Magnetoresistance due to enhanced electron-electron interactions in amorphous $Ca_{70}(Mg,Al)_{30}$

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We report measurements of the temperature and magnetic field dependence of the resistivity of $Ca_{70}Mg_{15}Al_{15}$ and $Ca_{70}Al_{30}$ amorphous alloys, in temperatures down to 0.18 K and fields up to 6 T. The values of B/T are such that we enter a regime where enhanced electron-electron interactions become at least as important as weak localization. Analysis of the data shows that current theories continue to be applicable in those very weak spin-orbit scattering systems, even when B/T is as high as 23 $\mathrm{T\,K^{-1}}$.

Recent measurements[1,2] on a number of free-electron-like amorphous metals (Ca-Al, Ca-Mg-Al, Ca-Mg, Mg-Cu, and Mg-Zn) have shown the extent to which the quantum correlations to the conductivity (QCC), known as weak localization (WL),[3] and enhanced electron-electron interactions (EEI),[4] quantitatively describe the magnetoresistance in highly disordered three-dimensional conductors. It was found that at low fields ($B/T \leq 0.5$ $\mathrm{T\,K^{-1}}$), where only WL contributes to the effect, the theoretical expressions described the data within error, but that as the field increased (so that EEI became progressively more important) significant differences between theory and experiment were found to occur *except* in the one alloy system (Ca-Mg-Al) where the spin-orbit scattering rate $\tau_{s.o.}^{-1}$ was less than, or of the order of, the electron wave-function dephasing rate τ_ϕ^{-1}. The origin of the discrepancy could not be determined, but one way to test the theories further is to increase the upper limit of B/T (in the above reference only values up to 1.8 $\mathrm{T\,K^{-1}}$ were used) by going to lower temperature and higher field.

In this Brief Report we present magnetoresistance measurements on two amorphous alloys in the $Ca_{70}(Mg,Al)_{30}$ system in a range of B/T where the upper limit has been extended by over an order of magnitude to 23 $\mathrm{T\,K^{-1}}$. The measurements were made down to 0.18 K where the contributions from EEI are approximately of the same order as from WL, so that these measurements apply a much more stringent test of QCC than the earlier work.[1] Furthermore, because τ_ϕ^{-1} saturates at low temperature, the only contribution to the temperature depen-

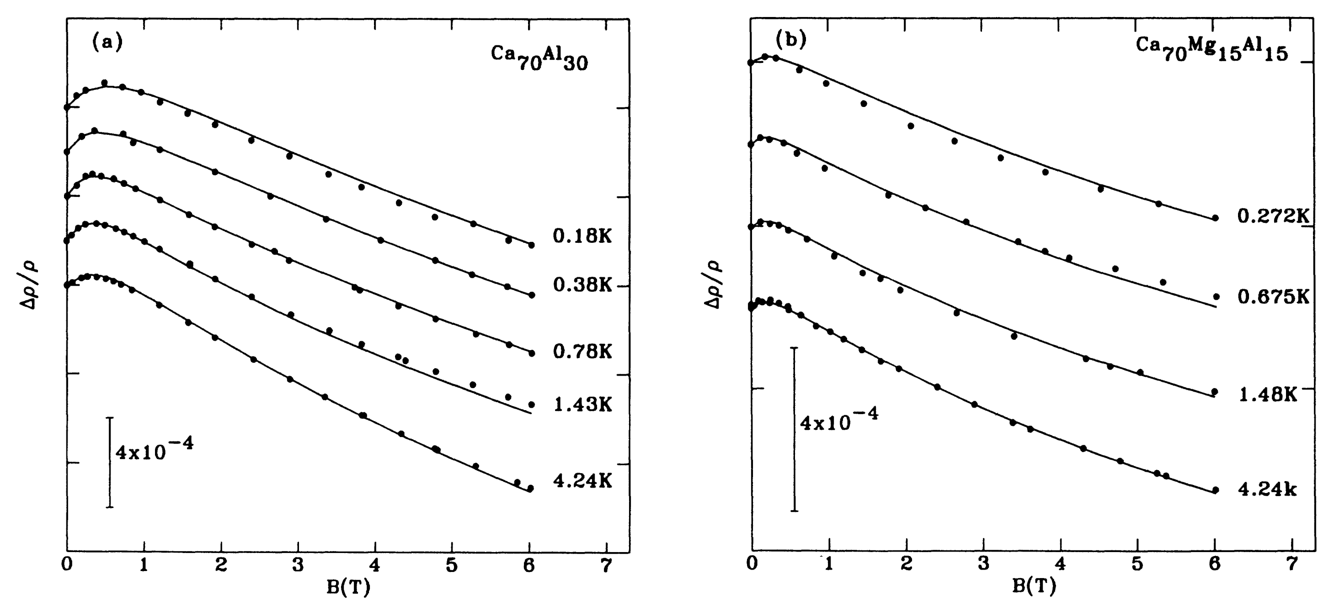

FIG. 1. Total magnetoresistance of (a) $Ca_{70}Al_{30}$ and (b) $Ca_{70}Mg_{15}Al_{15}$. The points are the experimental data and the solid line a fit taking into account both weak localization and electron-electron-interactions contributions. Temperatures are indicated in the figure.

dence of the magnetoresistance comes from EEI.

Samples were made by melt spinning, as outlined in Ref. 1. The resistance changes were measured down to 0.18 K by a conventional dc four-terminal technique in a field up to 6 T. The magnetoresistance is shown in Fig. 1 and, where it overlaps, is identical with previous data.[1] It has the expected characteristics of a very weak spin-orbit scattering system, being very small and positive at low fields then changing sign and increasing in magnitude approximately as $\sqrt{B}$ at high fields.

In fitting the data to the theory we take into account both WL and EEI contributions and extend the fit to the entire field range. There are somewhat different conventions for definitions of the spin-orbit scattering time $\tau_{\mathrm{s.o.}}$ and these differences must be kept in mind when comparing results between different groups. In the present case we wish to compare the results with those in Ref. 1, and therefore use the same expressions as given there. The details of the fitting procedure in evaluating the different magnetoresistance terms are the ones given in Baxter *et al.*[5] The diffusion constant D in the expressions is calculated using Einstein relation $D=1/e^2N(E_F)\rho$, where $N(E_F)$ is the density of states at Fermi level obtained from electronic specific heat data[6] and ρ the measured resistivity. The free parameters are the dephasing field B_ϕ, the spin-orbit characteristic field $B_{\mathrm{s.o.}}$ (which are related to the dephasing time τ_ϕ and the spin-orbit scattering time $\tau_{\mathrm{s.o.}}$, respectively), and the screening factor F, though the procedure is made more restricted since $B_{\mathrm{s.o.}}$ and F must be temperature independent and are the same for each family of curves. Agreement is very good over the full field range; moreover, it is equally good for both samples and at all temperatures, independent of the value B/T which can be as large as 23 T K^{-1} at 0.18 K. In previous work by Ousset *et al.*[7] on amorphous V_xSi_{1-x} alloys (where the spin-orbit scattering rate is larger than 10^{12} s^{-1}), there were discrepancies between the theory and the data which the authors attributed to the inadequacy of the WL expression at high B/T values. In our case, however, we show that in these particular simple Ca-based alloys, WL and EEI are still accurate in the high-field limit, which supports our previous conclusions[1] that the current theories are valid in the extreme weak spin-orbit scattering regime. The values of

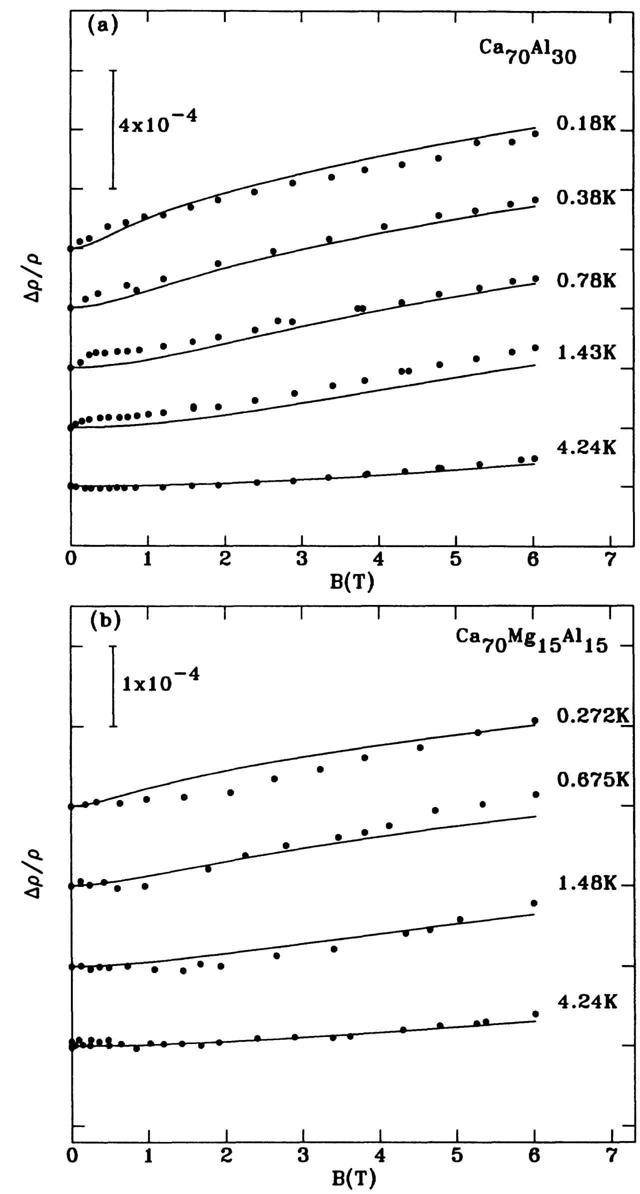

FIG. 2. Magnetoresistance due to electron-electron interactions obtained by subtracting the weak-localization contribution at 4.24 K from the data in Fig. 1. The solid line is the theoretical electron-electron interactions magnetoresistance.

TABLE I. Fitting parameters of $Ca_{70}Mg_{15}Al_{15}$ and $Ca_{70}Al_{30}$. (Error: ρ, ±5%; $\tau_{\mathrm{s.o.}}$ and τ_ϕ, ±10%.)

Alloy	ρ ($\mu\Omega$ cm)	T (K)	D (cm^2 s^{-1})	F	$\tau_{\mathrm{s.o.}}$ (10^{-11} s)	τ_ϕ (10^{-10} s)
$Ca_{70}Al_{30}$	308	0.18	1.5	0.29	1.13	0.86
	308	0.38	1.5	0.29	1.13	1.21
	308	0.78	1.5	0.29	1.13	1.44
	308	1.43	1.5	0.29	1.13	1.18
	308	4.24	1.5	0.29	1.13	0.59
$Ca_{70}Mg_{15}Al_{15}$	122	0.272	3.0	0.24	0.98	0.47
	122	0.675	3.0	0.24	0.98	0.61
	122	1.48	3.0	0.24	0.98	0.46
	122	4.24	3.0	0.24	0.98	0.42

τ_ϕ, $\tau_{s.o.}$, and F are listed in Table I. The spin-orbit scattering time and dephasing time are in excellent agreement with the results presented in Ref. 1. In this temperature range, τ_ϕ is almost constant for both samples, perhaps because of residual spin scattering from magnetic impurities present in the alloys. The screening factor, however, is smaller than the predictions of the free-electron model implying a reduction in the screening of the Coulomb interaction as the motion of the electrons is very diffusive in these high-resistivity samples.

A further point emerges from the saturation of the WL contribution below 4.2 K. Below this temperature any change in the magnetoresistance is controlled by EEI. The EEI contributions are thus shown in Fig. 2 by substracting WL contribution at 4.24 K from the data. In this way the effects from EEI are clearly displayed without reference to any detailed theory. That the EEI theories account satisfactorily for this contribution is shown by the solid lines, which were calculated using values of F obtained from Table I.

The temperature dependence of the resistivity of $Ca_{70}Al_{30}$, between 0.03 and 4.24 K, is shown in Fig. 3. The solid line is a fit to the data using EEI contribution only [Eq. (2) in Ref. 1]. The WL contribution is small and can be neglected, since the temperature dependence of the resistivity comes through the dephasing time τ_ϕ which is constant, as mentioned earlier. As for the magnetoresistance, the fit is excellent over the full temperature range, though the screening factor is smaller, the best fit being obtained for $F=0.1$, as compared with the value obtained from the magnetoresistance.

In conclusion, we have shown that QCC work very well in very weak spin-orbit scattering three-dimensional conductors up to very high B/T values. The saturation of the WL below 4.2 K allowed us to clearly demonstrate the contribution of the EEI to the magnetoresistance in bulk disordered conductors. The spin-orbit and dephasing times were extracted from the fits. The latter is found to be constant, for both samples, in this temperature regime. The values of the screening factor are small and consistent with the EEI theory.

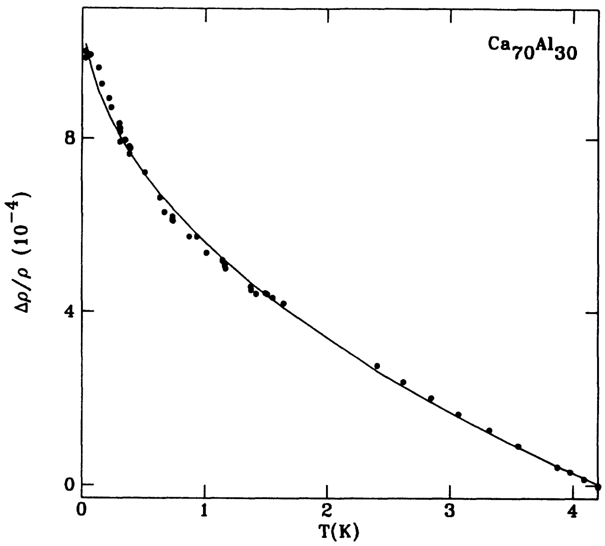

FIG. 3. Low-temperature resistivity of $Ca_{70}Al_{30}$. The points are the experimental data and the solid line a fit using electron-electron interactions expression (Ref. 1).

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