambient temperatures. $\Delta\rho(B,T)$ was observed to change sign in the range 90–120 K. Different analyses were made encompassing different assumptions about the background resistivity to which quantum corrections (QIE) should be added. In all cases accurate descriptions of $\Delta\rho(B,T)$ were found, demonstrating that QIE is observable in i-AlCuFe at least up to 280 K. Common results for the parameters in these different analyses include estimates of the temperature dependence of the Coulomb interaction parameter F_σ in electron-electron interaction, and a low value of the inelastic scattering time τ_{ie} at 280 K of order 100 fs, consistent with an elastic-scattering time of at most some femtoseconds. Using parameters determined from $\Delta\rho(B,T)$ in the analysis of the temperature dependence, $\Delta\rho(T)$, it was found that quantitative agreement between descriptions of $\Delta\rho(B,T)$ and $\Delta\rho(T)$ in terms of QIE could be obtained up to 150 K. Weak localization thus contributes also to $\Delta\rho(T)$ in i-AlCuFe at least up to this temperature. [S0163-1829(97)04622-5]

I. INTRODUCTION

It is well known that the large magnetoresistance, $\Delta\rho(B,T)/\rho$, of icosahedral Al-Cu-Fe can be understood by conventional quantum correction theories (QIE).[1–5] In particular, it was found[4] that QIE can describe observations with reasonable parameters and quantitative precision over a large range of temperatures and magnetic fields, with temperature varied between 80 mK and 80 K and magnetic fields reaching 12 T. In earlier observations of QIE in three dimensions, e.g., in amorphous metals,[6,7] the temperature range over which $\Delta\rho(B)/\rho$ is observable is in general more limited. Nevertheless, deviations are regularly observed between calculated and observed $\Delta\rho/\rho$ at the lowest or highest measuring temperatures or both. The results for the magnetoresistance of i-Al-Cu-Fe therefore reestablishes confidence that QIE theories can correctly describe the dominating contributions to $\Delta\rho/\rho$ in non-superconductors at least for some three-dimensional materials.

Hence, icosahedral Al-Cu-Fe presents a unique possibility to attempt to extend applications of QIE to problems which have previously been too difficult. In this paper we report on measurements and analyses of $\Delta\rho(B,T)/\rho$, of i-Al-Cu-Fe to address three such problems: (i) Up to what temperatures can the magnetoresistance from weak localization (WL) be followed? (ii) Can the expected vanishing of the electron-electron interaction (EEI) in the magnetoresistance with increasing temperature be observed? (iii) Are QIE present in the temperature dependence of the resistivity, $\rho(T)$, also above cryogenic temperatures?

(i) It is interesting to attempt to establish an upper temperature limit for observable $\Delta\rho(B)/\rho$. With increasing temperature one would expect breakdown of the condition that the inelastic-scattering time $\tau_{ie}(T) \gg \tau$, the elastic-scattering time. Such measurements could then give new upper limits of τ in i-Al-Cu-Fe, which is of interest in understanding transport properties in these materials. It may also be possible to study WL in the regime where the condition above is relaxed to $\tau_{ie}(T) > \tau$.

(ii) The EEI contribution to $\Delta\rho(B)/\rho$ in the diffusion channel is proportional to the Coulomb interaction parameter F_σ. A condition for observing this contribution is that the momentum transfer in the scattering event remains much smaller than the inverse mean free path.[8] With increasing temperature this condition will eventually break down, but it is not known where and how. Due to the small magnitude of $\Delta\rho(B)/\rho$ in, e.g., amorphous metals, and to the mathematical complexity, this problem has been too difficult, experimentally as well as theoretically. The more stringent description of $\Delta\sigma(B)$ by QIE in i-Al-Cu-Fe therefore provides a new tool for this problem.

(iii) The question of possible intermediate-temperature range quantum corrections in $\rho(T)$ in electronically disordered materials is a long-standing controversy. The difficulty is mainly due to the fact that $\rho(T)$ is a smoothly varying function. Therefore almost any theory can be supported by finding suitable fitting parameters to describe the observations. Since the same parameters of QIE enter both in $\rho(T)$ and in $\rho(B)$, analyses of both these properties provide a more rigorous test.

In Sec. II the samples and the experiments will be described with some emphasis on methods used to extend the measurements to ambient temperatures. Our fitting procedures are described in Sec. III, including special considerations required when the magnetoresistance is to be analyzed over a temperature range with strongly varying resistivity. The observations and analyses of the magnetoresistance are presented in Sec. IV, and of the electrical resistivity in Sec. V. Open problems and conclusions are discussed and summarized in Sec. VI. Some aspects of problems (ii) and (iii) have each recently been described in preliminary conference submissions.[9,10]

II. EXPERIMENTAL DETAILS

A. Sample characteristics and standard measurements

Single-phase icosahedral samples of compositions $Al_{62.5}Cu_{25}Fe_{12.5}$ (sample I) and $Al_{62.5}Cu_{25.5}Fe_{12}$ (sample II) were prepared as described earlier.[11,12] Samples were typically 5 mm long, 1 mm wide, and 30 μm thick. The quality of the samples was checked with x-ray diffraction. All peaks were narrow and could be indexed as a pure icosahedral phase.

The electrical resistance measurements were made with a standard four-pole technique. Electrical contacts were made with silver paint. The resistivity was determined from the average of several measurements on different samples with the same composition, and are estimated to be accurate to $\pm 15\%$. The results evaluated at 4.2 K were 10 000 and 4500 $\mu\Omega$ cm for samples I and II, respectively.[11]

Different cryostats were used with varying conditions in the experiments. For measurements of the temperature dependence of the resistivity between 1.5 and 300 K, a ^{4}He cryostat was used. The measurements below 1.5 K were made in a dilution refrigerator and were reported previously.[4] The magnetoresistance at higher temperatures was measured in a flowing gas cryostat equipped with a 12 T superconducting magnet. The sample holder is situated inside a shield, which is kept at constant temperature by regulating a flow of ^{4}He gas outside the shield. If necessary a heater can also be used. A precise adjustment of the temperature on the sample holder is obtained with a regulated heater.

B. High-temperature measurements

The magnetoresistance is most conveniently measured at a fixed temperature as a function of the magnetic field. A major experimental problem in extending such measurements to higher temperatures for the present samples is temperature regulation in magnetic field. As an example, at 100 K the magnetoresistance, $\Delta\rho/\rho$, of our high-resistivity sample increases with magnetic field to $+7\times10^{-5}$ at 12 T, while the average temperature coefficient of resistance $(1/R)$ dR/dT is about 2.8×10^{-3} K^{-1}. Therefore, if the quite demanding experimental task can be solved to limit temperature drift to below 10 mK during a sweep time of about 90 min, the error in $\Delta\rho/\rho$ at this temperature can be reduced to 30%.

The following procedures were used for the measurements. Temperature regulation was facilitated by using a long sample holder of high-purity copper, extending into a low-field region above the superconducting magnet, achieved through a cancellation coil. This gives a possibility to position a thermometer in this region, which is in thermal contact with the sample. In our measurements the shield surrounding the sample holder was kept at a temperature normally 5 K below that of the sample holder. The temperature of the sample holder was regulated with a Pt thermometer in the low-field region. Measurements were taken in increasing and decreasing magnetic field, up to 12 T and down to zero field. The temperature of the sample was measured before and immediately after a field sweep by another thermometer in close proximity to the sample, which gave an estimate of the temperature drift during measurements. We assumed that this drift was linear in time, and compensated for it by averaging data for the two field sweeps. An example is shown in Fig. 1 from a measurement at 280 K.

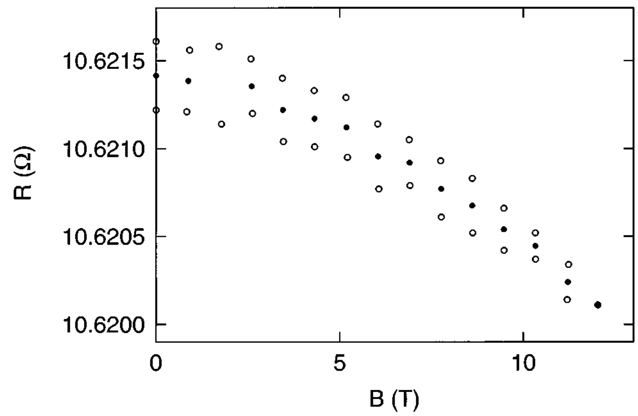

FIG. 1. The magnetic field dependence of the resistance of sample I at 280 K. The open circles are data taken during 90 min, on increasing and decreasing field sweeps. Sample resistance at $B=0$ increased corresponding to a cooling of 20 mK. Assuming a linear temperature drift, the average values, filled circles, were used in the analyses.

III. METHODS OF ANALYZING THE MAGNETORESISTANCE

The methods of analyses are briefly described with emphasis on consequences of the presently extended temperature range. Weak localization (WL) and electron-electron interaction (EEI) theories give expressions for quantum corrections to the conductivity and the magnetoconductivity of the form[13–15]

$$\Delta\sigma_{\mathrm{WL}}=\Delta\sigma[\tau_{\mathrm{ie}}(T),\tau_{\mathrm{so}},D,g^*,B], \tag{1}$$

$$\Delta\sigma_{\mathrm{EEI}}=\Delta\sigma(F_\sigma,D,g^*,T,B). \tag{2}$$

$\tau_{\mathrm{ie}}(T)$ is the inelastic scattering time, τ_{so} the spin-orbit scattering time, D the diffusion constant, g^* the electron Landé factor, F_σ the Coulomb interaction parameter, and B and T magnetic field and temperature. A contribution in Eq. (1) from magnetic interactions might also be considered. However, such interactions are presumably small in the present samples, which display a diamagnetic susceptibility in the temperature range 1.5–300 K,[11] and magnetic phase breaking was neglected. Equation (2) gives the contribution from EEI in the diffusion channel. EEI in the Cooper channel[16] was estimated and found to be small, and was therefore neglected.

For a small magnetoresistivity the approximation $\Delta\sigma(B,T)=-\Delta\rho(B,T)/\rho^2(0,T)$ is adequate. When the magnetoresistance is large, as is often the case for quasicrystals at low temperatures, we must retain the full expression $\Delta\sigma(B,T)=\sigma(B,T)-\sigma(0,T)=-\Delta\rho(B,T)/[\rho(0,T)\rho(B,T)]$. This form has been used in all the present analyses of the magnetoresistance. Furthermore, when each of the contributions in Eqs. (1) and (2) to $\Delta\rho/\rho$ are small, of order 10^{-3} or below, as in amorphous metals, there may be some empirical justification for considering them to be independent, and simply add them to obtain the total magnetoconductivity. In quasicrystals, where the WL and EEI contributions to the magnetoresistance may each reach 10% or more, this is not necessarily true. However, there is no theory

TABLE I. Summary of assumptions and notations in different analyses.

A:	$D = D(300\text{ K})$
B:	$D \sim 1/\rho(T)$
a:	$F_\sigma(T)$ was fitted independently at each T
b:	F_σ decreases linearly from 10 K to a temperature T_l
	$F_\sigma(0\text{ K})$ and T_l are fitted in the analyses
Three characters, e.g., IIBb, specifies the analysis: sample II with assumptions B and b.	

treating interference between these QIE, and we will adopt the simplification that they are still independent.

In Eqs. (1) and (2) above, the corrections should be calculated from a background state where there are no quantum corrections. In traditional cases, where the temperature range studied is limited, the temperature variations in QIE corrections to this background can be neglected, and the correct temperature dependence of QIE in $\Delta\rho(B)/\rho$ is nevertheless approximately obtained. When the magnetoresistance of quasicrystals is studied in the temperature range above 100 K this assumption may not be valid. In particular, the diffusion constant in Eqs. (1) and (2) can depend on temperature, $D = D(T)$. This is difficult to handle since it is not known in detail in what temperature range QIE affect $\rho(T)$. This problem was pointed out previously by us.[4,5] In those cases the measurements were either limited to below[4] 80 K, or no full analyses of $\Delta\sigma(B)$ were performed,[5] and an assumption of a constant average D would then be adequate.

In the present case we want to investigate if the detailed descriptions of the magnetoresistance by QIE can be extended to higher temperatures. Since the problem mentioned above cannot be readily solved, we use two extreme assumptions; (A) all of $\Delta\rho(T)$ up to a temperature T_m is due to QIE, and (B) all of $\Delta\rho(T)$ is due to other mechanisms. Any temperature dependence of the density of states, $N(0)$, is neglected. This assumption could be questioned if $N(0)$ is spiky at the level below 50 meV.[17] However, recent high-sensitivity photoemission experiments do not indicate such spikeness.[18] $N(0)$ is then obtained from the electronic specific heat and related to ρ and D by $\rho(T) = 1/[e^2 N(0) D(T)]$. The real situation should be in between these two extreme assumptions, and is then encompassed by two different analyses: (A) $D(T)$ is a constant $D(T_m)$, and T_m is somewhat arbitrarily chosen to be 300 K and (B) $D(T)$ is proportional to $1/\rho(T)$. The low-temperature D values used to calculate these various D's were quoted and discussed previously.[4]

$\rho(T)$ is taken from our measurements, g^* is assumed to be 2. $\tau_{ie}(T)$, τ_{so}, and F_σ were then determined from the experiments. As discussed in Ref. 4 it is preferable to use a measured value of ρ, rather than fitting it. All data at different temperatures and magnetic fields were used simultaneously in the analysis providing for more stable numerical procedures. τ_{so} was thus taken to be a constant to fit data at all temperatures and fields, and $\tau_{ie}(T)$ was allowed to vary freely as a function of temperature. For F_σ two alternatives were used: (a) F_σ was allowed to vary freely at each temperature, and (b) F_σ was assumed to decrease linearly to 0 in the range 10 K to T_l with T_l and $F_\sigma(0\text{ K})$ as free parameters. This latter assumption will be discussed below.

For each of the two samples we thus use two alternative assumptions about D and two about F_σ. In total, eight different analyses were attempted. However, as will be described below, in a few of these combinations useful results could not be obtained. For easy reference to the different methods of analysis, the notations are summarized in Table I.

IV. ANALYSES AND RESULTS FOR THE MAGNETORESISTANCE

A. The magnetoresistance up to 280 K

The results for the magnetoresistance show the first clear observation of a sign change for quasicrystals. In a previous publication by one of us,[5] indication of such a sign change was obtained for a number of quasicrystals and approximants in the temperature range 100–200 K, but the sensitivity was reduced and details could not be resolved. A previous contention[19] of a sign change at about 30 K has not been confirmed by other measurements in that temperature region.[1,4,5]

Our results are illustrated in Fig. 2 in the form of $\Delta\rho/\rho$ vs temperature at $B = 12$ T. The error bars were calculated from an estimated uncertainty of the correction for the temperature drift. A change of sign of $\Delta\rho/\rho$ is unambiguously observed in both samples and occurs at 12 T at temperatures T_s of about 120 K for sample I and 90 K for sample II. In weak localization T_s depends only on the interplay between D,

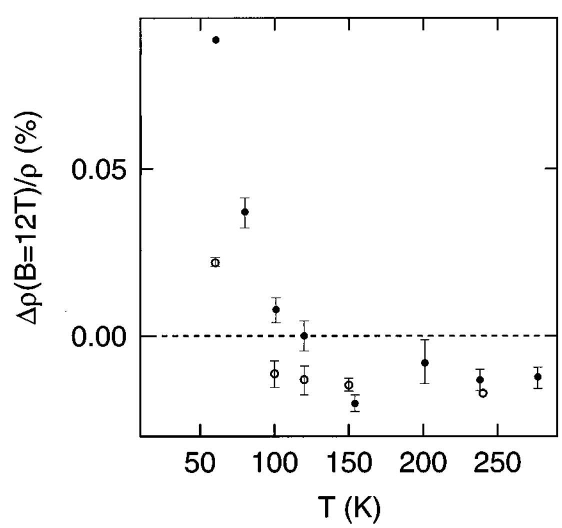

FIG. 2. Observed $\Delta\rho/\rho$ at $T > 50$ K and $B = 12$ T; ●, sample I; ○, sample II. Error bars shown were estimated from an assumed maximum temperature error of half the observed drift after sweeping the magnetic field 0→12→0 T. A clear change of sign is observed in both samples in the temperature range 90–120 K.

$\tau_{ie}(T)$, and τ_{so}, as can be seen, e.g., from a low-field expansion of the general WL expression.[20] However, we found that EEI still makes an appreciable contribution at this temperature. This will be illustrated below. The observed $\Delta\rho(B,T_s)/\rho=0$ therefore does not provide an additional useful criterion in the analyses.

B. Analysis of the magnetoresistance

Data from previous measurements[4] below 10 K were included in the analyses for both samples. A larger range of variations of field and temperature provides more stringent conditions for the numerical work. Furthermore, since the assumption was made previously of a constant, low-temperature diffusion coefficient, adequate in icosahedral AlCuFe for $T\leqslant 80$ K, we wanted to investigate if the present generalized analyses also could provide adequate descriptions of the low-temperature data.

The results of the analyses are illustrated in the different sections in Fig. 3 for sample I. The inset in the middle panel will be discussed below. Data over the full temperature range are illustrated in the main panels, but several field sweeps have been omitted for clarity. F_σ and τ_{ie} were allowed to vary freely at each temperature, τ_{so} was a temperature-independent constant, and D was taken to be D at 300 K, (analysis IAa). It can be seen that the description in terms of WL and EEI is excellent at all temperatures. For sample I, similar good results were obtained for the other analyses methods.

Figures 4 and 5 show $F_\sigma(T)$ and $\tau_{ie}(T)$, respectively, for sample I in the top panels and for sample II, to be discussed below, in the bottom panels. A freely varying F_σ gives somewhat more scattered results at low and high temperatures. However, in both analyses a (filled and open circles), $F_\sigma(T)$ is roughly constant up to about 10 K and then decreases strongly towards zero in the next decade of temperatures. The results for $\tau_{ie}(T)$ in these two analyses, top panel of Fig. 5, show an unphysical downward trend for $T<0.5$ K. However, the calculations are quite insensitive to variations in $\tau_{ie}(T)$ at these temperatures and a constant τ_{ie} is consistent with the analyses as suggested by the estimated errors indicated by bars. We took this uncertainty as an indication that our analyses are close to being overflexible under the present conditions, and therefore attempted to reduce this flexibility by imposing an additional condition.

Based on the results with F_σ as a free parameter and previous analyses[4] restricted to $T\leqslant 80$ K, where F_σ was closely constant below 10 K, we therefore adopted method b, assuming F_σ to be constant up to 10 K and then to decrease linearly to a temperature T_l. In this method the problem to determine $F_\sigma(T)$ at all T has thus been reduced to fitting two constants, $F_\sigma(0)$ and T_l, to all data. The results are shown by the filled and open squares in Figs. 4 and 5. It can be seen that this method gives an almost constant τ_{ie} at low temperatures. Furthermore, the quality of fits b to $\Delta\sigma(B,T)$ are the same or only slightly worse than for method a, as can be seen by the rms means in Table II.

The main results of the four different analyses for sample I are similar. There is a clear trend for a saturation of $\tau_{ie}(T)$ at temperatures below 1 K, at a value which is not well determined and may be in the range 5 $\times 10^{-11}$–10^{-9} s. In the range 1–100 K, τ_{ie} decreases strongly with an average temperature exponent of roughly $T^{-1.4}$. This behaviour is similar in all analyses. At $T>100$ K, the calculated results are fairly insensitive to variations in τ_{ie} and errors in τ_{ie} are therefore larger.

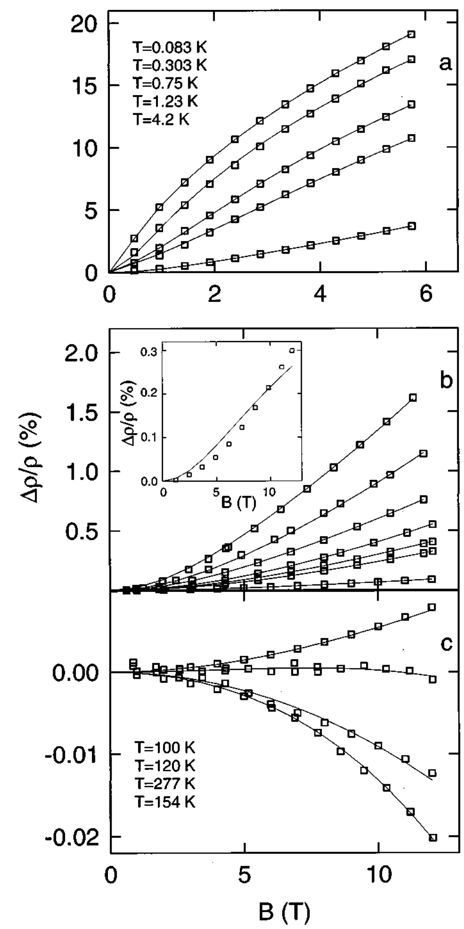

FIG. 3. Data and analysis of the magnetoconductivity of sample I plotted as $\Delta\rho/\rho$ vs B. Analyses IAa (see text). The temperatures in (a) and (c) are given (in K) in the order from top to bottom of the curves in that panel. In (b) the temperatures are, from top to bottom, 14.8, 20.1, 25.4, 30.0, 35.6, 40.4, and 60.5 K. The inset in (b) shows data for sample II at 30 K analysis IIBb, illustrating one of the worst fits at any temperature.

For F_σ we find evidence that it is constant at low temperatures at a value 1.1 ± 10 % for analyses B and at about 1.7 for analyses A. At higher temperatures F_σ decreases strongly towards zero. However, an estimate where this happens is quite uncertain. Relying on method b, it can be conjectured that F_σ falls to zero in the interval 80–150 K.

For sample II it was found that method a was too flexible to obtain any reasonable results. Method b was therefore used. In order to avoid unphysical oscillations in $\tau_{ie}(T)$ at the lowest temperatures we further had to impose the condition that $\tau_{ie}(T)$ must either be constant or decrease with increasing temperature. The quality of these fits then detoriated somewhat when compared to those for sample I, as seen by the mean rms values in Table II. To illustrate this point we show in the inset of Fig. 3(b) the analysis IIBb at 30 K which is one of the worst fits for this sample at any temperature and nevertheless is still acceptable by usual standards.

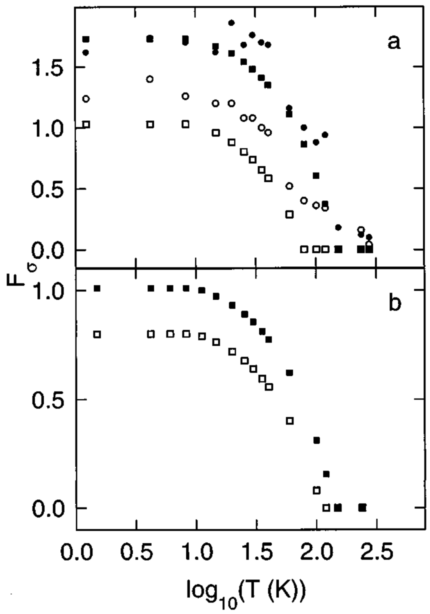

FIG. 4. Results for F_σ vs $\log_{10} T$ from four different analyses. Top panel, sample I; bottom panel, sample II. Filled circles, analysis IAa; open circles, analysis IBa; filled squares, analyses Ab; open squares, analyses Bb.

F_σ vs T for sample II is shown in the bottom panel of Fig. 4. $F_\sigma(0\text{ K})$ is 0.9±10 % and vanishes at 135±15 K. $\tau_{\text{ie}}(T)$ for this sample is shown in the bottom panel of Fig. 5. With the restriction imposed on $\tau_{\text{ie}}(T)$ it stays constant up to 4 K and varies approximately as $T^{-1.5}$ from about 4 to 100 K. Above 100 K, data for $\tau_{\text{ie}}(T)$ are more scattered, with a tendency towards a weaker T dependence.

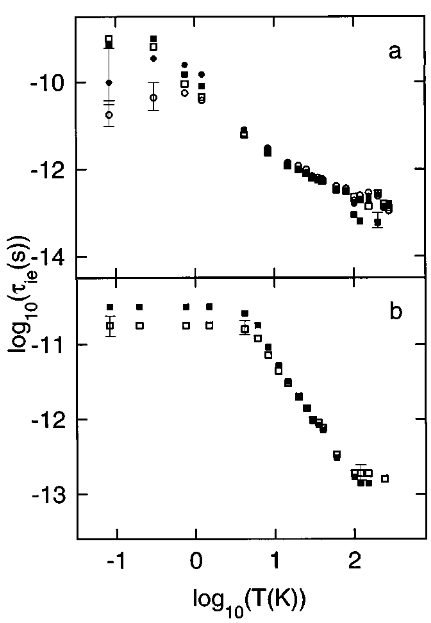

FIG. 5. $\tau_{\text{ie}}(T)$ vs T for sample I (top panel) and sample II (bottom panel) for the same analyses and with the same symbols as in Fig. 4. Estimated error bars are indicated at low and high temperatures.

TABLE II. Results from analyses of the magnetoconductivity. ''rms mean'' is a quality factor indicating the average of the relative root-mean-square deviations for each of about 20 field sweeps. A bar indicates that a meaningful fit could not be obtained.

Analysis	τ_{so} (ps)	rms mean (%)
IAa	1.8	0.3
IAb	1.6	0.5
IBa	5.0	0.4
IBb	2.8	0.4
IIAa	–	–
IIAb	0.85	1.4
IIBa	–	–
IIBb	1.5	1.1

A noteworthy feature of these analyses is the importance of EEI at rather high temperatures. This implies that the WL contribution to $\Delta\rho/\rho$ is negative at temperatures well below the temperature of the sign change in Fig. 2. The importance of EEI at a rather elevated temperature is illustrated in Fig. 6 by the observed $\Delta\rho(B)/\rho$ at 120 K and a calculation decomposed into WL and EEI contributions. It can be seen that the magnitudes and field dependences of these contributions are similar and of opposite signs, with a sum close to the observed $\Delta\rho(B)/\rho \approx 0$.

V. TEMPERATURE DEPENDENCE OF THE RESISTIVITY

As mentioned in the Introduction an analysis of the temperature dependence of the resistivity in terms of QIE requires information from other measurements in order to obtain a reliable result. This is readily appreciated from Eqs. (1) and (2) above, which for $B=0$ require four free parameters [with two for $\tau_{\text{ie}}(T)$ and excluding g^*] to describe a smooth

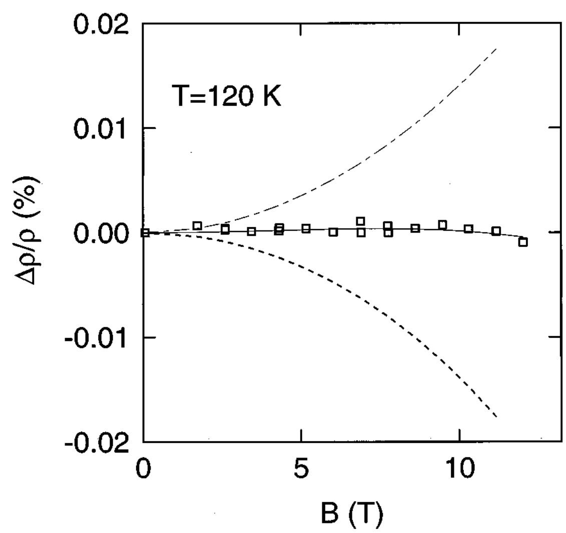

FIG. 6. Magnetoresistance at 120 K for sample I. Observations are shown by the symbols and analysis IAa by the curves. Dashed curve, WL contribution; dash-dotted curve, EEI contribution; and full curve, the sum of these contributions.

function of T. A further complication is the treatment of the diffusion channel EEI contribution, which contains two terms, both of which are proportional to $\sqrt{T}$; the exchange term, which does not enter in the magnetoresistance, and the Hartree term which is proportional to F_σ.[8] We simplified this problem by assuming that both these terms have a similar temperature dependence. Based on the analyses of the magnetoconductivity, the EEI term was therefore taken to be constant below 10 K and then to decrease linearly and vanish at a temperature T_l.

Taking $D \approx 1/\rho(T)$ (analyses B), implies that no part of $\Delta\rho(T)$ is due to quantum corrections, and would thus not be compatible with an analysis of $\Delta\rho(T)$ in terms of QIE. Analyses B were thus discarded when studying $\Delta\rho(T)$.

However, this fact offers a consistency check for the magnetoresistance; when using the parameters from analyses B of $\Delta\sigma(B,T)$ together with a constant $D = D(300\ \mathrm{K})$, no appreciable temperature dependence in the calculated $\Delta\rho(T)$ should result. We found this to be well obeyed for sample B, where the calculated $\Delta\rho(T)$ was almost constant, and approximately obeyed for sample A, with a much reduced temperature dependence [a factor of 3 in $\sigma(300\ \mathrm{K}) - \sigma(50\ \mathrm{K})$] as compared to the observations.

Furthermore method a, with a freely varying F_σ, was not possible to test, since strongly overdetermined fitting procedures would result. The only realistic method is thus Ab for both samples. Finally, to further stabilize the fitting procedures, we assumed that $\tau_{ie}(T)$ followed a simple temperature dependence above the extreme low temperature behavior, $\tau_{ie}(T) = \tau_{ieo} T^{-p}$, and either fitted τ_{ieo} and p, or derived them from the magnetoresistance to be used as input parameters in the analyses. Although this expression is useful for limited temperature ranges, it is clearly an oversimplification to employ it over more than a decade in temperatures. Within this scheme a few different analyses were investigated.

For sample II we took $\tau_{so} = 0.85$ ps, $F_\sigma(0\ \mathrm{K}) = 1.01$ and $T_l = 140$ K from analysis IIAb of the magnetoresistance. $\tau_{ie}(T)$ in the WL part of $\rho(T)$ was then fitted by adjusting τ_{ieo} and p. The result for the conductivity is shown in Fig. 7, and $\tau_{ie}(T)$ from this analysis is compared in the inset with the results from analysis IIAb of the magnetoresistance. There is good agreement between results for $\tau_{ie}(T)$ from $\Delta\sigma(B)$ and $\Delta\sigma(T)$ from the saturation region at about 4 K up to at least 150 K. Above this temperature, the results for $\tau_{ie}(T)$ from $\Delta\sigma(B)$ become rather uncertain, as mentioned above. For $T > 200$ K, $\tau_{ie}(T)$ from resistivity falls below the results from $\Delta\sigma(B)$. However, as is illustrated in Fig. 7, a good description of $\Delta\sigma(T)$ is obtained from 4 to 280 K.

For sample I we first fitted $\tau_{ie}(T)$ to the results of analysis IAb of $\Delta\sigma(B)$ from 0.3 to 200 K. A simple power law, $\tau_{ie}(T) = 7.96 \times 10^{-11} \mathrm{T}^{-1.33}$ s, is seen in the inset of Fig. 7 to well describe $\tau_{ie}(T)$, and was used in analyzing $\Delta\sigma(T)$. We further took $T_l = 150$ K from analysis IAb and fitted two constants to $\Delta\sigma(T)$, i.e., τ_{so} and $F_\sigma(0)$. The results were $\tau_{so} = 0.4$ ps and $F_\sigma(0) = 1.09$, to be compared with 1.6 ps and 1.73, respectively, from analysis IAb. The correct temperature dependence of $\Delta\sigma(T)$ is obtained by this method up to 150 K as can be seen in Fig. 7, although there is considerable disagreement between τ_{so} and $F_\sigma(0)$ from $\Delta\sigma(B)$ and $\Delta\sigma(T)$.

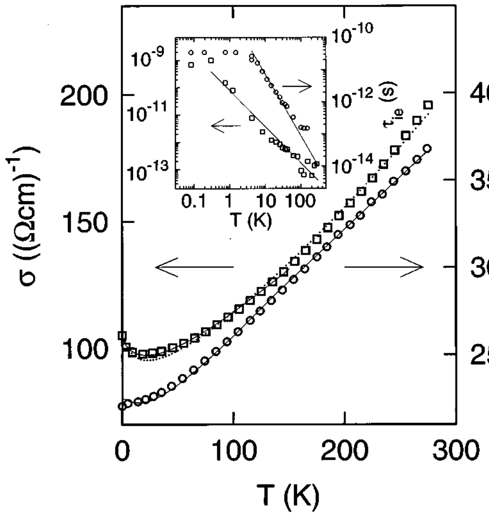

FIG. 7. $\sigma(T)$ for both samples. Symbols are observations: squares, sample I, left-hand scale; circles, sample II, right-hand side scale. The curves are calculations from QIE described in the text. For sample I there are two calculations. The full curve describes data up to 150 K, takes $\tau_{ie}(T)$ and T_l from the magnetoresistance and fits the constants τ_{so} and F_σ. The dotted curve, almost indistinguishable from the full curve below 150 K, extends up to room temperature, takes $\tau_{ie}(T)$ and τ_{so} from the magnetoresistance and fits the constants T_l and F_σ. Inset: squares, results from analysis IAb with a power law fitted for $\tau_{ie}(T)$ to be used in the analysis of $\Delta\sigma(T)$; circles, results from analysis IIAb. The straight line was obtained from fitting $\tau_{ie}(T)$ to $\Delta\sigma(T)$.

As an alternative we analyzed sample I with the same $\tau_{ie}(T)$, took $\tau_{so} = 1.6$ ps from analysis IAb, and fitted the two remaining constants, i.e., $F_\sigma(0)$ and T_l. The result was $F_\sigma(0) = 1.60$ and $T_l = 275$ K. The calculated $\Delta\sigma(T)$ is also shown in Fig. 7. Below 150 K it is indistinguishable from the previous analysis for this sample, and it is seen to continue to describe data excellently up to 280 K. $F_\sigma(0)$ is satisfactorily close to 1.73 from the corresponding analysis of $\Delta\sigma(B)$, but the large T_l indicates that the temperature dependence of $\tau_{ie}(T)$ from $\Delta\sigma(B)$ is not sufficient to account for the strong temperature dependence of $\Delta\rho(T)$ at the highest measuring temperatures. Restricting the conclusions of these analyses to temperatures up to 150–200 K, there is a quantitative agreement for both samples between results from $\Delta\sigma(T)$ and $\Delta\sigma(B,T)$. For sample II, τ_{so}, $F_\sigma(0)$ and T_l were taken from $\Delta\sigma(B,T)$, and $\tau_{ie}(T)$ obtained from $\Delta\sigma(T)$ was found to satisfactorily reproduce the corresponding result from $\Delta\sigma(B,T)$. For sample I, taking $\tau_{ie}(T)$ and τ_{so} from $\Delta\sigma(B,T)$ results in a good description of $\Delta\sigma(T)$, with a value of $F_\sigma(0)$ in acceptable agreement with that from $\Delta\sigma(B,T)$, albeit with a larger T_l. Below about 150 K these differences in different temperature dependences of F_σ are small, however, and both fitted constants in $\Delta\sigma(T)$ are in fair agreement with those obtained from $\Delta\sigma(B,T)$.

Attempting to extend this analysis to room temperature does not give unique parameters. Although a description of $\Delta\sigma(T)$ in terms of QIE appears to be possible with reasonable results for the parameters, the lack of agreement with results from the magnetoresistance does not allow for a definite conclusion.

VI. DISCUSSION, PROBLEMS, CONCLUSIONS

A. Discussion of main results

The results of our extended measurements of the magnetoresistance of icosahedral AlCuFe clearly show that quantum corrections account for the magnetoresistance from temperatures well below 1 K up to at least 280 K. The precision which can be obtained in this description is illustrated in Fig. 3, and covers a range exceeding 3 orders of magnitude in temperature and 5 orders of magnitude in $|\Delta\rho/\rho|$. This result is a striking illustration of the precision of 3D quantum correction theories, in strong contrast, e.g., to previous work in 3D amorphous metals. At the same time our result is disappointing in the sense that this large range of variation of $\Delta\rho(B,T)/\rho$ is nevertheless insufficient to determine a unique consistent set of parameters of QIE theories from experiments.

On the other hand, lack of knowledge of the background $\rho(T)$ has forced us to the rather extreme assumptions A and B. Identifying results and trends common to both these assumptions therefore provides additional support for the conclusions and more reliable estimates of the range of variation of parameters consistent with a description from QIE. We discuss such common features: (i)–(vi).

(i) A clear trend of a saturating τ_{ie} at temperatures below 1 K is obtained in all analysis of sample I. Imposing for sample II the physically reasonable condition that $\tau_{\mathrm{ie}}(T)$ must decrease or stay constant with increasing temperatures, gives an acceptable analysis and a constant τ_{ie} up to 1.5 K. Previous values for the saturated τ_{ie}, obtained from a more limited temperature range,[4] are comprised within the present results.

(ii) At 280 K, τ_{ie} is of order 10^{-13} s $\pm 25\%$ for sample I and $1-2\times10^{-13}$ s for sample II. Since quantum corrections can clearly be identified at this temperature, it would seem that the condition $\tau_{\mathrm{ie}}\gg\tau$ requires values of τ smaller than several fs. This estimate is consistent with the result of Burkov *et al.*[21] of $\tau\approx5\times10^{-16}$ s for an i-AlCuFe sample with the same composition as our sample I. Scattering is thus quite strong in these quasicrystals, and it is appropriate to characterize them as atomically well-ordered materials with strong electronic disorder.

(iii) The temperature dependence of τ_{ie} at intermediate temperatures is remarkably similar in all samples and analyses, and a description with an average temperature exponent T^{-p} with p of about 1.33 and 1.5 for samples I and II describes data well in a temperature region from a few K up to 280 and 150 K, respectively. Similar results have been obtained in a number of quite different analyses in part of this temperature region[1–5] and thus appear to be particularly well established.

(iv) In both analyses a for sample I it was found that F_σ is roughly constant at low temperatures, starts to decrease above about 10 K in an approximately linear way, and reaches very low values at high temperatures. On this basis, model b was investigated, confirming in all four analyses that F_σ indeed goes to zero at some high temperature and stays zero above this temperature. The temperature T_l where this occurs is analysis dependent. Our results indicate that T_l is in the range 80–150 K for sample I and 120–150 K for sample II. However, the difference between these results and the smaller values of T_l obtained from our preliminary analysis,[10] shows that estimates of T_l are uncertain. Nevertheless, our extended measurements provide a possibility to study the temperature dependence of F_σ, and give qualitative results for how and when it vanishes.

(v) Some further common trends can also be pointed out supporting the consistency of all analyses. The results for $F_\sigma(0)$ in Fig. 4 are larger for the high-resistivity sample (I) than for the low-resistivity one. From Fig. 2 it can be seen that the sign change of $\Delta\rho/\rho$ at 12 T occurs at a higher temperature for sample I than for sample II consistent with such a stronger EEI interaction in the high-resistivity sample. This trend is in agreement with previous observations in i-AlCuFe from more limited temperature ranges of investigations,[1,4] and is expected in a range where QIE increases with increasing resistivity. At larger ρ values, e.g., in i-AlPdRe, the opposite trend takes over.[22]

τ_{so} is usually a parameter with largely scattered results in fits to QIE theories. In Table II this variation is within a factor of 3 for each sample, which for this parameter is a rather limited variation. All estimates are seen to give a larger value of τ_{so} for sample I than for sample II. This result and the one quoted above for F_σ are consistent with the predicted decrease of EEI in the presence of a strong spin-orbit interaction[23] and the observation of such a relation, e.g., in noble-metal-doped amorphous CaAl.[24]

(vi) Finally, the analyses of the resistivity suggest that QIE dominate in the temperature dependence of $\rho(T)$ up to temperatures of 150 K or above, considerably higher values than usually considered. Support from the analyses of $\Delta\rho(B)$, particularly up to about 150 K, strengthens this conclusion. However, a unique set of parameters describing $\Delta\rho(T)$ as well as $\Delta\rho(B)$ up to room temperature has not been found.

B. Problems and outlook

Some additional considerations are pointed out which appear to merit further investigations. $\tau_{\mathrm{ie}}\gg\tau$, is a necessary condition to apply the conventional WL theory of Ref. 14, (FH), and is expected to break down with increasing temperature. Since consistent fits could be obtained from 80 mK to the highest measuring temperatures, for a range of different assumptions and samples, this condition would not seem to be violated in our case.

However, a better estimate of τ should result if the condition $\tau_{\mathrm{ie}}\gg\tau$ were relaxed, and the sums of Ref. 14 integrated exactly. This has been made by Matsuo and coworkers (MNSMI),[2] who obtained an expression for $\Delta\sigma$ as the sum of 18 terms with τ as an additional free parameter. We employed this expression, and calculated $\Delta\sigma$ as a function of τ for sample I at 12 T and 280 K, with parameters from fit IAa. Corresponding to the estimated error of 25% in $\Delta\rho/\rho$ at that point, we then required that the deviations between values of $\Delta\rho/\rho$ calculated with MNSMI and FH should be smaller than 25%. This condition gave $\tau\lesssim0.4$ fs. Although this result is in fair agreement with $\tau\approx0.5$ fs,[21] we nevertheless want to exercise considerable caution in the interpretation. The reason is that our calculated values of

$-\Delta\rho/\rho$ with MNSMI are larger than those obtained with FH, while instead one would expect the opposite: when τ_{ie} approaches τ, QIE should break down and vanish. We have not been able to resolve this paradox, neither from Ref. 2 nor from our own attempts to perform exact integrations of the expressions of Ref. 14. Clearly further work is needed to determine how QIE are destroyed when $\tau_{ie}(T)$ approaches τ.

Another point where the analyses may have been oversimplified is the following: Roughly, WL affects the diffusion constant and EEI affects the density of states. However, the EEI contribution depends on D, Eq. (2). Therefore one can argue that an EEI contribution at temperature T should be calculated on the background at T including the WL contribution, and that our method A should take $D(T)$ as an input in the calculation of the EEI contribution. However, such a correction is likely small since methods A and B gave similar main results.

A third point is the remarkable transport properties of icosahedral AlCuFe also at more elevated temperatures than presently studied. An accelerated increase of the conductivity with increasing temperature up to 1000 K has been observed.[25] This property is expected to be unrelated to quantum interference effects. However, the nature of this new conductivity mechanism is not known, nor the temperature range where it sets in. We have observed that $\Delta\sigma(B)$ can be qualitatively described by QIE up to (at least) 280 K, while a similar precision for $\Delta\rho(T)$ is lost for both samples above about 150 K. In particular, for sample I it was found that the temperature dependence of $\Delta\sigma(T)$ above 150 K was stronger than could be accounted for by $\tau_{ie}(T)$ from $\Delta\sigma(B,T)$. It is tempting to ascribe this difference to the onset of such alternative conductivity mechanisms. This is speculative at present however.

C. Brief conclusion

It has been found that measurements of the magnetoresistance of i-AlCuFe to ambient temperatures can give information on quantum corrections in quasicrystals. Several different analyses were used, compensating for lacking knowledge of input parameters in the analyses. Within some variations of the relevant parameters, reasonable, and in most cases excellent descriptions of $\Delta\sigma(B,T)$ could be obtained from below 0.1 to 280 K. These results give compelling evidence that QIE account for the magnetoresistance of i-AlCuFe up to 280 K, strongly suggest that $\Delta\rho(T)$ is dominated by QIE at least up to 150–200 K, and also give some interesting detailed results such as a new and slightly lower upper bound for the inelastic scattering time in i-AlCuFe, and a qualitative study of the temperature dependence of F_σ.

However, measurements of $\Delta\sigma(B,T)$ do not suffice to determine microscopic parameters in a unique way in spite of the large range of variation of $|\Delta\sigma(B)|$ and the sign change of $\Delta\sigma(B)$, both of which contribute significantly to numerical stability. The special properties of quasicrystals, including the strong temperature dependence of $\rho(T)$ aggravate this problem. Some directions for attacking this problem have been briefly outlined.

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