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19. Treating z_0 as a free parameter but neglecting the finite width of the wires of the pickup loop (0.8 μm), the field expelled by the shielded leads, and the angle between the loop and the surface (~20°), it is possible to describe the amplitude and shape of monopole (point-like) sources of magnetic flux to within 10%.
20. The Tl-2201 single crystals were grown from a flux in an alumina crucible with an alumina lid that was sealed to avoid loss of thallium oxide. Tl_2O_3, BaO_2, and CuO powders were mixed at the atomic ratio of Tl:Ba:Cu = 2.2:2:2 using excess Tl_2O_3 and CuO as the flux. The crucibles, containing ~50 g of charge, were loaded in a vertical tube furnace and heated rapidly to 925° to 950°C. This temperature was held for 30 min. The furnace was then cooled at about 5°C/hour to 875°C, and finally furnace-cooled to room temperature. The crystals were annealed for 3 days in flowing, gettered, high-purity argon at 400°C to remove any interstitial oxygen so as to obtain a high transition temperature. The ac faces were polished to optical flatness before imaging. The superconducting transition temperature was measured by ac susceptibility (ac applied field, 1 G) before polishing and magnetic imaging, and by dc field–cooled susceptibility (dc applied field, 1 G + Earth's field) after other measurements were complete. The transition temperatures and widths were T_c = 79 K, ΔT_c = 10 K (crystal 1, before), T_c = 74 K, ΔT_c = 11 K (crystal 1, after), T_c = 79 K, ΔT_c = 8 K (crystal 2, before), and T_c = 77 K, ΔT_c = 9 K (crystal 2, after).
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c-Axis Electrodynamics as Evidence for the Interlayer Theory of High-Temperature Superconductivity

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In the interlayer theory of high-temperature superconductivity, the interlayer pair tunneling energy (similar to the Josephson or Lawrence-Doniach energy) is the motivation for superconductivity. This connection requires two experimentally verifiable identities: the coherent normal-state conductance must be smaller than the "Josephson" coupling energy, and the Josephson coupling energy must be equal to the condensation energy of the superconductor. The first condition is well satisfied in the only case that is relevant, $(La,Sr)_2CuO_4$, but the second condition has been questioned. It is satisfied for all dopings in $(La,Sr)_2CuO_4$ and also in optimally doped $Hg(Ba)_2CuO_5$, which was measured recently, but seems to be strongly violated in measurements on single crystals of $Tl_2Ba_2CuO_6$.

The theory that ascribes the phenomenon of high–transition temperature (T_c) superconductivity in the cuprates primarily to interlayer coupling (*1*) correlates electromagnetic coupling along the *c* axis (that is, perpendicular to the CuO_2 planes) with the condensation energy of the superconductor. This correlation, which should be particularly sharp for "one-layer" materials, was proposed and roughly tested against data on $(La,Sr)_2CuO_4$ ("214") (*2*), and the equations were refined by van der Marel *et al.* (*3*) and Leggett (*4*). In these latter papers, the apparent failure of the relation in $Tl_2Ba_2CuO_6$ ("Tl 2201") was emphasized, and rather unequivocal measurements of the *c*-axis penetration depth λ_c (*5*) confirm this contradiction. However, there is quite good agreement in a growing number of other cases: 214 at several different doping levels (*6*) and $HgCa_2CuO_4$ (Hg "1201" cuprate) (*7*). It appears then, that the Tl salt is the "odd man out" or perhaps is not a true one-layer case; this compound exhibits wide swings in T_c with preparation treatment. Because both the Tl and Hg salts have relatively large *c*-axis spacings and comparable values of T_c $\approx$ 90 K, the contradiction between the two is particularly striking, and it is important to confirm the measurements of (*7*), preferably by another experimental method.

Additional evidence for a major role for interlayer coupling is the observation of a strong bilayer correlation in neutron scattering in yttrium barium copper oxide (YBCO) both in the superconducting state (for optimal doping) (*8*) and in the spin-gap regime (*9*), which is not explicable in one-layer theories but is predicted by the interlayer theory (*10*). Thus, Tl 2201 stands out in providing contravening evidence against the theory of (*1*).

The interlayer theory is simple in principle. For the cuprates, electron motion in the *c* direction is incoherent in the normal state. This anisotropy is unlike most normal metals, which are Fermi liquids and exhibit coherent transport in all directions. The interlayer hypothesis is that electron pairing in the superconducting state makes this transport coherent, which is actually observed and is responsible for the Josephson-like or Lawrence-Doniach–like superconducting coupling between the layers. In conventional superconductors, the Lawrence-Doniach coupling replaces coherent transport in the normal state, so that the superconductor gains no relative energy, but in the cuprates, experimental observations exclude coherent transport in the normal state, so that the *c*-axis energy is available as a pairing mechanism. [In my theory (*1*), the mechanism blocking coherent transport is the non–Fermi liquid nature of the normal metal state.] Thus, superconductivity occurs in connection with a crossover from two-dimensional to three-dimensional transport; if one desires a "quantum critical point" to be associated with high T_c, that is its nature.

There are then two independent ways of measuring the energy that couples the planes together in the superconductor, each direct. The first method is, in analogy with the Josephson energy-current relation, to measure the electromagnetic response to vector

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potentials along the c axis, either by measuring the c-axis penetration depth or the c-axis transverse plasma frequency. Because of the correlation referred to above, this plasmon in the cuprates lies, unusually, within the superconducting gap and is visible as a sharp edge in the reflectivity followed by a dip.

The second measurement is of the condensation energy of the superconductor. I postulate that this energy is wholly, or almost wholly, due to the c-axis coupling—so that it should be equal numerically to the maximum possible value of electromagnetic coupling—when all layers are equivalently coupled, that is, in one-layer superconductors. This is equivalent to the statement that the c-axis correlation length $\xi_c \approx c/2$, which is the maximum possible value for ξ_c or the minimum for λ_c for multilayer systems such as YBCO or $Bi_2Sr_2CaCu_2O_8$ (BISCO 2212) (2). The condensation energy can be estimated from T_c or the band-gap energy Δ, using Bardeen-Cooper-Schrieffer (BCS) expressions, but because I am arguing that BCS theory does not use the correct form of interaction, it can give no better than an order of magnitude estimate; it is far better to use specific-heat data when available. In particular, the dependence of the condensation energy on doping, according to such data, is steeper than that of T_c^2, so that for underdoped materials one must be especially careful. Roughly, T_c is proportional to the doping percentage x, and $E_{cond} \propto x^p$, with p previously estimated as ~3 to 4. The theory of Lee and Wen (*11*) gives $p = 3$, but this value has been seriously questioned (*12*); specific-heat data are therefore more convincing, if hard to interpret quantitatively (*13*). The sharp dependence of λ_{ab} on x predicted by Lee and Wen (*11*) was observed in 214 (*13*), contrary to the criticisms (*12*), which used figures from YBCO where the effects of doping are less straightforward. Such data show that the condensation energy falls off with x more rapidly than T_c^2.

The basic formulas are as follows: First, for the electromagnetic theory of an interlayer superconductor, the basic London equation for current **j** is

$$\mathbf{j} = \frac{1}{\lambda^2}\frac{c}{4\pi}\mathbf{A} \qquad (1)$$

where c is the speed of light and **A** is the vector potential. This relation defines the penetration depth λ. Focusing on $T \ll T_c$ and ignoring the difference between free energy F and energy E

$$\mathbf{j} = c\frac{\partial F}{\partial A} \approx c\frac{\partial E}{\partial A} \qquad (2)$$

The pairing energy in the interlayer theory comes entirely from the coupling between planes, so that one can take E to be the condensation energy E_b and assume the coupling energy has the Josephson form

$$E_b = -E_b^{\circ} \cos\theta \qquad (3)$$

where θ is the phase difference between the pairs of planes. In the presence of a vector potential

$$\nabla\theta = \frac{2e}{\hbar c}A \qquad \theta = \frac{2ed}{\hbar c}A \qquad (4)$$

where d is the spacing between layers, e is the charge of an electron, and $\hbar$ is Planck's constant divided by 2π. Combining Eqs. 2, 3, and 4

$$j = 4cE_b^{\circ}\left(\frac{ed}{\hbar c}\right)^2 A \text{ and } \lambda_c = \frac{\hbar c}{2ed}\frac{1}{\sqrt{4\pi E_b^{\circ}}} \qquad (5)$$

A nearly equivalent measure of the electromagnetic coupling is the c-axis plasma frequency ω_p. The dielectric constant ε is given in terms of the δ-function "Drude weight"

$$\omega_p^2 = \frac{c^2}{\lambda^2} \qquad (6)$$

by

$$\varepsilon = -\frac{\omega_p^2}{\omega^2} + \varepsilon_0 \qquad (7)$$

and the edge occurs where ε changes sign, at

$$\hbar\omega_p^c = \frac{\hbar c}{\sqrt{\varepsilon_0}\lambda} = \sqrt{\frac{4\pi E_b^{\circ}}{\varepsilon_0}} \times 2ed \qquad (8)$$

In the cases of 214 (Fig. 1), $\sqrt{\varepsilon_0} \approx 5 \pm 1$ can actually be measured from the normal-state reflectivity, because no appreciable Drude weight appears in the normal state. In the cases of Tl and Hg one-layers, ε_0 is not well measured; however, λ has no dependence on ε_0 and is the measured quantity in both cases.

The thermodynamics of optimally doped YBCO has been thoroughly studied by Loram *et al.* (*14*) and their estimate for the condensation energy per unit volume is

$$E_b^{\circ}(\text{YBCO}) = 3.5 \times 10^6 \text{ erg/cm}^3 \qquad (9)$$

[Per unit cell per layer, this is about 3 K, which is not far from the BCS estimate of $N(O)(kT_c)^2/2$, taking the density of states $N(O)$ to be ~2 to 3 eV^{-1} and where k is the Boltzmann constant.]

The binding energy for 214 must be estimated from the curves of Loram and colleagues (*13, 14*) (Fig. 2), which also, fortunately, shows several doping levels. For the optimal doping level, 17 to 20%, E_b can be estimated with the identities

$$\int(c_N - c_s)dT = E_b = \int T\Delta\gamma(T)dT \qquad (10)$$

$$\int(c_N - c_s)dT/T = 0 = \int\Delta\gamma(T)dT \qquad (11)$$

where $\gamma = c/T$ (Fig. 2), and c_N is the normal and c_s the superconducting specific heat. The total binding energy is considerably smaller than that of YBCO, roughly

$$E_b^{\circ} \approx 220 \pm 50 \text{ mJ/gm·atom} \qquad (12)$$
$$= (1.7 \pm 0.4) \times 10^5 \text{ erg/cm}^3$$

Interestingly, this value is below (by a factor of 2) what I would predict from scaling from YBCO by T_c^2, perhaps partly because of a contribution from the chains. With less accuracy because of the critical fluctuation ef-

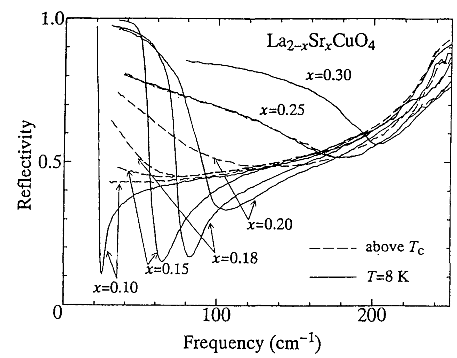

Fig. 1. Reflectivity measurements for $La_{2-x}Sr_xCuO_4$ from (*6*).

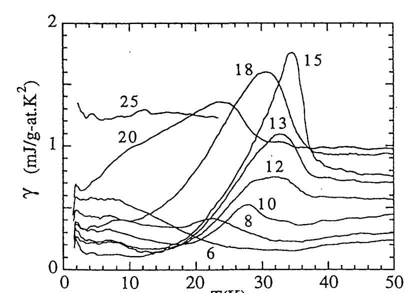

Fig. 2. Specific heat ($\gamma = c/T$) of 214 samples. The curves are labeled with the doping percentage x.

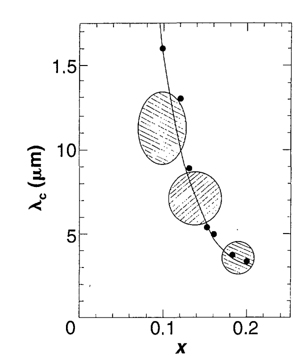

Fig. 3. Comparison of (points) the measured values of λ_c from (*6*) (as calculated from Fig. 1 with the use of Eq. 9) and (hatched ovals) the result of the interlayer theory (Eq. 6), including rough estimates of limits of error.

fects on c_s for low doping, I can also estimate E_b for the doping levels 13.5% and 10%.

Using the value from (*13*), I obtain $\lambda_c = 3 \pm 1$ μm for optimal doping, which is embarrassingly close. The agreement between the measured and estimated values of λ_c (Fig. 3) both as to numerical value and trend is heartening. For 214, driving a critical Josephson current is precisely sufficient to erase the energy of the superconducting correlation. Undoubtedly, it is possible to invent a system of carefully balanced cancellations that would nonetheless ascribe the source of superconductivity to internal correlations in the planes, but such logical contortions seem improbable and may even be impossible. There is no plausible intraplanar mechanism that would correlate its T_c and its energy precisely with the strength of interplanar coupling over a range of 5 to 1 in λ.

The case of Hg 1201 is much less airtight but still strong. Without satisfactory specific heat measurements, we are reduced to scaling the binding energy according to T_c^2, and hence, λ_c according to T_c. I predict, then, for Hg 1201

$$\lambda_c = 3\ \mu m \times \frac{40}{90} \times \frac{d_{214}}{d_{Hg}} = 1.0 \pm 0.5\ \mu m \qquad (13)$$

The observed value (*7*) is quoted as 1.34 μm ± ~10%. The agreement is spectacular.

The prediction for Tl 1201, on the same basis, would give $\lambda_c \approx 0.8$ μm, because *d* is even greater than that for Hg, but Moler *et al.* (*5*) find that $\lambda_c > 15$ mm for the single crystals for which they have imaged vortices, and this figure is in agreement with estimates by van der Marel (*3*) (and with my own estimates using transport theory). This agreement is a severe anomaly. The above direct evidence for interplanar coupling in the other cases is supplemented by the neutron scattering evidence in YBCO, which shows that the gap structure is strongly correlated between planes in the close pair in just such a way as to optimize interplanar kinetic energy (*10*). I cannot emphasize too strongly the need to assure ourselves that Tl 1201 is genuinely a one-layer case. Some evidence for structural defects exists.

The interlayer hypothesis for the high-T_c cuprates was based from the start on an experimental observation: that conductivity along the *c* axis is nonmetallic and incoherent, whereas that in the *ab* plane is metallic, if in many respects anomalous. This behavior is presumed to be a result of a non-Fermi–liquid, charge-spin–separated state; but the hypothesis can be directly tested in a manner completely independent of that conjecture. There are two experimentally testable consequences of the idea, if one is able to measure the *c*-axis electrodynamics in the superconducting state, as has been done in a number of cases. The first is violation of the "Josephson identity", which expresses the fact that in BCS superconductors, pair tunneling replaces the coherent normal-state conduction. This violation has been noted previously by Timusk (*15*). The second is the requirement that the supercurrent kernel $c/4\pi^2\lambda^2$ almost precisely match the condensation energy of the superconductors. This agreement effectively rules out any intralayer theory of high T_c and points to the interlayer concept, for those cases in which it occurs; but we are left at a loss in the one clear case where it does not.

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Communication with Chaotic Lasers

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Recent experiments with chaotic electronic circuits have shown the possibility of communication with chaos. The experimental demonstration of chaotic communication with an optical system is described. An erbium-doped fiber ring laser (EDFRL) was used to produce chaotic light with a wavelength of 1.53 micrometers. A small 10-megahertz message was embedded in the larger chaotic carrier and transmitted to a receiver system where the message was recovered from the chaos. Chaotic optical waveforms can thus be used to communicate masked information at high bandwidths.

The demonstration of transmission and reception of information with synchronized electronic circuits (*1*) raised the question of optical communication with chaotic lasers. Communication with light waves with chaotic fluctuations of intensity has been considered in recent years by several investigators (*2*). The natural masking of information by chaotic fluctuations has served as a practical motivation for the research. Great interest also exists in understanding the basic mechanisms by which information can be encoded and decoded through the use of synchronized chaotic systems.

Although chaotic communication experiments with electronic circuits (*1*) have typically demonstrated information transmission at bandwidths of tens of kilohertz or less, the fast dynamics often displayed by optical systems offers the possibility of communication at bandwidths of hundreds of megahertz or higher. In the past few years, we have explored the fast dynamics of erbium-doped fiber ring lasers (EDFRLs) (*3*) with the goal of achieving optical communication with chaotic lasers. These lasers are particularly well suited for communication purposes because their lasing wavelengths roughly correspond to the minimum-loss wavelength in optical fiber. Such fiber ring lasers are capable of displaying both low- (≤3) and high-dimensional (>3) dynamics under different conditions of operation. We report optical experiments that demonstrate message transmission and reception at 10 MHz with a chaotic carrier at ~1.53 μm.

The output beam from an external cavity, tunable semiconductor laser is amplitude modulated with a 10-MHz square wave (the "message") by a lithium niobate Mach-Zehnder modulator (Fig. 1). The message is

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