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The metal–insulator transition induced by a magnetic field

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ABSTRACT

The importance is discussed of experimental studies of the metal–insulator transition induced by a magnetic field in systems that exhibit an anomalous critical exponent in the absence of a field. Comments are presented on the search for the intrinsic field-driven behaviour in an example of such a system (Ge:Sb), including some of the difficulties.

The motivation for this type of study is to test theoretical attempts at understanding the critical behaviour of the metal–insulator transition (Thomas 1985, Lee and Ramakrishnan 1985). We would like to compare our findings in particular with the most recent scenario of which we are aware. This suggestion by Castellani, Kotliar and Lee (1986) is based on a successful formulation of a Fermi-liquid theory which allows a physical interpretation of the analysis of Coulomb interactions by Finkelstein (1983, 1984), who had achieved considerable progress by mapping the problem onto the nonlinear sigma model.

The aspect of this Fermi-liquid approach which is of interest here is that the model exhibits strong coupling runaway when its scaling behaviour is evaluated to all orders in interactions, but to only first order in a perturbation theory of the disorder. This singular behaviour is associated with the disorder expansion parameter becoming a dangerously irrelevant variable in systems that are 'clean' in the unusual sense that symmetry-breaking fields are negligible. The possibility then arises that this case may provide an explanation for the anomalous critical exponent (Thomas, Ootuka, Katsumoto, Kobayashi and Sasaki 1982, Thomas, Paalanen and Rosenbaum 1983, Rosenbaum, Andres, Thomas and Bhatt 1980) that has been observed in uncompensated Si:P and Ge:Sb.

A new discussion is needed for this uncompensated case because a previous scenario (Thomas 1986) appears to be untenable. This speculation was that the observed exponent 1/2 arose because of strong spin-flip scattering describable within the non-interacting scaling theory of localization (Abrahams, Anderson, Licciardello and Ramakrishnan 1979). However, the strong enhancement of the spin susceptibility (Ikehata and Kobayashi 1985, Paalanen, Ruckenstein and Thomas 1985, Paalanen, Sachdev and Bhatt 1986) that is observed in Si:P is directly linked (Sachdev 1986) to a spin-scattering rate that is much less than experimental thermal energies. Furthermore, the Mott limit (Mott 1972) that the localization-length exponent (thc same as the conductivity exponent in the non-interacting mode 1) must be greater than 2/3 has recently been confirmed rigorously (J. Chayes, L. Chayes, D. L. Fisher and T. Spenser, 1987, preprint).

Consequently, we turn to models based on inclusion of Coulomb interactions (Efros and Pollak 1985) and the Fermi-liquid approach (Castellani *et al.* 1986). Here, the anomalous case is that of no symmetry-breaking fields, and the conductivity exponent is not necessarily the same as that of the localization length. An important aspect of this scenario is that the strong-coupling runaway is controlled by the presence of symmetry-breaking fields, such as magnetic field, spin-orbit coupling or spin scattering. The large number of systems that display exponents near one (Thomas *et al.* 1982, Hertel, Bishop, Spenser, Rowell and Dynes 1983, Lee and Ramakrishnan 1985) can then be understood as ones in which such processes are important. Of particular interest are materials that can be changed in a controlled way from one limit to the other, as in the case of materials having small symmetry-breaking fields to which magnetic field can be applied.

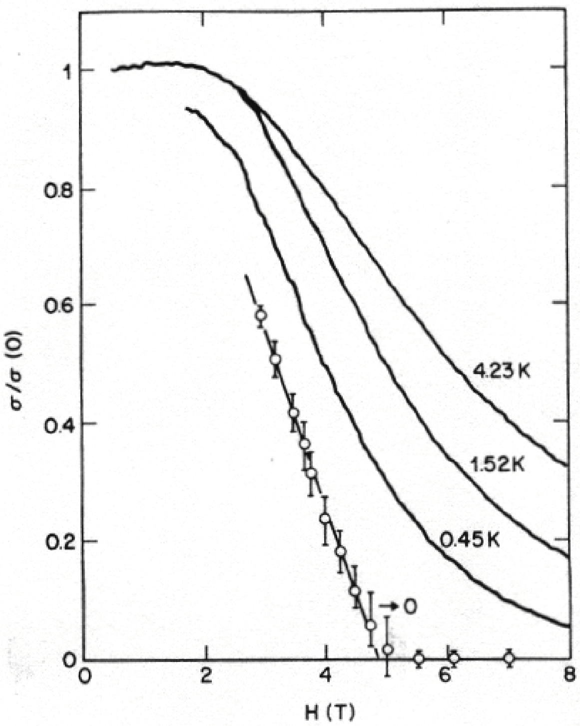
A simple consequence of this interacting Fermi-liquid scenario is that the critical exponent of the conductivity in Ge:Sb, for example, should change to one in a large magnetic field. We report on work in progress to test this prediction and on preliminary findings consistent with an exponent of unity.

One difficulty that we have encountered in our search for the intrinsic behaviour in the case of uncompensated degenerately doped Ge has been to obtain samples that have sufficient macroscopic homogeneity for a study of the critical behaviour. These difficulties have proven much greater than in doped Si crystals (Castner, Lee, Cieloszyk and Salinger 1975, Capizzi, Thomas, DeRosa, Bhatt and Rice 1980), perhaps because of the more substantial use of Si in technology. We have investigated an extensive series of samples of Ge:As and Ge:Sb to compare reproducibility of the conductivity parallel and perpendicular to the applied current at temperatures below 1 K and at magnetic fields sufficient to drive the samples to insulation. We have also studied the reproducibility of the Hall density and mobility in this same regime.

One result of this series of experiments is the finding that the sample anisotropy parallel and perpendicular to the applied field is particularly sensitive to macroscopic inhomogeneities in the field-induced insulating state. We checked the intrinsic anisotropy by measuring first with the field aligned along a $\langle 100 \rangle$ direction and then taking measurements again after having rotated the sample to align an equivalent axis. (We also compared the directions perpendicular to the field.) We observed some anisotropy that followed the sample orientation. Our preliminary conclusion is that anisotropies close to unity in the insulating state are indicative of the best reproducibility and the closest approach to macroscopic homogeneity.

Preliminary results for a sample of Ge:Sb with a donor density about twice the critical density and an anisotropy close to unity are shown in fig. 1. The conductivity normalized to its zero-field value is plotted as a function of applied field with the different curves corresponding to the temperatures 4·23, 1·52 and 0·45 K. The open circles represent conductivity values obtained from extrapolations of the finite-temperature data to zero temperature, examples of which are shown in fig. 2. The zero-temperature points have large error bars because even those temperatures that are used in fig. 2 are relatively high compared with the millikelvin values that have been found necessary in studies (Thomas *et al.* 1983, Thomas 1985, 1986, Rosenbaum *et al.* 1980, Lee and Ramakrishnan 1985) of Si:P. The long extrapolations necessary here give rise to the errors that we have shown in the figure, but there may also be systematic errors arising from possible increases in slope of the curves in fig. 2 at lower temperatures. Such increases have been observed (Thomas *et al.* 1983) in Si:P, but may not be present here because effects related to the suggested strong-coupling runaway are cut off by the

Fig. 1



Electrical conductivity of a sample of Ge:Sb as a function of applied magnetic field (in tesla) normalized to the value in zero field. Curves are shown at three sample temperatures: 4·23, 1·52 and 0·45 K. The open circles are points obtained from extrapolations to zero field as illustrated in fig. 2, and the solid line through these points is a fit corresponding to a critical exponent of unity. The zero-field conductivity has only a very small temperature dependence for this sample with density twice the critical density.

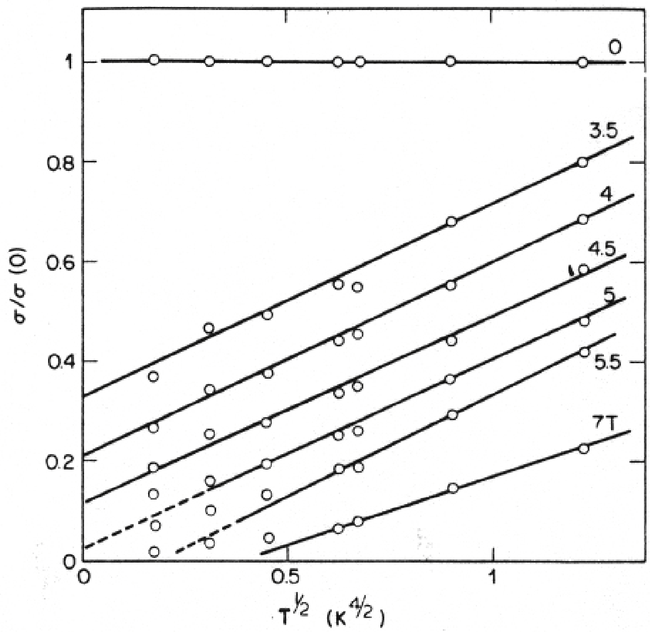
symmetry-breaking applied field. The solid line through the points in fig. 1 is a fit over the range from about 3 to 5 T, corresponding to a critical exponent of unity.

Figure 2 shows the conductivity normalized to that in zero field as a function of the square root of temperature. The points (open circles) are taken from curves similar to those shown in fig. 1 at a few selected values of the field. The linear fits (ignoring some rounding at the lowest temperatures near the transition) are used to obtain the zero-temperature intercepts, which determine the open circles in fig. 1. The square-root linear behaviour against temperature was found (Rosenbaum, Andres, Thomas and Lee 1981) in Si:P and has since been well established by a number of studies (Hertel *et al.* 1983) in zero and finite fields: it is a correction to the zero-temperature conductivity arising from Coulomb interactions and is an indication that these interactions play a significant role in the behaviour at low temperature.

These results are preliminary because they must be extended to lower temperatures and they must be reproduced in several samples.

If the findings remain consistent with unity critical exponent in an applied field, it will be an encouraging indication for models of the metal–insulator transition incorporating Coulomb interactions.

Fig. 2



Conductivity normalized to its zero-field value as a function of the square root of temperature for the sample as in fig. 1. Five curves are shown at different values of the magnetic field: 3·5, 4, 4·5, 5 and 7 T. The solid lines are linear fits to the data and are used to determine the zero-temperature intercepts plotted in fig. 1.

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