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High-T_c Superconductors: Evidence on the Electron–Phonon Interaction from Transport Measurements

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Abstract

We discuss the interpretation of measurements of thermal conductivity, thermopower, Hall coefficient, resistivity and magnetoresistance in high-temperature superconductors. The thermal conductivity of $YBa_2Cu_3O_7$ shows an increase below the transition temperature T_c, demonstrating the importance of the electron–phonon interaction in reducing the phonon current in the normal state. Many features of resistivity and thermopower can be interpreted in terms of conventional metallic models, although more exotic interpretations have been proposed. We show how measurements on more disordered samples should help resolve controversy regarding the interpretation of the electronic transport properties.

1. Introduction

In spite of the phenomenal effort to investigate the new high-T_c superconductors, following the seminal work of Bednorz and Müller (1986), there is still no clear understanding and much controversy regarding the origin of the spectacular superconductivity. Theoretical considerations have been of little assistance in the search for materials with high superconducting transition temperatures. There have been tantalising indications of superconductivity, in the form of a decrease in resistivity of orders of magnitude, around 230 K (e.g. Huang *et al.* 1987) or even well above room temperature at up to 500 K (Erbil *et al.* 1988). One of the unsatisfactory features of these observations, however, is that the resistivity in the possible 'superconducting' state of the Y–Ba–Cu–O compound of Erbil *et al.* (1988) is still more than six orders of magnitude larger than that in normal metals. We also find, using the approximate dimensions of the Eu–Ba–Cu–O sample given by Huang *et al.* (1987), that their experimental resolution means that the 'zero-baseline' resistivity below 230 K could be as high as 70 $\mu\Omega$ cm, still larger than that of normal metals. Further, the extremely high resistivity (usually with negative temperature coefficient of resistivity) *above* the 'superconducting transition' certainly resembles semiconducting behaviour, and Grader *et al.* (1987) see an apparent temperature-induced metal-semiconductor transition in some of their oxygen-deficient Y–Ba–Cu–O samples. It is therefore still conceivable that the observed dramatic decreases in resistivity are due to some kind of semiconductor–metal transition. Indications of superconductivity around room temperature through Josephson-like behaviour (Chen *et al.* 1987*a*; Erbil *et al.* 1988) are perhaps more significant, although indirect.

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Our main purpose in this paper is to interpret transport measurements on La–Sr–Cu–O and Y–Ba–Cu–O superconductors with a view to determining to what extent their behaviour can be understood in terms of conventional models. Since electron–electron correlations are expected to be strong in these superconductors (e.g. Oles *et al.* 1987), it is not *a priori* clear how good band-theory calculations and one-electron models are as a starting point for understanding their electronic structure and properties. A breakdown of the usual one-electron models could give important clues for the superconductivity. We also seek evidence regarding the importance of the electron–phonon interaction. These questions are of particular interest since the well-known resonating-valence-bond theory of Anderson *et al.* (1987), and other theories (e.g. Lee and Read 1987), propose novel electronic mechanisms for superconductivity not based on the electron–phonon interaction, as well as novel interpretations of the resistivity above the transition temperature. Isotope effect measurements to indicate the importance of the electron–phonon interaction for superconductivity have not been conclusive, with early results indicating no effect in Y–Ba–Cu–O, but later results giving a significant effect in La–Sr–Cu–O (e.g. Batlogg *et al.* 1987) and even some effect in Y–Ba–Cu–O (Leary *et al.* 1987).

Many of the transport data we discuss have been presented in a series of letters (Uher *et al.* 1987; Uher and Kaiser 1987*a*, 1987*b*, 1988), to which the reader is referred for detailed data points, although other data are also mentioned. We are led to propose that measurements on deliberately disordered superconductors could be of particular significance in helping understand the nature of the conduction mechanism and the origin of the superconductivity.

2. Thermal Conductivity

An unexpectedly dramatic effect was discovered in the thermal conductivity of $YBa_2Cu_3O_7$, namely a strong increase below the superconducting transition temperature T_c, as shown in Fig. 1 (Uher and Kaiser 1987*a*). [Typically for research on the new superconductors, the same effect was independently discovered by several other groups (Jezowski *et al.* 1987; Morelli *et al.* 1987; Bayot *et al.* 1987; Gottwick *et al.* 1987).] A La–Sr–Cu–O superconductor showed a somewhat similar but much more muted effect, i.e. a bulge rather than a peak below T_c (Uher and Kaiser 1987*a*). Although thermal conductivity normally decreases below T_c (since the paired electrons cannot transport heat), the observed peak in Y–Ba–Cu–O can easily be understood in terms of the dominance of lattice over electronic heat conduction. Since paired electrons cannot scatter phonons, the heat current due to phonons increases in the superconducting state (Berman 1976); this effect could dominate over the decrease in the electronic component K_e of thermal conductivity if K_e is small.

In the present case the maximum size of K_e estimated from the electrical resistivity, using the value of the Wiedemann–Franz ratio for elastic scattering, confirms dominant heat conduction by the lattice (for inelastic scattering of electrons as from phonons K_e is reduced below the maximum shown in Fig. 1). It is very difficult to imagine any circumstances in which the electronic system could give an increase of K_e below T_c, even in strongly-correlated systems.

The only previous observations of an increase in thermal conductivity K below T_c are for a disordered alloy where heat conduction by phonons dominates over that by electrons (Berman 1976). The sintered ceramic samples of the new superconductors also contain a substantial amount of disorder, but another major factor making the electronic contribution K_e small is the very small density of carriers (as shown by Hall effect and resistivity measurements discussed below).

We therefore have strong evidence that a large fraction of the thermal resistivity above T_c arises from scattering of the phonons by electrons, indicating a strong electron–phonon interaction (particularly in view of the disorder which is a competing scattering mechanism for the phonons). The only escape from this conclusion would be to find a mechanism whereby the phonon system itself shows a dramatic change as the temperature drops below T_c. This is not supported by neutron measurements (Renker *et al.* 1987) or observations of heat capacity (e.g. Junod *et al.* 1987), and it is unlikely that the phonon softening observed near T_c by Boolchand *et al.* (1988) is a large enough effect.

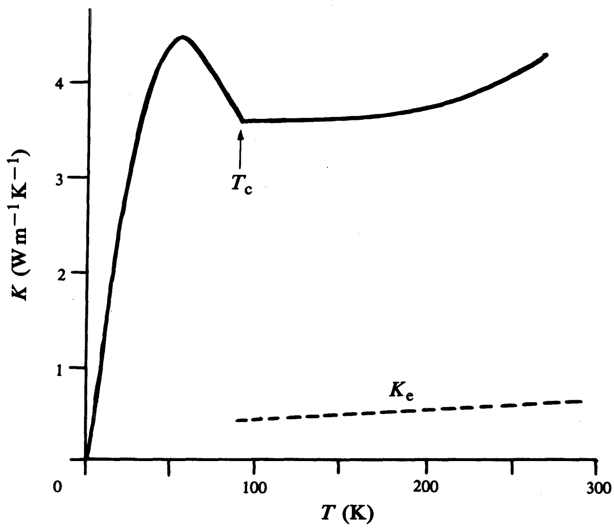

Fig. 1. Thermal conductivity K of $YBa_2Cu_3O_7$ (Uher and Kaiser 1987*a*), with the dashed line showing the maximum contribution of the electronic component K_e. The peak below T_c arises from the disappearance of scattering of phonons by electrons as superconducting pairs form.

The size and temperature dependence of the thermal conductivity above T_c are intermediate between that typical of good crystals and amorphous materials. We can make a rough estimate of the average phonon mean-free path l_{ph} as follows. The thermal conductivity arising from phonons is (Ziman 1960, p. 259)

$$K = \tfrac{1}{3} C v l_{ph}, \tag{1}$$

where C is the heat capacity per unit volume and v the speed of sound. For Y–Ba–Cu–O, we use $K = 3\cdot5$ W mK^{-1} (Uher and Kaiser 1987*a*), $C = 1\cdot4\times10^6$ J m^{-3} K^{-1} (Nevitt *et al.* 1987) and $v \sim 3000$ m s^{-1} (Lang *et al.* 1988) to obtain $l_{ph} \sim 25$ Å. This mean-free path is within an order of magnitude or so of typical interatomic spacings, showing the samples contain considerable disorder. Similar arguments apply for the La–Sr–Cu–O samples.

It is difficult to make any quantitative comment about the electron–phonon interaction from thermal conductivity, but we can make a very rough estimate of the electron density using the usual metallic models by extending the calculation of Bayot *et al.* (1987). When heat transport is by phonons limited by scattering from electrons, the ratio of thermal resistivity W_{Le} to ideal electrical resistivity ρ_i is (Ziman 1960, p. 321)

$$\frac{W_{Le}\,T}{\rho_i} \sim n_a^2\left(\frac{e}{k}\right)^2\left(\frac{C_{max}}{C}\right)^2, \tag{2}$$

where k is Boltzmann's constant, e is electronic charge, n_a is the number of free electrons per atom, and C_{max} is the maximum value $3Nk$ of the specific heat C (N is the density of atoms). From our arguments above, the lattice thermal resistivity W_{Le} must be a large fraction of the total lattice thermal resistivity K_L^{-1}, so that the density of free carriers is very roughly of order

$$n_a < \frac{k}{e}\,\frac{C}{C_{max}}\,(\rho_i\,K_L)^{-\frac{1}{2}}\,T^{\frac{1}{2}}. \tag{3}$$

Taking K_L from Fig. 1, ρ_i of order 100 $\mu\Omega$ cm (see next section) and $C/C_{max} \sim 0{\cdot}45$ (all values at about 100 K) gives a density of carriers of $n \leqslant 10^{22}$ cm^{-3}. That this seems a reasonable order of magnitude for n supports the applicability of the usual ideas of metallic conduction.

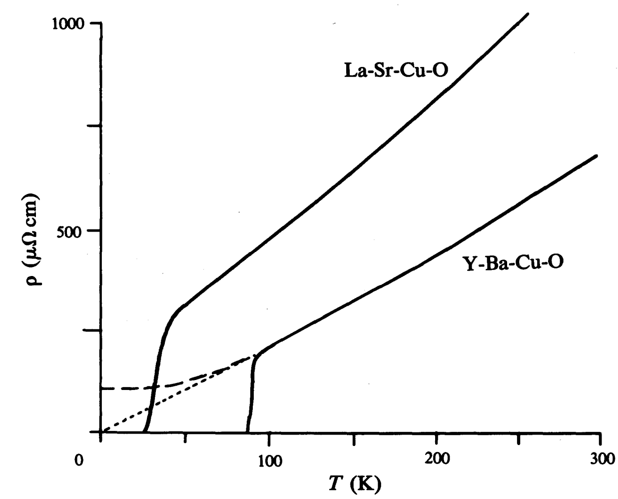

Fig. 2. Resistivity of $La_{1.8}Sr_{0.2}CuO_4$ (Uher *et al.* 1987) and a sample of $YBa_2Cu_3O_7$ in which the linear law 'extrapolates' to the origin (Cava *et al.* 1987). The dotted line shows the extrapolation of resistivity below T_c suggested by Anderson *et al.* (1987), while the dashed line shows the conventional extrapolation assuming that the temperature dependent contribution arises from scattering by the carrier-phonon interaction.

3. Electrical Resistivity

The main features of interest in the resistivity, apart of course from the zero resistance state, are firstly the large size of the resistivity above T_c, and secondly the remarkably linear increase of resistivity with temperature in most samples (see Fig. 2). The interpretation of resistivity is a matter of controversy. Anderson *et al.* (1987) suggested that conduction occurred by boson holes with very small residual resistivity owing to the difficulty of scattering the bosons, and with the linear law due to scattering by spinons. They quoted the lack of an extrapolated residual resistivity for good samples, as indicated by the dotted line in Fig. 2, as confirming their model.

However, the extrapolation of the resistivity below T_c is not necessarily an extrapolation of the linear law as in model of Anderson *et al.* (1987). A more conventional extrapolation according to the usual Bloch–Gruneisen function (Gottwick *et al.* 1987) or a lower power of T as in disordered systems (Froböse and Jäckle 1977) is suggested by the dashed line in Fig. 2. The upturn from the linear law at lower temperatures will be camouflaged in the region above T_c by superconducting fluctuations. In addition, the upturn could possibly be depressed to temperatures lower than $T_D/5$ (where T_D is the Debye temperature) as in the Bloch–Gruneisen law by the effect of disorder, of two-dimensional conduction (Micnas *et al.* 1987), or of a phonon spectrum with more weight at low energies than for a Debye spectrum. In this conventional interpretation, we obtain large extrapolated residual resistivities of order 100 $\mu\Omega$ cm even for samples in which the linear law extrapolates to near zero.

The plausibility of this interpretation can be tested as follows. The carrier density n and electronic mean-free-path l required to give a residual resistivity of order 100 $\mu\Omega$ cm in the conventional picture can be estimated using the Boltzmann-like expression

$$\rho = \hbar(3\pi^2)^{\frac{1}{3}}/n^{\frac{2}{3}}e^2 l. \tag{4}$$

Of course, we are considering here averages over very anisotropic behaviour, and there is the complication in sintered materials that the real cross section for conduction is significantly less than the geometrical cross section of the sample (Gottwick *et al.* 1987; Uher and Kaiser 1987*a*). Nevertheless, the resistivity along the Cu–O planes (the direction of metallic conduction) in single crystals appears to be similar to that for sintered materials (Tozer *et al.* 1987). For $\rho \sim 200$ $\mu\Omega$ cm we find $n^{2/3} l \sim 6{\cdot}4\times10^7$ cm^{-1}, i.e. $l \sim 64$ Å for $n \sim 10^{21}$ cm^{-3} or $l \sim 14$ Å for $n \sim 10^{22}$ cm^{-3}. These mean-free-paths are relatively short but not unusual in disordered materials.

We can also analyse the size of the linear resistivity slope at higher temperatures, using the expression of Allen *et al.* (1986) for phonon-limited metallic resistivity:

$$\frac{d\rho}{dT} \approx \frac{2\pi k}{\hbar e^2}\left(\frac{m}{n}\right)_{\text{eff}} \lambda_{\text{tr}}, \tag{5}$$

where λ_{tr} is the electron–phonon coupling constant for transport and m_{eff}/m is an appropriate average enhancement of the carrier mass m at higher temperatures. Our experimental values of $d\rho/dT$ are $\sim 3{\cdot}6$ $\mu\Omega$ cm K^{-1} for highly-doped La–Sr–Cu–O (Uher *et al.* 1987) and ~ 3 $\mu\Omega$ cm K^{-1} for $YBa_2Cu_3O_7$ (Uher and Kaiser 1987*a*).

Using n values between 10^{21} and 10^{22} cm^{-3}, we obtain the range of values

$$(m_{\rm eff}/m)\lambda_{\rm tr} \sim 1\text{–}12, \tag{6}$$

which is consistent with a strong electron–phonon interaction and/or an enhanced mass.

A problem for the conventional interpretation of the linear resistivity law in terms of electron–phonon scattering comes from the fact that the linearity appears to extend up to rather higher temperatures than expected, e.g. 1000 K for La–Sr–Cu–O (Gurvitch and Fiory 1987). It is found rather generally (e.g. Gurvitch 1981) that when the electronic mean-free-path l decreases to the order of the interatomic spacing in metals, the resistivity as a function of temperature shows a 'saturation' effect, i.e. the rate of increase of resistivity with temperature is reduced. Gurvitch and Fiory (1987) found that the resistivity of La–Sr–Cu–O shows no sign of saturation up to 4000 $\mu\Omega$ cm, in which case the estimated mean-free-path from equation (4) would be 3 Å for $n \sim 10^{21}$ cm^{-3} and less than 1 Å for $n \sim 10^{22}$ cm^{-3}, the latter being less than the Cu–O bond length of 2 Å. Clearly a low density of carriers is required to account for the lack of saturation. But this means, from equations (5) and (6), that the electron–phonon coupling $\lambda_{\rm tr}$ may not be particularly large. Gurvitch and Fiory (1987) estimated the plasma frequency $\omega_{\rm p}$ from measurements of the London penetration depth, and replaced $(m/n)_{\rm eff}$ in equation (5) by $4\pi e^2/\omega_{\rm p}^2$. Their results imply $(m/m_{\rm eff})n \sim 10^{20}$ cm^{-3}, a rather small value which leads to small values of $\lambda_{\rm tr}$. If this were the case, however, it is difficult to see how the small number of electrons could scatter phonons nearly as effectively as the significant amount of disorder which is required to account for the thermal conductivity data.

Complications of the resistivity analysis are anisotropy and the nature of the sintered material, as mentioned, and also increases of resistivity due to loss of oxygen above 600 K in $YBa_2Cu_3O_{7-\delta}$. A masking of a saturation effect by such an increase of resistivity in La–Sr–Cu–O remains a possibility. It would clearly be of great interest to force saturation by deliberately introducing additional disorder into the samples, to reach eventually a relatively temperature-independent resistivity with mean-free-path comparable with the atomic spacing, as in amorphous metals. The way electrical and thermal resistivity changes upon strong irradiation of the samples should help to clarify the extent to which conventional models for conduction are applicable.

4. Magnetoresistance

We have suggested (Uher and Kaiser 1988) that magnetoresistance can be a sensitive probe of trace filamentary superconductivity, particularly in samples with semiconductor resistivity behaviour in which small changes of slope arising from superconductivity are difficult to see. We found superconductivity islands clearly revealed in magnetoresistance in a La–Sr–Cu–O sample (Fig. 3), which showed a resistivity in excellent agreement with the Mott variable-range-hopping law at low temperatures with only a barely detectable anomaly near 30 K.

Above 40 K however, the magnetoresistance was less than one part in 5000 for a field of 7 T. (These small values of magnetoresistance are typical of disordered systems, in which the deflecting effect of the magnetic field is very limited owing to the short electron mean-free-path.) We are led to suggest 40 K as an upper limit for traces of superconductivity in the La–Sr–Cu–O system at normal pressure, in disagreement with suggestions of superconducting effects up to 100 K seen in thermopower, which are discussed in Section 6 below.

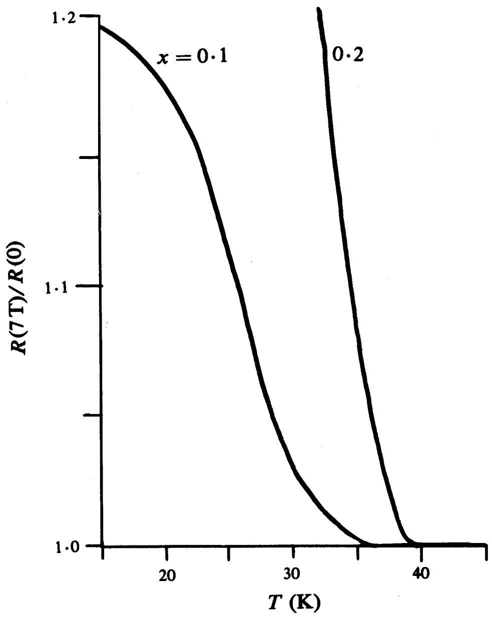

Fig. 3. Magnetoresistance of a non-metallic $La_{2-x}Sr_xCuO_4$ ($x = 0\cdot1$) sample showing the large effect below 35 K ascribed to superconducting filaments (the resistivity showed almost no anomaly), compared with data for a superconducting sample ($T_c \sim 30$ K, $x = 0\cdot2$) (Uher and Kaiser 1988). Here R(7 T) is the value of the resistance in a field of 7 T.

5. Hall Coefficient

The size of the Hall coefficient R_H is often used as an indicator of carrier sign and density, since for a single homogeneous band $R_H = (nq)^{-1}$, where q is the carrier charge. In metals, R_H is essentially independent of temperature for a single band, so temperature dependence is taken as a sign of multi-carrier conduction.

In the case of high-temperature superconductors, R_H is strongly temperature dependent, so multi-carrier cancellation appears to be present and an estimate of carrier density n using a single-band model will give an overestimate. For the multi-carrier case we have

$$R_H = \sum_i (\rho/\rho_i)^2 R_{Hi}, \tag{7}$$

where ρ_i and R_{Hi} are the resistivity and Hall coefficient for the ith band.

Although for a full description more complex models are required, Uher and Kaiser (1987*b*) found that the Hall coefficient of highly-doped La–Sr–Cu–O superconductors (see Fig. 4) was consistent with the usual two-carrier model, with a hole density of a few times 10^{21} cm^{-3} and a smaller number of electrons. The temperature dependence of R_H can arise from different temperature dependences of the resistivities ρ_i for each carrier group. A large ratio for holes (compared with electrons) of the scattering by phonons to that by structural defects gives rise to R_H decreasing with temperature, as seen. The observed behaviour is consistent with a strong hole–phonon interaction.

Although the Hall coefficient, like the resistivity, will be highly anisotropic, our data in Fig. 4 are similar to those of Suzuki and Murakami (1987) for a single crystal

La–Sr–Cu–O thin film. In the sintered samples we see some average over different directions, but this will be weighted very strongly in the direction of high conduction along the Cu–O planes. It is interesting to note that for this direction (but not in the poor conductivity direction) Allen *et al.* (1987) predicted a positive Hall coefficient from their band-theory calculations for $La_{2-x}Sr_xCuO_4$ for $x < 0{\cdot}24$, in agreement with experiment.

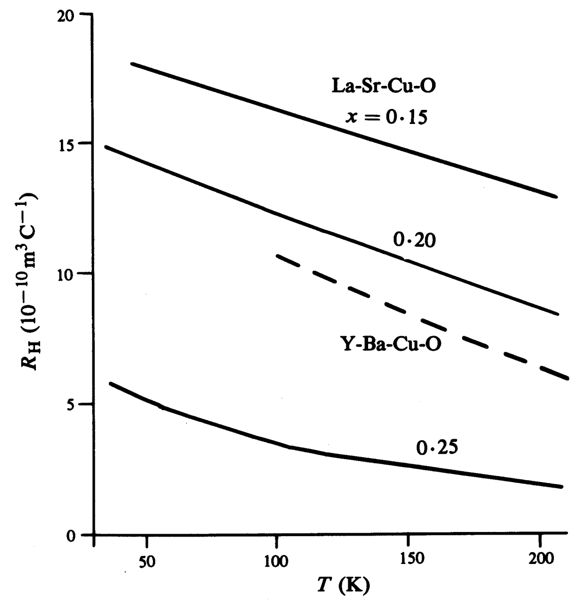

Fig. 4. Hall coefficient for $La_{2-x}Sr_xCuO_4$ for $x = 0{\cdot}15$ (Hundley *et al.* 1987), for $x = 0{\cdot}20$ and $0{\cdot}25$ (Uher and Kaiser 1987*b*), and for $YBa_2Cu_3O_7$ (Gottwick *et al.* 1987).

6. Thermopower

We come now to the least understood of the transport properties, but one that we argue is potentially rewarding. Grant *et al.* (1987) suggested that thermopower might be the transport measurement most sensitive to minute superconducting components in an otherwise normal sample. The reason is that thermopower arises from regions of the sample with a temperature gradient, so samples with disconnected superconducting filaments may have zero thermopower but finite resistivity [the argument is somewhat similar to that used (Kaiser 1987) to explain why the thermopower of conducting polymers often shows more metallic behaviour than their conductivity]. Grant *et al.* (1987) found that thermopower could be zero in sintered La_2CuO_4 at about 40 K even though resistivity was only just beginning to decrease. Further, they and Cooper *et al.* (1987) suggested that the decrease of thermopower beginning as the temperature decreased below 90 K indicated trace amounts of superconductivity in nominally pure La_2CuO_4 with an onset temperature not much below 100 K.

However, these samples show a very large nearly constant non-metallic thermopower

(200–300 $\mu V K^{-1}$) at higher temperatures. For thermodynamic reasons, thermopower must go to zero at zero temperature, and a thermopower similar to that seen in La_2CuO_4 appears to be typical of systems near the metal–semiconductor transition (Ovadyahu 1986). The interpretation of a decrease in thermopower as incipient superconductivity is therefore open to question, and our magnetoresistance data suggest 40 K as the upper limit of superconductivity in the La–Sr–Cu–O system. We see a decrease of thermopower below 200 K in our semiconducting $La_{1\cdot9}Sr_{0\cdot1}CuO_4$ sample (Uher and Kaiser 1988), but we do not interpret this as due to incipient superconductivity.

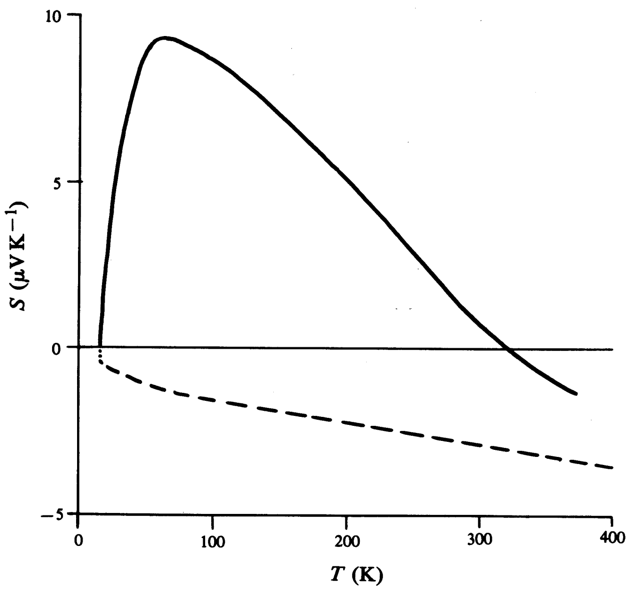

Fig. 5. Thermopower of $La_{2-x}Sr_xCuO_4$ ($x = 0\cdot25$) (Uher *et al.* 1987). A possible interpretation is a negative diffusion thermopower (dashed curve) and a large positive phonon-drag peak. The diffusion thermopower has a knee due to electron–phonon enhancement at lower temperatures (Kaiser 1988).

Turning now to the highly-doped $La_{2-x}Sr_xCuO_4$ samples ($x > 0\cdot15$), we find that thermopower has much smaller values typical of metals as the resistivity becomes metallic. Some of our data are shown in Fig. 5; Chen *et al.* (1987*b*) found similar results for La–Ba–Cu–O. We suggest that these data could be consistent with normal metallic thermopower, namely a phonon-drag peak at around $T_D/5$ dying out at higher temperatures to leave an approximately linear diffusion thermopower. If this interpretation is correct, the diffusion thermopower (at least in the most highly-doped specimens) is negative, as indicated approximately by the dashed curve. The contrast with the positive Hall coefficient in the same samples (Section 5) is surprising, yet this is just what is predicted by the band-theory calculations of Allen *et al.* (1987) for conduction along the Cu–O planes (the dominant conduction direction). The opposite sign of R_H and S can arise in situations with a complicated Fermi surface with different groups of carriers, because the weighting factors for combining thermopower and Hall coefficient contributions are different. For example, for thermopower in a multi-band system we have

$$S = \sum_i (\rho/\rho_i) S_i, \tag{8}$$

where S_i are the thermopowers of each band in isolation, in contrast to equation (7) for the Hall coefficient. In addition, the thermopower sign is affected by the energy dependence of scattering.

It should be noted that the diffusion thermopower sketched in Fig. 5 (above the superconducting region where thermopower must be zero) is nonlinear, because it is enhanced at low temperatures by the electron–phonon interaction; the enhancement shown is that calculated by Kaiser (1988) using the Eliashberg function $\alpha^2 F(E)$ derived by Weber (1987). This effect is well-established in glassy metals in which phonon-drag is absent (Kaiser *et al.* 1986). When the electron–phonon interaction is strong, the knee at low temperatures is pronounced and the high-temperature thermopower does not extrapolate to the origin (Kaiser 1988). If the large peak is phonon-drag and could be eliminated by increasing disorder, information about the electron–phonon interaction could be deduced from the remaining diffusion thermopower. Other effects may also enhance thermopower (e.g. Ashcroft 1987).

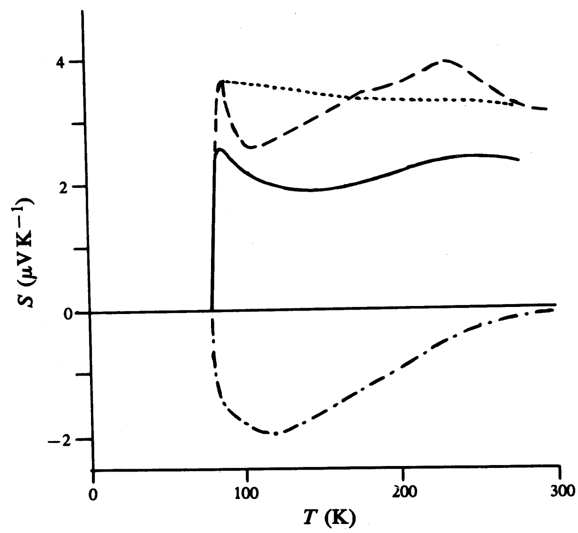

Fig. 6. Thermopower data (smoothed) for $YBa_2Cu_3O_7$ from Uher and Kaiser (1987*a*) (full curve), Mawdsley *et al.* (1987) (dashed curve), Cheong *et al.* (1987) (dotted curve) and for one sample from Gottwick *et al.* (1987) (dot–dash curve), showing the variability for different samples.

The data for $YBa_2Cu_3O_7$, examples of which are shown in Fig. 6, are rather variable, even as to sign. This is partly because the thermopower is small, possibly signifying cancellation of different contributions. Some data sets (e.g. Uher and Kaiser 1987*a*) suggest a small phonon-drag peak, but the sharp peak of Mawdsley *et al.* (1987) just above T_c looks like a precursor effect of superconductivity instead. We have suggested mechanisms that could enhance phonon-drag just above T_c (i.e. a decrease in effective carrier density and an increase in phonon current due to superconducting fluctuations), but the normal effect of superconducting fluctuations is to reduce thermopower as they short out the thermoelectric voltage.

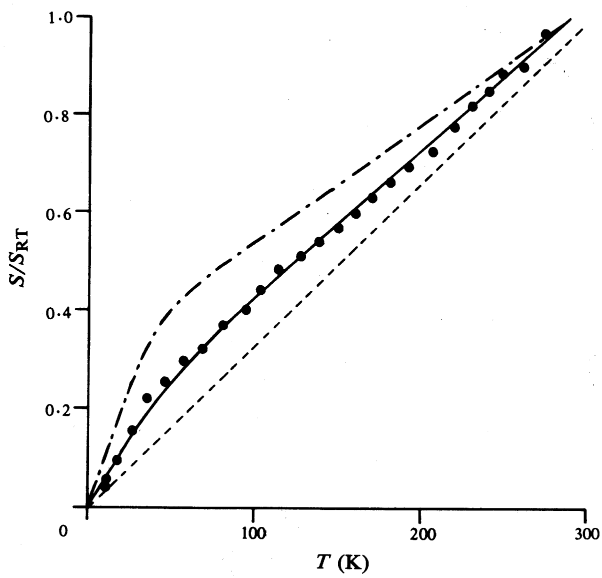

Fig. 7. Comparison of experimental points (dots) from Vasudeva Rao *et al.* (1984) with theory (full curve) (Kaiser 1988) for the thermopower of the disordered Chevrel superconductor $Cu_{1.8}Mo_6S_5Te_3$. The thermopower enhancement, i.e. the deviation above the straight dashed line, is calculated without adjustable parameters. Here S_{RT} is the room-temperature value of the thermopower. The dot–dash curve shows the corresponding diffusion thermopower shape for high-T_c superconductors (Kaiser 1988).

There is a suggestion in some of the data sets that the thermopower extrapolates to positive values at zero temperature, as predicted (Fig. 7) for the diffusion thermopower enhanced by the electron–phonon interaction (Kaiser 1988). However, no clear conclusions can be drawn from present data, particularly in view of the unexplained drop sometimes seen above about 240 K [according to the high-temperature data of Fisher *et al.* (1987) this decrease appears to continue up to about 600 K where a dramatic increase in thermopower begins].

7. Conclusions

The importance of the electron–phonon interaction in high-temperature superconductors is clearly demonstrated by the increased thermal conductivity just below T_c, especially in $YBa_2Cu_3O_7$. If the large thermopower peak around 70 K in La–Sr–Cu–O is indeed a phonon-drag peak, this also indicates a significant electron–

phonon interaction. Other transport properties of highly-doped La–Sr–Cu–O and $YBa_2Cu_3O_7$ generally appear consistent with traditional metallic concepts with a very small carrier density. These observations are suggestive of a significant role for the electron–phonon interaction in the superconductivity, although electronic interactions (for example) would need to at least remove the usual Coulomb repulsion which opposes superconductive pairing to produce T_c values near 100 K. However, the apparent lack of saturation in the linear resistivity is a problem worthy of further investigation, and the thermopower of $YBa_2Cu_3O_7$ in particular is difficult to interpret.

While single-crystal measurements are undoubtedly of great interest, it seems to us that thermopower, for example, is likely to suffer from the difficulties of interpretation which have made it such a notoriously difficult property for metallic crystals.

We therefore point out the interest of data on deliberately disordered samples, where our experience in glassy metals (Kaiser *et al.* 1986) indicates that, if the new superconductors do indeed follow usual metallic behaviour, quantitative analysis should be possible. For Chevrel superconductors, this prescription works extremely well; as disorder scattering increases, excellent agreement with calculations is obtained (Kaiser 1988), as shown in Fig. 7, favouring a traditional electron–phonon interaction in these materials compared with the more exotic model of Yu and Anderson (1984). It would clearly be of great interest to check whether a similar simple pattern emerges in heavily disordered high-temperature superconductors. If it does not, a clear difference from the previous 'high-temperature' superconductors and the importance of additional effects such as electron–electron correlations are established. If it does, information could be gained regarding the electron–phonon interaction. The enhancement effect would have to be considerably larger than in other materials if the electron–phonon effect is a major cause of the high T_c value, as indicated in Fig. 7. If the giant defect-enhanced electron–phonon interaction proposed by Phillips (1987) to account for the high-temperature superconductivity is correct, even more dramatic enhancements would be seen.

In addition, the observation of saturation in resistivity measurements on highly disordered samples could help to determine the quasi-particle carrier density, and even whether the usual quasi-particle picture is valid.

Acknowledgments

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References

Allen, P. B., Beaulac, T. P., Khan, F. S., Butler, W. H., Pinski, F. J., and Swihart, J. C. (1986). *Phys. Rev.* B **34**, 4331.

Allen, P. B., Pickett, W. E., and Krakauer, H. J. (1987). *In* 'Novel Superconductivity' (Eds S. A. Wolf and V. Z. Kresin), p. 489 (Plenum: New York).

Anderson, P. W., Baskaran, G., Zou, Z., and Hsu, T. (1987). *Phys. Rev. Lett.* **58**, 2790.

Ashcroft, N. W. (1988). Fluctuation effects in electron systems: their role in electron-pairing mechanisms. Proc. Fifth Int. Conf. on Recent Progress in Many-Body Theories, Oulu, Finland, August 1987, in press.

Batlogg, B., *et al.* (1987). *Phys. Rev. Lett.* **59**, 912.

Bayot, V., *et al.* (1987). *Solid State Commun.* **63**, 983.

Bednorz, J. G., and Müller, K. A. (1986). *Z. Phys.* B **64**, 189.

Berman, R. (1976). 'Thermal Conduction in Solids', p. 164 (Oxford Univ. Press).

Boolchand, P., *et al.* (1988). Softening of Cu–O vibrational modes as a precursor to onset of superconductivity in $EuBa_2Cu_3O_{7-\delta}$. *Phys. Rev.* B, in press.

Cava, R. J., *et al.* (1987). *Phys. Rev. Lett.* **58**, 1676.

Chen, J. T., Wenger, L. E., McEwan, C. J., and Logothetis, E. M. (1987*a*). *Phys. Rev. Lett.* **58**, 1972.

Chen, J. T., McEwan, C. J., Wenger, L. E., and Logothetis, E. M. (1987*b*). *Phys. Rev.* B **35**, 7124.

Cheong, S. W., *et al.* (1987). *Phys. Rev.* B **36**, 3913.

Cooper, J. R., Zhou, L. W., Dunn, B., Chu, C. T., Alavi, B., and Grüner, G. (1987). *Solid State Commun.* **64**, 253.

Erbil, A., Wright, A. C., and Boyd, E. P. (1988). *Phys. Rev.* B **37**, 555.

Fisher, B., Genossar, J., Lelong, I., Kessel, A., and Ashkenazi, J. (1987). Thermoelectric power measurements of $YBa_2Cu_3O_{7-\delta}$ up to 950°C, and their application to test the band structure near E_F. Physics Dept, Technion, Haifa 32000, Israel.

Froböse, K., and Jäckle, J. (1977). *J. Phys.* F **7**, 2331.

Gottwick, U., *et al.* (1987). *Europhys. Lett.* **4**, 1183.

Grader, G. S., Gallagher, P. K., and Gyorgy, E. M. (1987). *Appl. Phys. Lett.* **51**, 1115.

Grant, P. M., Parkin, S. S. P., Lee, V. Y., Engler, E. M., Ramirez, M. L., Vazquez, J. E., Lim, G., and Jacowitz, R. D. (1987). *Phys. Rev. Lett.* **58**, 2482.

Gurvitch, M. (1981). *Phys. Rev.* B **24**, 7404.

Gurvitch, M., and Fiory, A. T., (1987). *Phys. Rev. Lett.* **59**, 1337.

Huang, C. Y., Dries, L. J., Hor, P. H., Meng, R. L., Chu, C. W., and Frankel, R. B. (1987). *Nature* **328**, 403.

Hundley, M. F., Zettl, A., Stacy, A., and Cohen, M. L. (1987). *Phys. Rev.* B **35**, 8800.

Jezowski, A., *et al.* (1987). *Phys. Lett.* A **122**, 431.

Junod, A., *et al.* (1987). *Jap. J. App. Phys.* **26–3**, 1119.

Kaiser, A. B. (1987). *In* 'Electronic Properties of Conjugated Polymers' (Eds H. Kuzmany *et al.*), p. 2 (Springer: Heidelberg).

Kaiser, A. B. (1988). Thermopower and the electron–phonon interaction in high-T_c superconductors. *Phys. Rev.* B **37**, 5924.

Kaiser, A. B., Christie, A. L., and Gallagher, B. L. (1986). *Aust. J. Phys.* **39**, 909.

Lang, M., *et al.* (1988). *Z. Phys.* B **69**, 459.

Leary, K. J., zur Loye, H.-C., Keller, S. W., Faltens, T. A., Ham, W. K., Michaels, J. N., and Stacy, A. M. (1987). *Phys. Rev. Lett.* **59**, 1236.

Lee, P. A., and Read, N. (1987). *Phys. Rev. Lett.* **58**, 2691.

Mawdsley, A., Trodahl, H. J., Tallon, J. L., Sarfati, J., and Kaiser, A. B. (1987). *Nature* **328**, 233.

Micnas, R., Ranninger, J., and Robaszkiewicz, S. (1987). *Phys. Rev.* B **36**, 4051.

Morelli, D. T., Heremans, J., and Swets, D. E. (1987). *Phys. Rev.* B **36**, 3917.

Nevitt, M. V., Crabtree, S. W., and Klippert, T. E. (1987). *Phys. Rev.* B **36**, 2397.

Oles, A. M., Zaanen, J., and Fulde, P. (1987). *Physica* B **148**, 260.

Ovadyahu, Z. (1986). *J. Phys.* C **19**, 5187.

Phillips, J. C. (1987). *Phys. Rev. Lett.* **59**, 1856.

Renker, B., Gompf, F., Gering, E., Nücker, N., Ewert, D., Reichhardt, W., and Rietschel, H. (1987). *Z. Phys.* B **67**, 15.

Suzuki, M., and Murakami, T. (1987). *Jap. J. Appl. Phys.* **26**, L524.

Tozer, S. W., Kleinsasser, A. W., Penney, T., Kaiser, D., and Holtzberg, F. (1987). *Phys. Rev. Lett.* **59**, 1768.

Uher, C., and Kaiser, A. B. (1987*a*). *Phys. Rev.* B **36**, 5680.

Uher, C., and Kaiser, A. B. (1987*b*). *Phys. Lett.* A **125**, 421.

Uher, C., and Kaiser, A. B. (1988). *Phys. Rev.* **37**, 127.
Uher, C., Kaiser, A. B., Gmelin, E., and Walz, L. (1987). *Phys. Rev.* B **36**, 5676.
Vasudeva Rao, V., Rangrajan, G., and Srinivasan, R. (1984). *J. Phys.* F **14**, 973.
Weber, W. (1987). *Phys. Rev. Lett.* **58**, 1371.
Yu, C. C., and Anderson, P. W. (1984). *Phys. Rev.* B **29**, 6165.
Ziman, J. M. (1960). 'Electrons and Phonons' (Oxford Univ. Press).

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