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Scaling behavior of amorphous *Fe*Mn in magnetic fields

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We have carefully characterized the low-temperature magnetotransport of a series of samples of the metallic glass $(Fe_{1-x}Mn_x)_{75}P_{16}B_6Al_3$. We find that both localization and electron interactions are important, but the variation of the magnetoresistance with x indicates that this amorphous metal will only satisfy scaling theories which include spin fluctuations.

The transport properties of disordered materials can arise from a multitude of competing effects and can involve complicated analyses. For example, recent magnetoresistance measurements on granular aluminum[1] were explained by a combination of four separate contributions: Coulomb interactions, localization, spin-orbit scattering, and superconducting fluctuations. Nonetheless, we would like to determine the universal characteristics of disorder, even in view of the apparent complexity of individual systems.

McMillian's scaling theory[2] of the metal-insulator transition in amorphous materials is one such attempt, heuristically including the effects of localization, electron correlation, and screening. Cochrane and Strom-Olsen have argued[3] that a wide variety of metallic glasses are described by this theory, based on the square-root variation with temperature of the low-temperature resistivity ρ. Furthermore, the correlation gap Δ, which is deduced from the temperature-dependence of the Metglas, scales with ρ in the identical manner determined by tunneling data[4] on amorphous NbSi and granular Al, materials with resistivities up to three orders of magnitude greater. That disordered materials with such different constituents, correlation energies, and resistivities should behave apparently so similarly is a surprising triumph for universality. In this paper we explore the extent of the universal behavior by carefully characterizing the low-temperature transport properties of one particular metallic glass, testing to see if the magnetic field behavior is consistent with the assumptions made in scaling the temperature-dependent properties.

We have made conventional four-probe resistance measurements on centrifugally quenched[5] ribbons of $(Fe_{1-x}Mn_x)_{75}P_{16}B_6Al_3$ for $0.05 < x < 0.45$, $10\ \text{mK} < T < 900\ \text{mK}$, and $0 < H < 80$ kOe. We spot welded 0.002-in. gold wires to samples of typical dimension $5 \times 1 \times 0.02\ \text{mm}^3$, which were cooled in a dilution refrigerator and measured using a lock-in technique at 16 Hz. All results are in the frequency-independent, Ohmic regime.

It is difficult to accurately determine the resistivity for a Metglas ribbon because of the uncertainty involved in measuring its thickness. Good relative values of ρ, however, may be obtained by weighing the samples and using a nominal density which varies appropriately with composition. We list in Table I the linear best-fit values of ρ vs Mn concentration x. The absolute resistivity scale was set by the measurement of Rapp and Grindborg[6] of $\rho = 162\ \mu\Omega$ cm for $x = 0$.

We plot in the top half of Fig. 1 the relative change in resistivity $\Delta\rho/\rho$ vs $T^{1/2}$ for three representative samples. The square-root variation with T indicates the importance of electron interactions.[7] The correlation gap Δ determined from the slope is in the appropriate range ($\Delta \sim 50$ eV) indicated by the Cochrane and Strom-Olsen scaling[3] of other metallic glasses, but the variation of ρ with x for amorphous FeMn alone is not sufficient to determine a functional form for Δ on ρ.

The bottom half of Fig. 1 presents the corresponding variation of $\Delta\rho/\rho$ with $H^{1/2}$ at $T = 50$ mK. The negative magnetoresistance with square-root variation at high H indicates that localization effects[8] dominate. Furthermore, we deduce that spin-orbit scattering is relatively unimportant in this system, because it would destroy the localization contribution.[9]

The scaling theory[2] of amorphous metals, which has been invoked[3,4] to describe $\rho(T)$ and $\Delta(\rho)$, considers the effects of localization and electron interactions. These processes contribute the following terms to the magnetoconductivity in the low-T, high-H limit:

$$\Delta\sigma(H)^{\text{LOC}} = \frac{e^2}{2\pi^2\hbar} \times 0.605 \left(\frac{eH}{\hbar c}\right)^{1/2}, \tag{1}$$

due to localization,[10]

$$\Delta\sigma(H)^{\text{INT(orb)}} = -g_c(T)\frac{e^2}{2\pi^2\hbar} \times 1.90 \left(\frac{eH}{\hbar c}\right)^{1/2}, \tag{2}$$

due to an orbital interaction term,[10] and

$$\Delta\sigma(H)^{\text{INT(Zeeman)}} = \frac{-e^2}{4\pi^2\hbar} F\left(\frac{g\mu_B H}{2k_B D}\right)^{1/2}, \tag{3}$$

TABLE I. $T = 4.2$ K values of the resistivity ρ for the $(Fe_{1-x}Mn_x)_{75}P_{16}B_6Al_3$ samples.

x	ρ ($\mu\Omega$ cm)
0.05	166.2
0.20	178.6
0.25	182.7
0.30	186.8
0.35	190.8
0.40	195.0
0.45	199.1

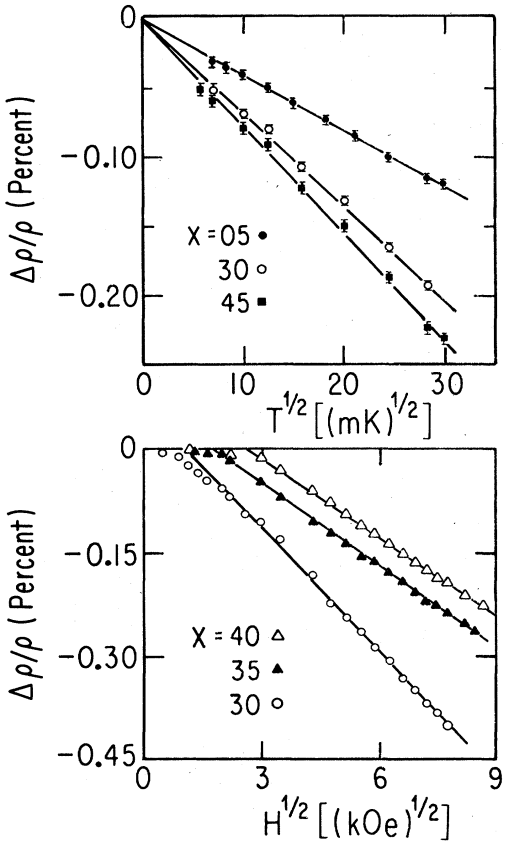

FIG. 1. Relative change in resistivity as a function of temperature ($H=0$) and magnetic field ($T=50$ mK) for samples of $(Fe_{1-x}Mn_x)_{75}P_{16}B_6Al_3$. The square-root variations indicate the importance of localization and electron interations.

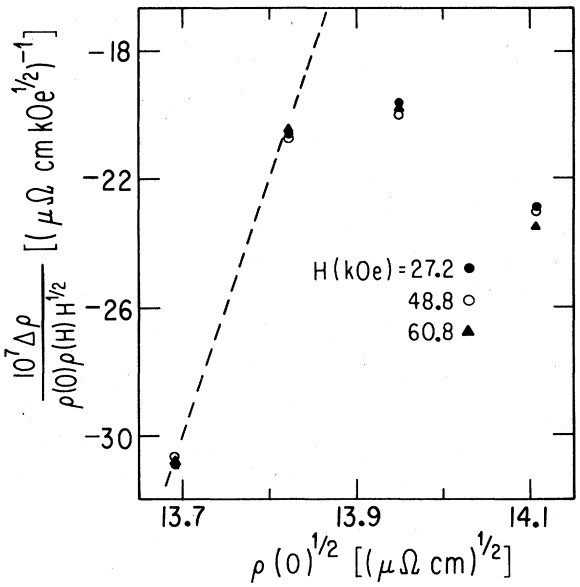

FIG. 2. The sum of localization and interaction terms should give a straight-line fit [see Eq. (4)]. Deviation can be explained by including spin fluctuations.

due to spin splitting from interactions,[11] where g_c is a coupling constant, g is the Lande g factor, μ_B is the Bohr magneton, k_B is Boltzmann's constant, F is a dimensionless number which sets the strength of the electron-electron interaction, and $D \propto 1/\rho$ is the diffusion coefficient. To lowest order we can add these contributions[12] and we find a functional form

$$\frac{\Delta\rho}{\rho} = \frac{\rho(H)-\rho(0)}{\rho(0)} = -[a - b\rho(0)^{1/2}]\rho(H)H^{1/2}, \qquad (4)$$

where a and b are constants determined by Eqs. (1), (2), and (3). Hence, a plot of $\Delta\rho/\rho(0)\rho(H)H^{1/2}$ vs $\rho(0)^{1/2}$ should collapse both measurements of a single sample at different H into one point and measurements of samples with different ρ (and x) onto a straight line.

We make this plot in Fig. 2. Data at different H do indeed overlap, but the variation with $\rho(0)^{1/2}$ is not linear as expected from Eq. (4) and suggested by the dashed line. The combination of localization and electron interaction terms does not explain the magnetic field data, but the deviation from linearity cannot be rectified simply by including additional contributions which are proportional to $H^{1/2}$. Spin-orbit scattering would lead to a correction of the wrong sign. Similarly, the cross term arising from the effect of the localization on the Coulomb interactions would enhance the positive magnetoresistance as ρ increased. The electrons diffuse more slowly and, hence, interact more strongly. Finally, superconducting fluctuations are not a pertinent concern here.

An important aspect of the amorphous FeMn system which we have not yet considered is its magnetic character. We plot in Fig. 3 the crossover H_c between the low-field (H^2) and high-field ($H^{1/2}$) behavior of the magnetoresistance for four different samples. As predicted by Kawabata,[8] and in contrast to the more complicated granular alumi-

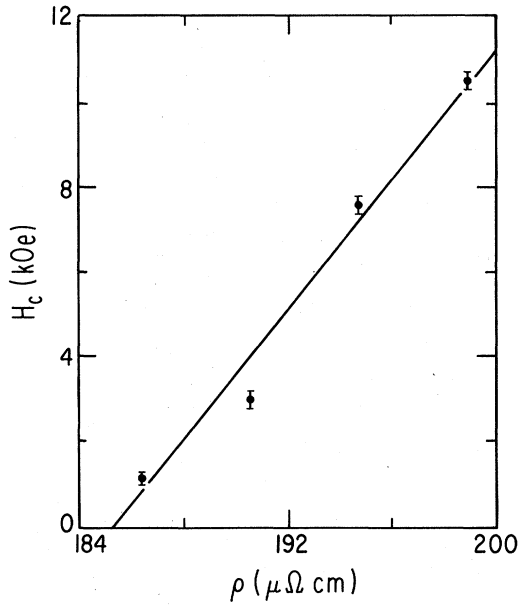

FIG. 3. Crossover H_c between low-field and high-field regimes in Fig. 1 (bottom) for different samples. $H_c=0$ indicates transition into amorphous ferromagnet.

num,[13] $H_c \propto \rho$. At $\rho_c = 185.6\ \mu\Omega$ cm, however, $H_c = 0$. This corresponds to an Fe concentration sufficiently high for the system to become an amorphous ferromagnet. The internal field of the ferromagnet effectively puts the system in the high-field limit independent of the applied H, decreasing the size of the H^2 regime to zero.

None of the samples in Fig. 2 are amorphous ferromagnets, but they are in a regime where spin fluctuations are presumably very important. We can understand the deviation from linearity as well as the eventual turnover in Fig. 2 in terms of the spin fluctuations of the conduction electrons which enter the magnetotransport through a Stoner enhancement of F in Eq. (3). Usually $0 < F < 1$, but for almost ferromagnetic materials[14] $F >> 1$. The magnitude of the spin-splitting interactions term scales with F, which would determine the slope of a smooth curve drawn through the data points in Fig. 2. Since F decreases with decreasing Fe concentration, the slope decreases with increasing ρ, eventually becoming negative. Although the variation in ρ itself is small, F depends on the more rapidly varying quantity $(\rho - \rho_c)$.

A large F near ρ_c, however, clearly indicates the inadequacy of the localization contribution to the magnetoresistance. Although the observed magnitude of the effect is within a factor of three of the value predicted by Eq. (1), a large positive contribution from Eq. (3) requires a negative magnetoresistance much larger than the localization contribution. We can identify the spin fluctuations associated with the d electrons[15] as a possible mechanism for this extra contribution. Application of a magnetic field decreases the spin fluctuations of the d electrons, and hence decreases the scattering of the conduction electrons from the d electrons. This can give rise to a large negative magnetoresistance which also shows $H^{1/2}$ and $T^{1/2}$ behavior.[16] As one goes farther away from the transition region, the d-electron spin fluctuations decrease, giving an increase in the magnetoresistance with resistivity. A combination of the d-electron and conduction-electron spin fluctuations can then qualitatively account for the data in Fig. 2. However, a quantitative analysis, obtaining, for example, the magnitude of F (from either the T or H dependence of ρ) and its variation with ρ cannot be made until a detailed calculation of the two-band spin scattering has been completed.[16]

Scaling theories which only consider localization and electron interactions may account for both the temperature-dependent[3] and magnetic-field-dependent[17] properties of some metallic glasses. There are a wide class of disordered materials, however, which require spin fluctuations to be treated within the scaling context. We have shown that spin fluctuations are certainly important in almost ferromagnetic systems and they may be significant for any amorphous concentrated spin system.[18]

The enhancement in F may not only be important for metallic glasses with magnetic constituents, but may bear on the universality of the critical behavior of disordered systems at the metal-insulator transition. Recent NMR results[19] on Si:P suggest the existence of intrinsic, quasistatic spins in the disordered metal, which may be responsible for the anomalous critical exponent of the electrical conductivity.[20] If these quasistatic spins exist, then they should show up through magnetotransport measurements as an enhancement in F at the approach to the transition.

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[1]K. C. Mui, P. Lindenfeld, and W. L. McLean, Phys. Rev. B **30**, 2951 (1984).
[2]W. L. McMillian, Phys. Rev. B **24**, 2739 (1981).
[3]R. W. Cochrane and J. O. Strom-Olsen, Phys. Rev. B **29**, 1088 (1984).
[4]G. Hertel, D. J. Bishop, E. G. Spencer, J. M. Rowell, and R. C. Dynes, Phys. Rev. Lett. **50**, 743 (1983); R. C. Dynes and J. Garno, *ibid.* **46**, 137 (1981).
[5]H. S. Chen and C. E. Miller, Mater. Res. Bull. **11**, 49 (1976).
[6]O. Rapp and J. E. Grindborg, J. Appl. Phys. **49**, 1733 (1978).
[7]B. L. Altshuler and A. G. Aronov, Zh. Eksp. Teor. Fiz. **77**, 2028 (1979) [Sov. Phys. JETP **50**, 968 (1979)].
[8]A. Kawabata, Solid State Commun. **34**, 431 (1980); J. Phys. Soc. Jpn. **49**, 628 (1980).
[9]S. Hikami, A. I. Larkin, and Y. Nagaoka, Prog. Theor. Phys. **63**, 707 (1980).
[10]B. L. Altshuler, A. G. Aronov, A. I. Larkin, and D. E. Khmelnitzkii, Zh. Eksp. Teor. Fiz. **81**, 768 (1981) [Sov. Phys. JETP **54**, 411 (1981)].
[11]P. A. Lee and T. V. Ramakrishnan, Phys. Rev. B **26**, 4009 (1982).
[12]T. F. Rosenbaum, R. F. Milligan, G. A. Thomas, P. A. Lee, T. V. Ramakrishnan, R. N. Bhatt, K. DeConde, H. Hess, and T. Perry, Phys. Rev. Lett. **47**, 1758 (1981).
[13]T. Chui, P. Lindenfeld, W. L. McLean, and K. Mui, Phys. Rev. Lett. **47**, 1617 (1981).
[14]A. J. Millis and P. A. Lee, Phys. Rev. B **30**, 6170 (1984).
[15]We thank H. Fukuyama for first suggesting this mechanism of spin fluctuations to us.
[16]H. Fukuyama (to be published). The effect of spin fluctuations in a single-component electron system is calculated in Y. Isawa and H. Fukuyama, J. Phys. Soc. Jpn. **53**, 1415 (1984).
[17]S. J. Poon, K. M. Wong, and A. J. Drehman, Phys. Rev. B **31**, 1668 (1985).
[18]G. Aeppli, J. J. Hauser, G. Shirane, and Y. J. Uemura, Phys. Rev. Lett. **54**, 843 (1985).
[19]M. A. Paalanen, A. E. Ruckenstein, and G. A. Thomas, Phys. Rev. Lett. **54**, 1295 (1985).
[20]M. A. Paalanen, T. F. Rosenbaum, G. A. Thomas, and R. N. Bhatt, Phys. Rev. Lett. **48**, 1284 (1982).