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LETTER TO THE EDITOR

Remarks on the normal-state resistivity of high-T_c superconductors

Gilson M Carneiro
Departamento de Física, Pontifícia Universidade Católica do Rio de Janeiro, CP 38071, 22453 Rio de Janeiro RJ, Brazil

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Abstract. The validity of semiclassical transport theory for two-dimensional Fermi and Bose conductors is analysed. It is pointed out that if the high-T_c materials are Bose conductors, this theory breaks down. It is also argued that the regime of 'resistivity saturation' in this case occurs at low temperatures with a resistivity that increases linearly with temperature.

One of the characteristic features of the new Cu oxide superconductors is the unusual temperature dependence of the normal-state resistivity ρ. Measurements show that ρ parallel to the ab-plane is nearly linear in T for $T > T_c$ [1–5].

Several theoretical explanations have been offered for this behaviour [6–11]. Common to all these proposals is the use of semiclassical transport theory which leads, essentially, to the Drude formula for ρ [12]:

$$\rho = m/ne^2\tau \tag{1}$$

where n is the carrier density, m its mass and τ the collision time. If one uses (1) to estimate τ, taking $\rho = \alpha T$, with $\alpha = 1\ \mu\Omega\ \mathrm{cm\ K^{-1}}$ [1], $m \simeq (1\text{–}5)m_e$ (m_e = electron mass and $n \simeq 3 \times 10^{21}\ \mathrm{cm^{-3}}$) one finds $\hbar/\tau \geqslant \kappa T$. Models that give $\hbar/\tau \propto \kappa T$ are: two-dimensional Fermi conductors, in which case the linear T-dependence comes from electron–phonon scattering [6–9] and from Umklapp electron–electron scattering [7, 10], and two-dimensional Bose conductors in which the charge-carrying quasiparticles are bosons. In this case $\hbar/\tau \propto \kappa T$ comes from boson–phonon scattering [11].

The conclusion that $\hbar/\tau \geqslant \kappa T$ suggests that in these systems the quasiparticles are not well defined excitations, in the sense that the linewidth $\Gamma \sim \hbar/\tau$ is greater than the excitation energy $\sim\kappa T$. One of the possible consequences of $\Gamma \geqslant \kappa T$ is that (1) may be invalid [12].

This problem was studied a long time ago in connection with the theory of normal metals. In this case $\Gamma \geqslant \kappa T$ occurs for $T \geqslant \Theta_D$ (Θ_D = Debye temperature) due to electron–phonon interactions. It was shown that (1) remains valid as long as $\Gamma < \varepsilon_F$, ε_F being the Fermi energy [13]. Introducing the electron mean free path $l = v_F\tau$, $v_F = \hbar k_F/m$ being the Fermi velocity and k_F being the Fermi wavevector, this condition may be written as $\Gamma \sim \hbar/\tau = \hbar v_F/l < v_F \sim \hbar v_F k_F$, or $l \geqslant k_F^{-1}$. This result was first obtained by Ioffe [14] and by Ioffe and Regel [15]. They pointed out that semiclassical transport theory must break down when the characteristic linear dimension of the wavepacket

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associated with the quasiparticle $\sim\lambda$ (λ = typical quasiparticle wavelength) exceeds l. Thus (1) remains valid as long as $l > \lambda$. In ordinary metals $\lambda \sim k_F^{-1} \sim a$, a being the interatomic distance, and $l > \lambda$ reads $l > a$.

The same condition, $l > \lambda$, must also dictate the region of applicability of (1) to Bose conductors. In the normal state, λ is the thermal De Broglie wavelength $\lambda_T = \sqrt{2m\kappa T/\hbar^2}$ and the particle characteristic velocity is $v_T = \sqrt{2\kappa T/m}$. Thus (1) is valid if $l = v_T\tau > \lambda_T$ or $\hbar/\tau < \kappa T$, a condition very different from that for ordinary conductors! If the Cu oxide superconductors are Bose conductors this restriction leads to a contradiction. As mentioned above, comparing ρ measured experimentally with (1) one finds $\hbar/\tau \geqslant \kappa T$ which in turn violates $l > \lambda$ rendering (1) invalid. This also suggests that scattering processes that give rise to $\hbar/\tau \propto \kappa T$ do not explain $\rho \propto T$, since, because $l > \lambda$ is violated, ρ is no longer proportional to $\hbar/\tau$.

The expression for ρ valid when $l < \lambda$ is not known. What is generally accepted is the Ioffe–Regel criterion [16]. It states that $l < \lambda$ is impossible. This means that as l decreases below λ, ρ no longer increases with l but assumes the value $\rho_{sat} \sim mv/ne^2\lambda$, obtained from (1) by setting $l = v\tau \sim \lambda$ (v = quasiparticle characteristic velocity). Experimental evidence for this type of behaviour is found in several metals [17, 18]. What is observed is that ρ for these systems stops increasing with rising temperature. This phenomenon, called 'resistivity saturation' [18], is interpreted as evidence that $l < \lambda$ in the temperature range where ρ no longer increases with T [17, 18].

This simple physical reasoning suggests that ρ can be written as

$$\rho = (m/ne^2\tau)f(\lambda/l) \tag{2}$$

where $f(x)$ is a well behaved function of x. For $\lambda/l \ll 1$, $f \rightarrow 1$, so (2) reduces to (1). For $\lambda/l \gg 1$ the Ioffe–Regel criterion gives $f \rightarrow \gamma l/\lambda$, γ being a constant ~ 1, so

$$\rho \rightarrow \rho_{sat} = \gamma(mv/ne^2\lambda). \tag{3}$$

For Fermi systems $v = v_F$, $\lambda \sim k_F^{-1} \sim a$ so $\rho_{sat} \sim \gamma m v_F/ne^2 a$. In metals where resistivity saturation is observed equation (3) correctly predicts the order of magnitude of the maximum ρ [19].

Application of these ideas to Bose conductors gives $\lambda/l \sim \lambda_T/v_T\tau \sim \hbar/\tau\kappa T$. Thus, according to (2),

$$\rho^B = (m/ne^2\tau)f(\hbar/\tau\kappa T). \tag{4}$$

For $\hbar/\tau\kappa T < 1$, ρ^B reduces to (1). For $\hbar/\tau\kappa T > 1$, $\rho^B \rightarrow \rho^B_{sat}$, where

$$\rho^B_{sat} = \gamma m v_T/ne^2\lambda_T = \gamma(m\kappa T/ne^2\hbar). \tag{5}$$

Thus, for Bose conductors in the regime $l < \lambda$, 'resistivity saturation' occurs not at a constant ρ but at ρ^B_{sat}, equation (5), which increases linearly with T.

If the Cu oxide superconductors are two-dimensional Bose conductors, then, due to boson–phonon scattering [11], $\hbar/\tau = \Lambda\kappa T$ (Λ is a constant that depends on the strength of the boson–phonon interaction). Thus, for $\Lambda > 1$, ρ is given by (5). Substituting in this equation the values appropriate for the oxide superconductors, $n = 3 \times 10^{21}$ cm^{-3}, $m \sim 5m_e$, and assuming $\gamma \sim 1$ one finds $\rho^B_{sat} = \alpha T$ with $\alpha \sim 1$ $\mu\Omega$ cm K^{-1}. This ρ^B_{sat} is of the same order of magnitude as ρ in these materials and has the same temperature dependence.

In the RVB theory [20] $\hbar/\tau$ has an additional contribution from holon–spinon scattering that varies as $T^{3/2}$ [21]. Whether or not this is the most important contribution depends on the relative strengths of the holon–phonon and holon–spinon contributions. In any case, as long as $\hbar/\tau > 1$, the above conclusion holds true.

In conclusion then, the simple physical arguments given above suggest that if the normal state of Cu oxide superconductors is a two-dimensional Bose conductor, the linear temperature dependence of ρ arises from resistivity saturation, rather than from an intrinsic scattering mechanism.

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