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Magnetoconductivity of AlPdRe quasicrystalline films

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Abstract. Magnetoconductivity (MC) and zero field conductivity have been measured at low temperatures in metallic and barely insulating AlPdRe quasicrystalline films. For a *metallic* film, both the magnetoconductivity and conductivity can be fitted well using the 3D weak localization (WL) and electron–electron interaction (EEI) theories. The AlPdRe films exhibit very strong spin–orbit scattering with $\tau_{so} \approx 1.5 \times 10^{-13}$ s. Therefore, the inelastic scattering times can be directly extracted from the low field magnetoconductivity data taken at various temperatures, yielding $\tau_{in}(T) \approx 1.6 \times 10^{-11}$ T^{-1} s^{-1}. Using the fitting parameters extracted from the MC data, the zero field conductivity as a function of temperature can be described nicely using the WL and EEI theories. MC data and conductivity data obtained on barely *insulating* films below the metal–insulator transition *cannot* be explained in the framework of the WL theory.

1. Introduction

Magnetoconductivity (MC) measurements, $\Delta\sigma(B) = \sigma(B) - \sigma(0)$, have been reported on several quasicrystalline systems, mainly on 3D samples. The quasicrystalline icosahedral i-AlPdRe system is of special interest as it shows the largest transport anomalies amongst quasicrystals, and some samples may even be insulating. For example, the Swedish group studied the MC of AlPdRe melt-spinning ribbons [1], the University of Tokyo group measured MC on bulk AlPdRe bulk samples [2], the University of Virginia group reported MC data on bulk AlPdRe and bulk AlCuCo samples [3, 4] and the Taiwan group of Lin summarized MC data on bar-shaped samples cut from ingots [5]. In some of the above publications, the electron–electron interaction (EEI) contribution has been neglected or the weak localization (WL) theory has been applied to MC data taken on *insulating* films. In these cases, we believe that the analyses are either incomplete or incorrect. As will be illustrated below, the weak localization and electron–electron interaction theories gave satisfactory fits to the experimental data only on the *metallic* side of the metal–insulator transition (MIT). Values for the inelastic scattering times and the spin–orbit scattering time were extracted from the fits. We were unable to fit the WL theory to MC data taken on a *barely insulating* film located just below the MIT.

2. Theoretical background

Electron–electron interactions (EEI) produce a dip in the density of states close to E_F. This dip results in a small correction to the zero field conductivity that reduces the conductivity

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with decreasing temperatures. According to the 3D prediction of Altshuler and Aronov [6], the particle–hole contribution arising from EEI to the zero field conductivity is:

$$\sigma_{EEI}(T) = \frac{1.294}{\sqrt{2}}\frac{e^2}{4\pi^2\overline{h}}\left(\frac{4}{3} - \frac{3}{2}\tilde{F}_\sigma\right)\left(\frac{k_B T}{\overline{h} D_{dif}}\right)^{1/2} \tag{1}$$

where the electron screening parameter $\tilde{F}_\sigma$ ranges between 0.2 and 0.4 for many thin metallic films.

Lee and Ramakrishnan have calculated the 3D magnetoconductivity (MC) contribution arising from EEI in the particle–hole channel [7]:

$$\Delta\sigma_{EEI}(B, T) = \frac{-e^2}{4\pi^2\overline{h}}\tilde{F}_\sigma\left(\frac{k_B T}{2\overline{h} D_{dif}}\right)^{1/2} g_3\left(\frac{g_e\mu_B B}{k_B T}\right) \tag{2}$$

where g_e is the Landé factor. Ousset *et al* have suggested suitable approximations for the function $g_3(x)$ [8]:

$$g_3(x) \approx 5.6464 \times 10^{-2}x^2 - 1.4759 \times 10^{-3}x^4 + 4.2747 \times 10^{-5}x^6 - 1.5351 \times 10^{-6}x^8 + 6 \times 10^{-8}x^{10} \qquad x \leqslant 3 \tag{3a}$$

$$g_3(x) \approx 0.645\,48 + 0.235(x-4) - 7.45 \times 10^{-4}(x-4)^2 - 2.94 \times 10^{-3}(x-4)^3 + 6.32 \times 10^{-4}(x-4)^4 - 5.22 \times 10^{-5}(x-4)^5 \qquad 3 \leqslant x \leqslant 8 \tag{3b}$$

and

$$g_3(x) \approx x^{1/2} - 1.2942 - \frac{\pi^2}{12x^{3/2}} - \frac{\pi^4}{16x^{7/2}} - \frac{5\pi^6}{32x^{11/2}} \qquad x \leqslant 8. \tag{3c}$$

The limiting forms of g_3 for large and small x are:

$$g_3(x \to \infty) \approx \sqrt{x} - 1.29$$

and

$$g_3(x \to 0) \approx 0.0565x^2. \tag{4}$$

Note that the high field behaviour of $\Delta\sigma_{EEI}$ has a $B^{1/2}$ dependence. It is useful to note that $g_e\mu_B/k_B \approx 4/3$ in units of kelvin/tesla if $g_e = 2$.

Owing to the lack of any other better formalism, we use the 3D weak localization (WL) theory close to the MIT for the *barely metallic* film No C5; the WL theory generally applies to very metallic films. Kawabata first derived the 3D WL correction to the *zero field* conductivity for the case of no spin–orbit scattering [9]. Fukuyama and Hoshino extended the Kawabata zero field results to include the spin–orbit scattering τ_{so} and obtained a zero field correction to the conductivity [10]. Hickey *et al* have suggested the following zero field expression that includes magnetic spin scattering [11]:

$$\sigma_{WL}(T) = \frac{e^2}{2\pi^2\overline{h}}\frac{1}{\sqrt{D_{dif}}}\left[3\left(\frac{1}{4\tau_{in}(T)} + \frac{1}{3\tau_{so}} + \frac{1}{\tau_s}\right)^{1/2} - \left(\frac{1}{4\tau_{in}(T)} + \frac{1}{4\tau_s}\right)^{1/2}\right] \tag{5}$$

where τ_{so} is the temperature independent spin–orbit scattering time, τ_s is the temperature independent magnetic spin scattering time and $\tau_{in}(T)$ is the temperature dependent inelastic scattering time. The characteristic fields are related to the scattering times through the expression $B_x = \overline{h}/(4eD_{dif}\tau_x)$. It should be noted that a number of different conventions are used in the definition of τ_{so}. The one followed here in equation (5) is that adopted by Bergmann [12] and by Baxter *et al* [13]. When comparing results of other authors, it might be necessary to redefine τ_{so} as $\tau_{so}/3$. A magnitude for the spin–orbit scattering time [14, 15] can be estimated from the expression $\tau_{so} \approx \tau_o(l37/Z)^4$ where Z is the atomic number ($Z = 75$

for Re and $Z = 46$ for Pd) and where $\tau_o \approx 10^{-15}$ s is the elastic scattering time. For the case of weak spin–orbit scattering when τ_{so} is large, equation (5) predicts that $\sigma_{WL} \propto (\tau_{in})^{-1/2}$; this is the case of weak localization that causes a *decrease* of the conductivity with decreasing temperatures. For our case of strong spin–orbit scattering and a small magnitude for τ_{so}, equation (5) predicts weak *anti*-localization where $\sigma_{WL} \propto (-1/2)(\tau_{in})^{-1/2}$; in this case, the WL contribution produces an *increase* in the conductivity with decreasing temperatures, in opposition to the EEI contribution [12]. However, the EEI contribution seems always to dominate, resulting in an overall major decrease of the zero field conductivity with decreasing temperatures.

For the 3D weak localization magnetoconductivity (MC) theory, Baxter *et al* extended the results of Fukuyama and Hoshino to include weak magnetic scattering for the case that $\tau_s^{-1} \ll \tau_{so}^{-1}$; the Zeeman splitting correction at high fields has also been included [13]:

$$\Delta\sigma_{WL}(B,T) = \frac{e^2}{2\pi^2\hbar}\sqrt{\frac{eB}{\hbar}}\left\{ f_3\left(\frac{B}{B_2}\right) + \frac{1}{2\sqrt{1-\gamma}}\left[f_3\left(\frac{B}{B_+}\right) - f_3\left(\frac{B}{B_-}\right)\right] + \sqrt{\frac{4B_{so}}{3B}}\left[\frac{1}{\sqrt{1-\gamma}}(\sqrt{t_+} - \sqrt{t_-}) + \sqrt{t} - \sqrt{t+1}\right]\right\} \tag{6}$$

where

$$\begin{aligned} B_\phi &= B_1 + 2B_s \\ B_2 &= B_i + 2B_s/3 + 4B_{so}/3 \\ B_\pm &= B_\phi + 2B_s + \tfrac{2}{3}(B_{so} - B_s)(1 \pm \sqrt{1-\gamma}) \\ \gamma &= \left[\frac{3g_e\mu_B B}{83D_{dif}(B_{so} - B_s)}\right]^2 \\ t &= \frac{3B_\phi}{4(B_{so} - B_s)} \\ t_\pm &= t + \tfrac{1}{2}(1 \pm \sqrt{1-\gamma}). \end{aligned} \tag{7}$$

For the case of weak magnetic fields where the Zeeman splitting correction can be neglected, the weak localization MC expression, equation (6), can be considerably simplified:

$$\Delta\sigma_{WL}(B,T) = \frac{e^2}{2\pi^2\hbar}\sqrt{\frac{eB}{\hbar}}\left[\frac{3}{2} f_3\left(\frac{B}{B_{in}(T) + \frac{4}{3}B_{so} + \frac{2}{3}B_s}\right) - \frac{1}{2} f_3\left(\frac{B}{B_{in}(T) + 2B_s}\right)\right]. \tag{8}$$

Baxter *et al* gave a numerically convenient approximation for the function $f_3(x)$, which is accurate over the entire range of x, and retains the correct asymptotic limits [13]:

$$f_3(x) \approx 2\sqrt{2 + 1/x} - 2\sqrt{1/x} - \frac{1}{\sqrt{1/2 + 1/x}} - \frac{1}{\sqrt{3/2 + 1/x}} + \frac{(2.03 + 1/x)^{-3/2}}{48}$$

$$f_3(x \to 0) \to \frac{x^{3/2}}{48}$$

and

$$f_3(x \to \infty) \to 0.6049. \tag{9}$$

Note that at high fields $\Delta\sigma_{WL}$ exhibits the $B^{1/2}$ dependence, since $f_3(x)$ saturates at 0.605. The WL expressions of equations (6) and/or (8) give the major negative contribution to the MC data. However, the EEI expression of equation (2) makes a smaller, but also significant negative contribution and hence cannot be neglected.

For the case of strong spin–orbit scattering at *small fields*, the above equations simplify to the important expression:

$$\Delta\sigma_{WL}\,(\Omega\,\mathrm{cm})^{-1} = -[e^2/(4\pi^2\overline{h}100)][e/\overline{h}]^{1/2}[B^2/48][1/B_{in}^{3/2}]. \tag{10}$$

If units of cm are used rather than m, then the factor of 100 must be accounted for in the conversion of conductivity and MC from $(\Omega\ \mathrm{m})^{-1}$ to $(\Omega\ \mathrm{cm})^{-1}$. If the *negative* MC data exhibit the parabolic dependence at small fields, then a value for the inelastic magnetic field can be estimated from equation (10). Hence, the magnitude of the inelastic scattering time can be determined at this measurement temperature using $\tau_{in}(T) = \overline{h}/[4\pi e D_{dif} B_{in}(T)]$.

3. Experimental details

Thin amorphous 2200 Å films of nominal $Al_{72}Pd_{20}Re_8$ compositions were prepared by co-sputtering with two magnetron sources onto quartz substrates. One target source contained a mixture of Al and Pd and the second source contained the Re element. Due to the positions of the two sources with respect to the substrate, a defined composition gradient could be achieved along the substrate. Thus, a set of about 20 amorphous samples was produced with a composition slightly and systematically changing from one sample to the next and cutting the ternary phase diagram close to the optimum composition for obtaining the quasicrystal structure. The amorphous films were heated in a vacuum for about 20 hours to a temperature of 870 K where the transition to the icosahedral structure took place for samples of a narrow range of composition around $Al_{71.5}Pd_{20.0}Re_{7.5}$. The low temperature conductivity and the resistivity ratio $R(4.2\,\mathrm{K})/R(300\,\mathrm{K})$ varied systematically with composition. Recent theoretical calculations by Krajci and Hafner predict a real gap in the density of states for icosaheral AlPdRe [16]. There is the possibility that even a minimal structural rearrangement of the icosahedral phase can place the Fermi energy into the gap, thus creating an insulating phase [16]. Here we focus on two quasicrystalline films which show metallic or barely insulating behaviours. Contacts were made to the films using silver paint. Additional details on film preparation and characterization by electron diffraction can be found in [17].

Measurements below 1 K were made with the films placed *inside* the mixing chamber of a dilution refrigerator. Thermometry was based upon an extrapolated CMN thermometry scale. The CMN salt pill thermometer was calibrated against the vapour pressure of ^{3}He and ^{4}He and a calibrated Ge thermometer from Scientific Instruments. Care was taken to prevent Joule heating of the films inside the mixing chamber. Above 1.4 K, measurements were made with the samples located in a standard liquid helium probe inserted in a 17 T superconducting magnet system from Cryogenic Limited. Some temperature drifts were present above 4.2 K, accounting for some of the 'gaps' in the MC data that appear in the following graphs.

4. Low temperature conductivity data and the metal–insulator transition

Films may be classified electronically as being either insulating or metallic. Insulating 3D films exhibit infinite resistivity or zero conductivity at absolute zero in temperature. In contrast, metallic 3D films always display a positive conductivity at absolute zero.

Strongly insulating films exhibit an activated hopping conductivity which can be described by the variable-range hopping (VRH) expression:

$$\sigma(T) = \sigma_0[\exp -(T_0/T)^y] \tag{11}$$

where σ_0 is the prefactor, T_0 is a characteristic temperature and y is an exponent.

In contrast, the conductivity of a *3D metallic* film at sufficiently low temperatures can be described by the power law expression:

$$\sigma(T) = \sigma(0) + CT^z \tag{12}$$

where $\sigma(0)$ is the positive zero temperature conductivity, C is the prefactor and z is the exponent of the temperature power law. Equation (12) might approximate the conductivity contribution from the 3D electron–electron interaction theory and/or from the 3D weak localization theory and a theory based upon the existence of critical states which decay following a power law [18]. Note that in the above procedures, the exponents y and z are free fitting parameters.

A useful technique to identify the metal–insulator transition was previously introduced [19, 20]. The mathematical function $w(T)$ exhibits distinctively different temperature behaviours for insulating and metallic films:

$$w(T) = \mathrm{d}\ln\sigma/\mathrm{d}\ln T = (T/\sigma)\,\mathrm{d}\sigma/\mathrm{d}T. \tag{13}$$

In practice, the w are calculated from two conductivity points $\sigma_1(T_1)$ and $\sigma_2(T_2)$ at closely separated temperatures T_1 and T_2 using one of the following expressions:

$$w \approx (\ln\sigma_1 - \ln\sigma_2)/(\ln T_1 - \ln T_2) \tag{14}$$

or from the approximation:

$$w \approx T_{ave}(\ln\sigma_1 - \ln\sigma_2)/(T_1 - T_2) \tag{15}$$

where $T_{ave} = (T_1 + T_2)/2$.

For *strongly insulating* films exhibiting variable-range hopping conductivity, inserting equation (1) into equation (3) yields:

$$w(T) = y(T_0/T)^y \tag{16}$$

notice that $w(T)$ *increases* to infinity as the temperature approaches absolute zero.

For 3D *metallic* films exhibiting slowly decreasing conductivities with decreasing temperatures at low temperatures, equation (2) can be substituted into equation (3) to yield:

$$w(T) = zCT^z/[\sigma(0) + CT^z] = zCT^z/\sigma(T). \tag{17}$$

Observe that if the film is indeed *metallic* and exhibits a finite positive conductivity $\sigma(0)$ at absolute zero, then $w(T)$ should *extrapolate to zero* at absolute zero.

For the special *insulating* case of the conductivity following a simple power law, $\sigma(T) = CT^z$ with $\sigma(0) = 0$, equation (7) predicts that the w are independent of temperature and equal to the constant value of $w = z$.

An example of metallic behaviour is shown in figure 1 where the quasicrystal AlPdRe film No C5 exhibits w which tend to zero as $T \to 0$ K. This film has an $R(4.2\text{ K})/R(300\text{ K})$ ratio of 2.4. For this *metallic* case, a least-squares regression fit of the $\log(w\sigma)$ versus $\log T$ data yields values for the exponent z and the prefactor C, according to equations (12) and (17). A value for $\sigma(0)$ follows directly from one of the data points. The empirical fit to the zero field low temperature conductivity data of film No C5 below 1.6 K is shown in figure 2 where the solid line is given by $\sigma(T) = 73.01 + 1.24T^{0.71}$ in $(\Omega\text{ cm})^{-1}$. The exponent z of 0.71 of the second term agrees poorly with the EEI theory prediction of an exponential value of 0.50.

In contrast, the w behaviour exhibited by the quasicrystal AlPdRe film No A4 in figure 3 suggests that the w extrapolates to a *finite small value* at $T = 0$ K. Certainly the w *do not* extrapolate to zero. Hence, film No A4 appears to be insulating down to 0.1 K. This film has an $R(4.2\text{ K})/R(300\text{ K})$ ratio of 4.2.

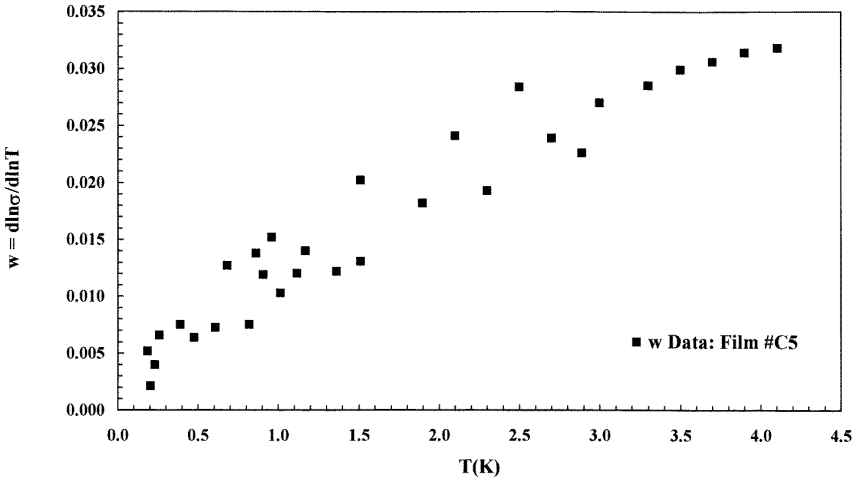

Figure 1. The $w = \mathrm{d}\ln\sigma/\mathrm{d}\ln T$ dependence upon temperature for the quasicrystal AlPdRe film No C5; the tendency for the w to extrapolate to zero as $T \to 0$ K suggests that this film is metallic.

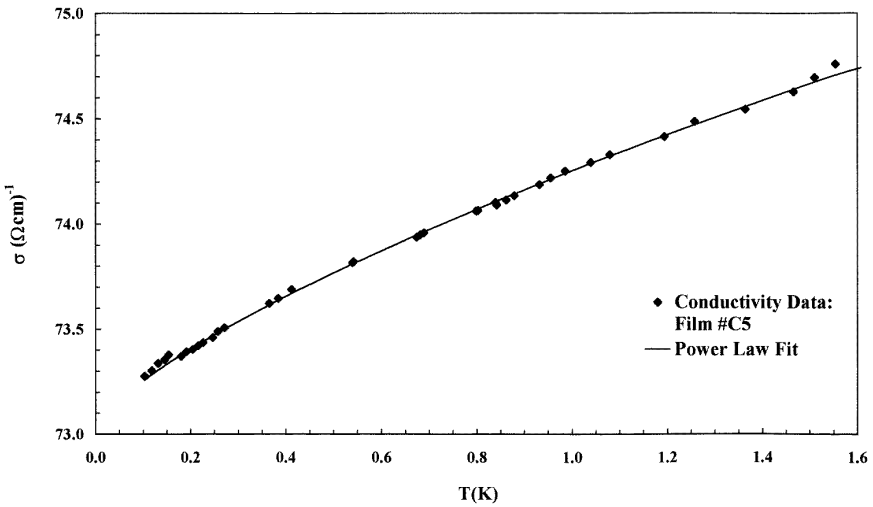

Figure 2. The zero magnetic field conductivity data of film No C5 compared to an empirical power law fit $\sigma(T) = 73.01 + 1.24T^{0.71}$ in $(\Omega\ \mathrm{cm})^{-1}$. Note the tendency for the conductivity to extrapolate to a finite value at $T = 0$ K, suggesting that this film is *metallic*.

5. Fits to the magnetoconductivity data of the metallic quasicrystalline AlPdRe film

The low temperature magnetoconductivity (MC) data yield values for the inelastic scattering time $\tau_{in}(T)$. The MC of film No C5, the quasicrystalline $Al_{71.9}Pd_{20.2}Re_{7.9}$ film located above the MIT, was investigated in detail.

The low temperature MC data, $\Delta\sigma = \sigma(B) - \sigma(0)$, for the metallic film No C5 are shown in figures 4 and 5. Notice that the MC data are negative, suggesting strong spin–orbit scattering. For the 3D theories to be valid, the thermal length $L_T = (D_{dif}\overline{h}/k_BT)^{1/2}$ and the inelastic length $L_{in} = [D_{dif}\tau_{in}(T)]^{1/2}$ should be considerably less than the film thickness of

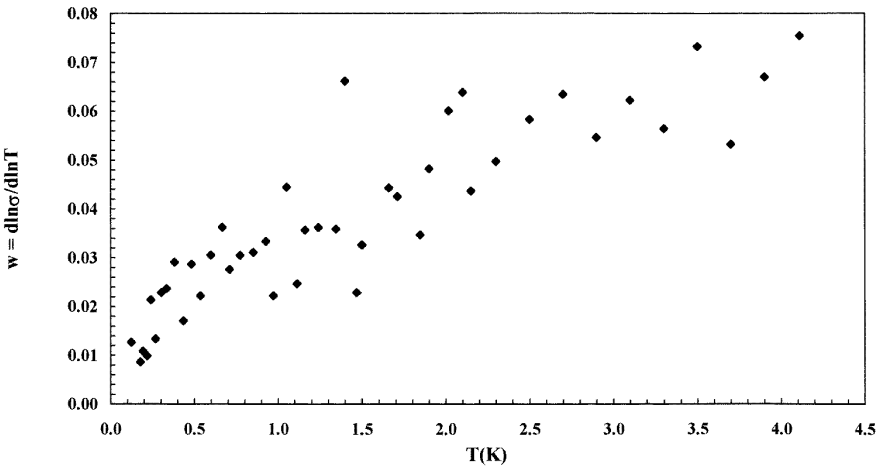

Figure 3. The $w = \mathrm{d}\ln\sigma/\mathrm{d}\ln T$ dependence upon temperature for the quasicrystal AlPdRe film No A4. The tendency for the w to extrapolate to a *finite value* at $T = 0$ K suggests that this film is *insulating*.

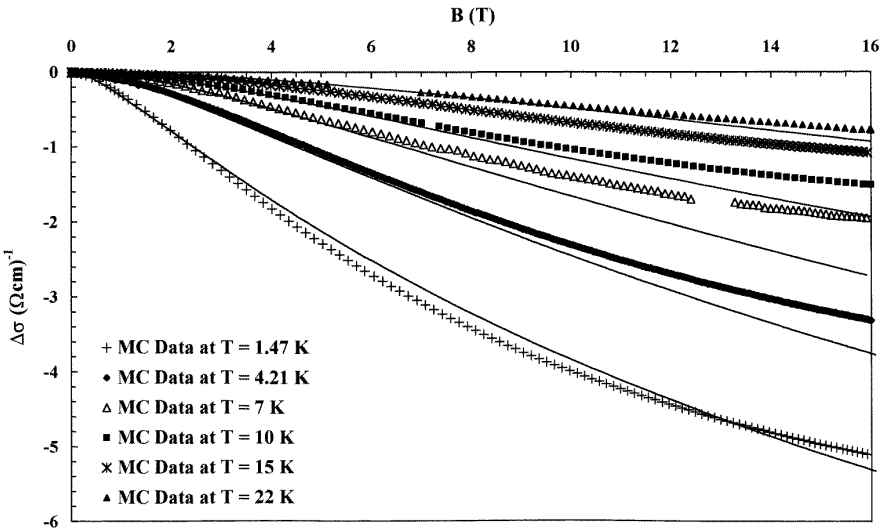

Figure 4. The magnetoconductivity data at various low temperatures for the metallic C5 film. Owing to instability of the temperature, some data have been lost and gaps appear. The solid lines are theoretical fits representing the combined contributions from the weak localization (WL) and electron–electron interaction (EEI) theories.

2200 Å. The condition for three dimensionality is satisfied provided that the diffusion constant D_{dif} is less than 1 cm^2 s^{-1}. Just above the MIT, Entin-Wohlman *et al* [21] predict that $D_{dif} = D_0(x - x_c)^{t-\beta}$ where t is the conductivity exponent equal to 1.9 in 3D [22] and to 1.3 in 2D [23] and β is the finite cluster mass exponent equal to 0.41 [24]. Since $D_0 \approx 50$ cm^2 s^{-1} for a very metallic film, the diffusion constant is estimated to take on values less than 1 cm^2 s^{-1} near the MIT. We chose a value of 0.75 cm^2 s^{-1} for D_{dif}.

The MC data for the metallic film No C5 are shown in figures 4 and 5; the theoretical fits using equations (2) and (6) are compared to the MC data in figures 4–7 at different temperatures.

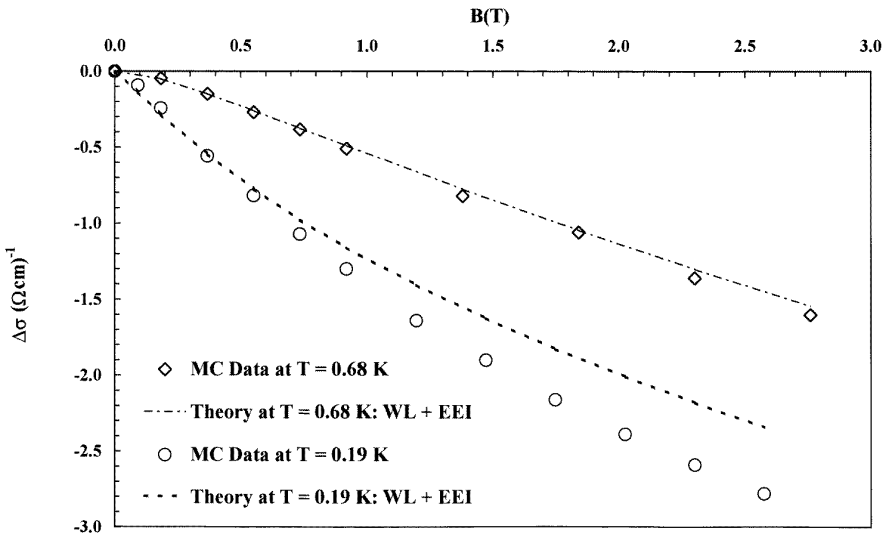

Figure 5. The magnetoconductivity data below 1 K for the metallic C5 film taken in a dilution refrigerator. The data are compared to the weak localization and electron–electron interaction theories for the magnetoconductivity. The only temperature where the theories gave a rather poor fit to the data was at $T = 0.19$ K. A value for the inelastic scattering time was obtained from each fit, where $\tau_{in}(T = 0.19\ \mathrm{K}) = 8.9 \times 10^{-11}$ s and $\tau_{in}(T = 0.68\ \mathrm{K}) = 2.3 \times 10^{-11}$ s.

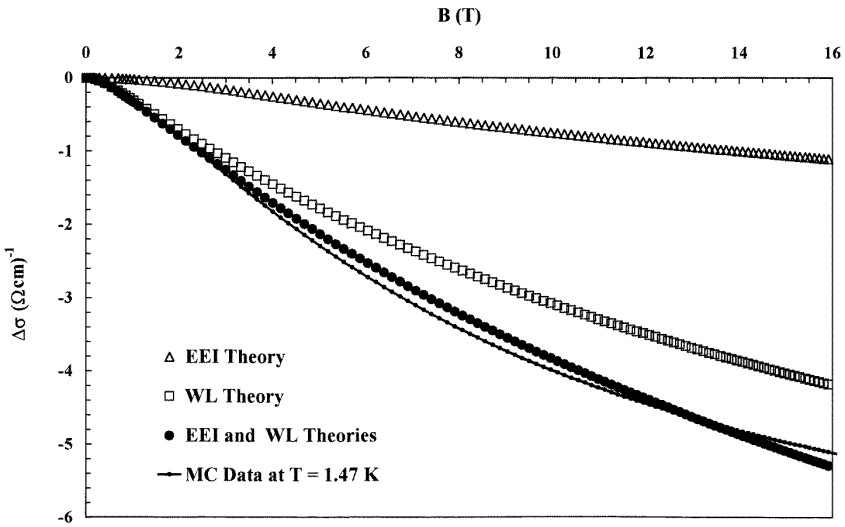

Figure 6. A fit of the weak localization and electron–electron interaction theories to the magnetoconductivity data taken at $T = 1.47$ K. Notice the small contribution from the EEI theory as compared to the contribution from the WL theory. A value for the inelastic scattering time was obtained from this fit where $\tau_{in}(T = 1.47\ \mathrm{K}) = 1.1 \times 10^{-11}$ s.

The MC fits are quantitatively good, particularly in the *low* and *middle* field ranges. In the high field regime, deviations between the fitting curves and data might arise from the field sensitivity of the thermometer and temperature drifts and instabilities that occurred over the two hour measuring periods. The fitting parameters used were $D_{dif} = 0.75\ \mathrm{cm}^2\ \mathrm{s}^{-1}$, $\tilde{F}_\sigma = 0.2$,

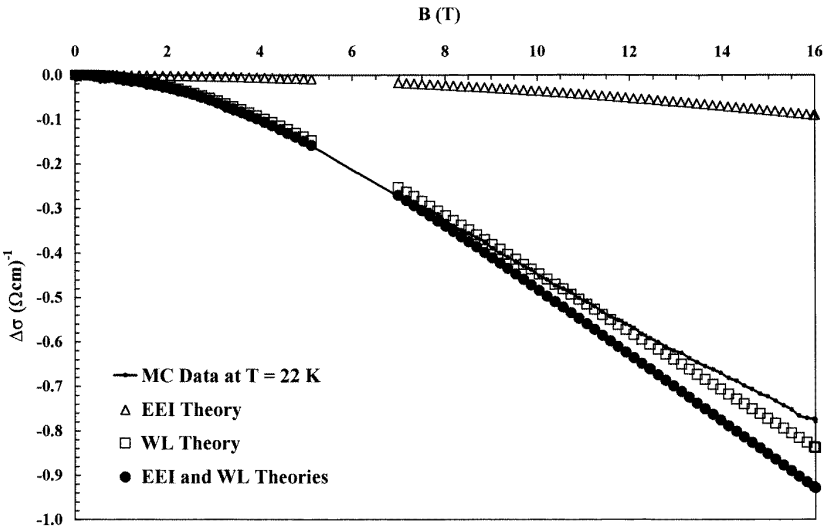

Figure 7. A fit of the weak localization and electron–electron interaction theories to the magnetoconductivity data taken at $T = 22$ K. The contribution from the EEI theory is very small at this high temperature. A value for the inelastic scattering time was obtained from this fit where $\tau_{in}(T = 22\ \mathrm{K}) = 5.2 \times 10^{-13}$ s.

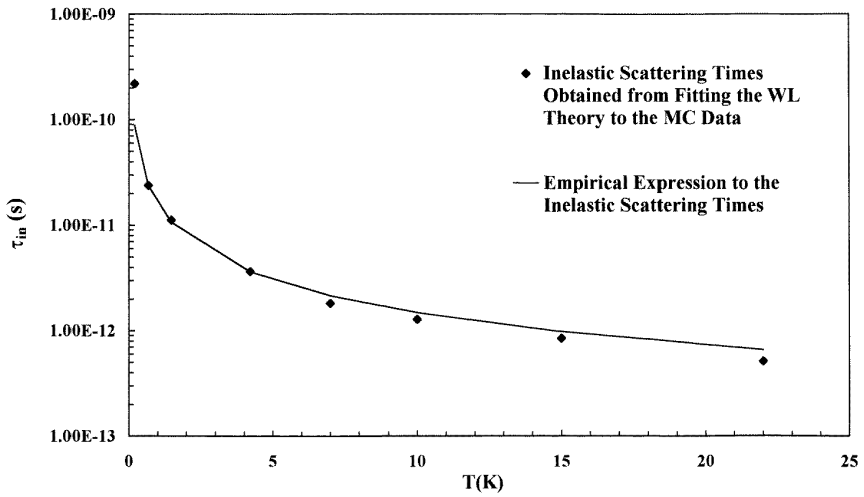

Figure 8. Values for the inelastic scattering time as a function of temperature. The solid line is an empirical fit where $\tau(T) = 1.55 \times 10^{-11}/T^{1.03}$ s.

$g_e = 2$ and $B_s = 0$ T. No magnetic moments have been observed in i-AlPbRe [25, 26]; hence $B_s = 0$ T. The following parameters were determined from the fitting procedure: $B_{so} = 15$ T, $B_{in}(T = 0.19\ \mathrm{K}) = 0.01$ T, $B_{in}(T = 0.68\ \mathrm{K}) = 0.092$ T, $B_{in}(T = 1.47\ \mathrm{K}) = 0.195$ T, $B_{in}(T = 4.21\ \mathrm{K}) = 0.60$ T, $B_{in}(T = 7\ \mathrm{K}) = 1.2$ T, $B_{in}(T = 10\ \mathrm{K}) = 1.7$ T, $B_{in}(T = 15\ \mathrm{K}) = 2.6$ T and $B_{in}(T = 22\ \mathrm{K}) = 4.25$ T. The uncertainties in all the fitting parameters are fair, about $\pm 25\%$. The WL expression, equation (6), contributes 80% to the total negative MC magnitude owing to the strong spin–orbit field value while the EEI

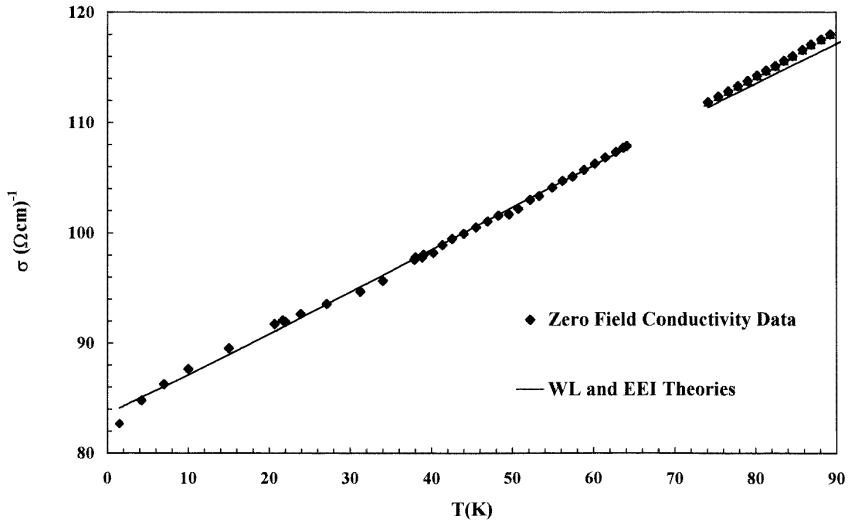

Figure 9. The zero magnetic field conductivity data for the metallic film No C5; the solid line is a fit that includes the contributions from the electron–electron interaction and weak localization theories. These quantum corrections explain the temperature dependence of the observed conductivity very well in the temperature interval between 4 and 65 K.

expression, equation (2) contributes the remaining 20%. Values of $B_{in}(T\ \mathrm{K})$ were then converted to inelastic scattering times $\tau_{in}(T)$ via $\tau_{in}(T) = \overline{h}/[4eD_{dif}B_{in}(T)]$. Both our temperature dependence and magnitudes for the inelastic scattering time and the magnitude for the spin–orbit scattering time ($\tau_{so} = 1.5\times10^{-13}$ s) are consistent with those values observed by the Swedish and Taiwan groups in *bulk metallic* AlPdRe samples [5, 27].

The results for the inelastic scattering time are illustrated in figure 8. Above 0.6 K, the inelastic time follows a simple power law dependence of $\tau_{in}(T) \approx 1.55\times10^{-11}\ T^{-1.03}$ s. This temperature dependence is weaker than a theoretical prediction of Al'tshuler and Aronov [28] that $\tau_{in}(T)^{-1} \propto T^{3/2}$ and a prediction of Schmid [29] that $\tau_{in}(T)^{-1} \propto T^2$ but agrees nicely with a 3D expression suggested by Isawa [30]:

$$\tau_{in}(T) = 4(E_F\tau_0)^2/(3^{1/2}3\overline{h}k_BT). \tag{18}$$

Reasonable magnitudes are obtained if one uses values of $E_F \approx 0.2$ eV and $\tau_0 \approx 10^{-14}$ s, suggested by Rapp. Isawa considered scattering processes leading to the inelastic scattering time to first order of the screened Coulomb interaction [30]. In addition, Belitz and Wysokinski have suggested the following expression for $\tau_{in}(T)$ [31]:

$$\tau_{in}(T) = \overline{h}/(2\gamma k_BT) \tag{19}$$

where γ ranges between 0.098 and 0.561. Their deviation is based upon charge density fluctuations using Wegner scattering near the Anderson transition [31]. Equation (19) predicts the same order of magnitude as equation (18). Interestingly, Lin points out that *many barely metallic* systems exhibit the simple $\tau_{in}(T) \propto 1/T$ dependence [32]; in these systems the diffusion constant D_{dif} always has a value less than 1 cm^2 s^{-1}.

The *zero field* conductivity data of film No C5 can be fitted using the two zero field expressions, equations (1) and (5), and the fitting parameters determined from the MC fits. The $\sigma(T)$ fit is impressively good between 4 and 60 K as shown in figure 9. In this case, the EEI expression contributes 70% to the total conductivity change with temperature,

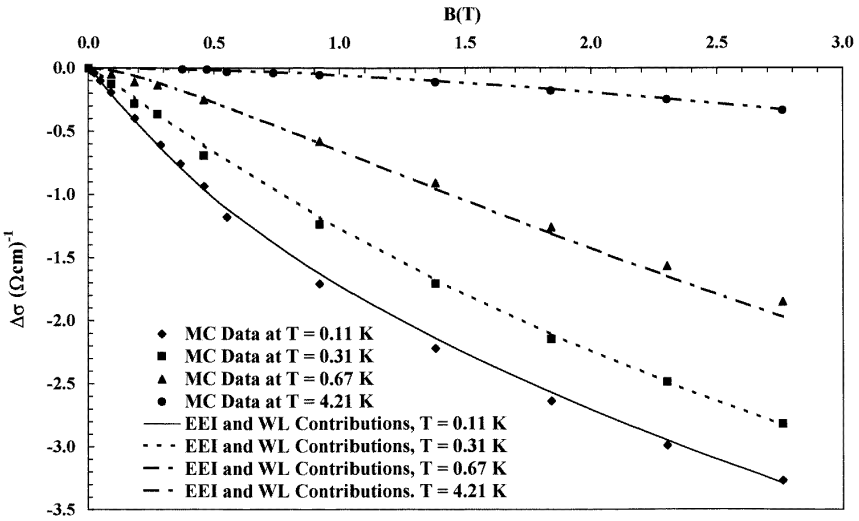

Figure 10. Magnetoconductivity at various low temperatures for the *barely insulating* quasicrystal AlPdRe film No A4. The lines are forced fits using the WL and EEI theories. This film is barely insulating according to figure 3.

while the WL expression makes a smaller 30% contribution. The expression used was $\sigma(T) = 18.68 + \sigma_{WL}(T) + \sigma_{EEI}(T)$ in units of $(\Omega\ \mathrm{cm})^{-1}$. The EEI contribution goes as $\sigma_{EEI} = 2.46T^{1/2}$ $(\Omega\ \mathrm{cm})^{-1}$; recall that below 4 K the combined EEI and WL contributions exhibited a $T^{0.71}$ dependence. Interestingly, the WL expression exhibits anti-localization below 6 K [12]. Above 60 K, a new conductivity process starts to dominate, possibly explained by using a Debye–Waller factor model [33].

A most important point of the zero field conductivity fit is the *positive* sign of the offset term, +18.68 $(\Omega\ \mathrm{cm})^{-1}$; had the sign of this term been *negative*, the entire fitting procedure would not be physical. This small value of the offset term suggests that this film is barely metallic.

Thus, it appears that the unique icosahedral structure of the *metallic* quasicrystal films has little influence upon the quantum corrections to the conductivity and MC at low temperatures, except for the fact that the quasicrystalline structure causes a strong elastic scattering.

6. Magnetoconductivity data of the barely insulating quasicrystalline AlPdRe film

Referring to figure 3, extrapolation of the high temperature w values of film No A4 to $T \rightarrow 0$ K suggests a *finite small* value for w at $T = 0$ K, rather than a *zero* value that is characteristic of metallic films. This behaviour identifies film No A4 as *barely insulating*. This film has an $R(4.2\ \mathrm{K})/R(300\ \mathrm{K})$ ratio of 4.2 and a composition of $Al_{71.95}Pd_{20.2}Re_{7.85}$.

The experimental MC data for the *insulating* film A4 are illustrated in figure 10. The fits using the WL and EEI theories to these MC data are extremely good. We simply used a smaller value for the diffusion constant $D_{dif} = 0.15\ \mathrm{cm}^2\ \mathrm{s}^{-1}$ for this more resistive film. But the WL theory should completely break down below the MIT transition, since the electrons are no longer extended but are localized near the donor sites. Thus, the Bergmann concept of many thousands of elastic scattering processes occurring prior to an inelastic scattering process should break down if the electrons are localized [12]. Yet, these MC fits seem to

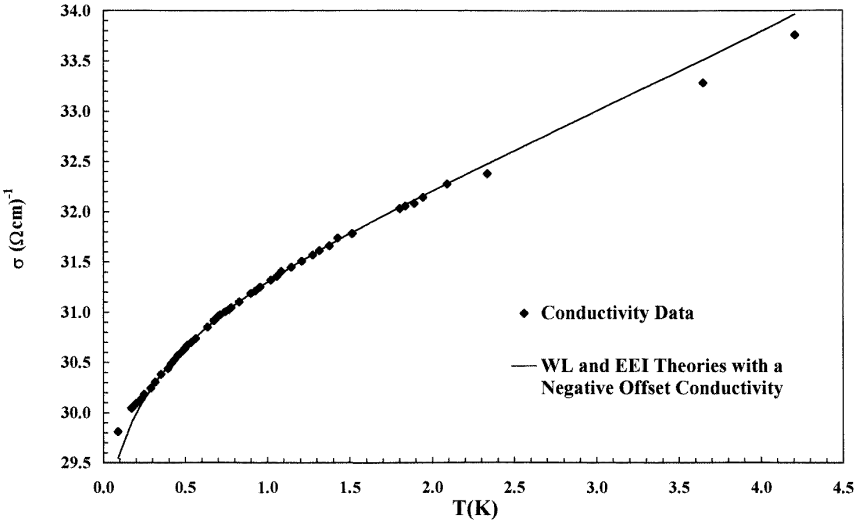

Figure 11. Failure of the weak localization (WL) theory to explain the behaviour of the zero field conductivity data of the *barely insulating* AlPdRe film No A4. The fit is given by the expression $\sigma(T) = -85.7 + \sigma_{WL}(T) + \sigma_{EEI}(T)$ in $(\Omega\ \mathrm{cm})^{-1}$. The negative sign in the conductivity offset term is unphysical and arises owing to the unphysically large magnitudes predicted from the WL contribution. An alternative theory is needed to explain the data of this figure and of figure 10.

contradict this conclusion. The conflict is resolved when we try to fit the WL and EEI theories to the zero field conductivity data as shown in figure 11. Initial inspection indicates beautiful agreement between data and theory, using the scattering times extracted from the MC fits. But the fit in figure 11 is *unphysical* since a *negative* conductivity offset value of $-85.7\ (\Omega\ \mathrm{cm})^{-1}$ had to be used. The problem lies in the magnitudes that the WL theory predicts—values that are three times greater than the actual measured values of about $32\ (\Omega\ \mathrm{cm})^{-1}$. Thus, the WL contribution of equation (5) greatly overestimates the zero field conductivity values; and the WL theory simply breaks down just below the MIT. We are not aware of any alternative theory to explain the MC data just below the MIT. The above illustration marks the importance of fitting both MC and zero field conductivity data only to *metallic* films and checking for consistency in magnitudes and in signs between fits to both the zero field conductivity data and the MC data.

Some of these quasicrystalline AlPdRe films exhibit *strongly insulating* properties, at least down to temperatures of 0.3 K. The magnetoresistance ratio data $R(B)/R(0)$ are summarized in [34] along with numerical calculations that predict the resistance behaviour in moderately strong magnetic fields for this special case of Mott 3D VRH conduction.

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References

[1] Rodmar M, Oberschmidt D, Ahlgren M, Gignoux C, Berger C and Rapp Ö 1999 *LAM 10 Conf. Proc. (Liquid and Amorphous Metals 10) J. Non Cryst. Solids* at press

[2] Tamura R, Sawada H, Kimura K and Ino H 1998 *Proc. 6th Int. Conf. on Quasicrystals* ed S Takeuchi and T Fujiwara (Singapore: World Scientific) p 631

[3] Poon S J, Pierce F S and Guo Q 1995 *Phys. Rev.* B **51** 2777

[4] Guo Q and Poon S J 1996 *Phys. Rev.* B **54** 6046

[5] Wang C R, Su Z Y and Lin S T 1998 *Solid State Commun.* **108** 681

[6] Altshuler B L and Aronov A G 1983 *Solid State Commun.* **46** 429

[7] Lee P A and Ramakrishnan T V 1985 *Rev. Mod. Phys.* **57** 308

[8] Ousset J C, Askenazy S, Rakoto H and Broto J M 1985 *J. Physique* **46** 2145

[9] Kawabata A 1980 *J. Phys. Soc. Japan* **49** 628

[10] Fukuyama H and Hoshino K 1981 *J. Phys. Soc. Japan* **50** 2131

[11] Hickey B J, Greig D and Howson M A 1987 *Phys. Rev.* B **36** 3074

[12] Bergmann G 1984 *Phys. Rep.* **107** 30

[13] Baxter D V, Richter R, Trudeau M L, Cochrane R W and Strom-Olsen J O l989 *J. Physique* **50** 1673

[14] Abrikosov A A and Gor'kov L P 1962 *Zh. Eskp. Teor. Fiz.* **42** 1088 (Engl. transl. 1962 *Sov. Phys.–JETP* **15** 752)

[15] Meservey R and Tedrow P M 1978 *Phys. Rev. Lett.* **41** 805

[16] Krajci M and Hafner J 1999 *Phys. Rev.* B **59** 8347

[17] Haberkern R, Roth C, Knöfler R, Schulze P and Häussler P 1998 *Quasicrystals: Mater. Res. Soc. Symp. Proc.* vol 553, ed J M Dubois *et al* (Pittsburgh, PA: Materials Research Society) p 13

[18] Sire C 1996 *Proc. 5th Int. Conf. on Quasicrystals* ed C Janot and R Mosseri (Singapore: World Scientific) p 415

[19] Möbius A 1989 *Phys. Rev.* B **40** 4194

[20] Rosenbaum R L, Slutzky M, Möbius A and McLachlan D S 1994 *J. Phys.: Condens. Matter* **6** 7977

[21] Entin-Wohlman O, Kapitulnik A, Alexander S and Deutscher G 1984 *Phys. Rev.* B **30** 2617

[22] Derrida B, Stauffer D, Herrmann H J and Vannimenus J 1983 *J. Physique Lett.* **44** L701

[23] Herrmann H J, Derrida B and Vannimenus J 1984 *Phys. Rev.* B **30** 4080

[24] Alexander S 1983 *Phys. Rev.* B **27** 1541

[25] Gavilano J L, Ambrosini B, Vonlanthen P, Chernikov M A and Ott H R 1997 *Phys. Rev. Lett.* **79** 3058

[26] Prejean J-J, Lasjarinias J-C, Berger C and Salpice A 1999 *LEPES-CNRS Preprint Phys. Rev.* B submitted

[27] Ahlgren M, Rodmar M, Gignoux C, Berger C and Rapp Ö 1997 *Mater. Sci. Eng.* A **226–228** 981

[28] Al'tshuler B L and Aronov A G 1979 *JETP Lett.* **30** 482

[29] Schmid A 1974 *Z. Phys.* **271** 251

[30] Isawa Y 1984 *J. Proc. Phys. Soc. Japan* **53** 2865

[31] Belitz D and Wysokinski K I 1987 *Phys. Rev.* B **36** 9333

[32] Wu C Y, Jian W B and Lin J J 1998 *Phys. Rev.* B **57** 11 232

[33] Haberkern R 1998 *Preprint* Technical University of Chemnitz *Quasicrystals—an Introduction to Structure, Physical Properties and Application of Quasicrystalline Alloys* ed J B Suck, M Schreiber and P Häussler (Berlin: Springer) at press

[34] Rosenbaum R, Schoepe W, Haberkern R and Häussler P 1999 *Preprint* Tel Aviv University *J. Phys.: Condens. Matter* submitted