Superconductivity theories narrow down

While the explanation of ceramic superconductivity remains elusive, new data serve to eliminate conventional strong coupling between electron pairs and phonons.

THE discovery[1] of superconductivity in Cu–O perovskite-type materials with transition temperatures from 30 to 100 K has raised the question of the dynamical mechanism responsible. Superconductivity in metallic systems has hitherto invariably been caused by an attractive interaction, mediated by the exchange of lattice vibrational excitations (phonons), between electrons forming coherent pairs in the superconducting state[2].

That phonons are essential for the understanding of conventional superconductivity was clear in 1950, with the discovery of the 'isotope effect'[3,4]. The substitution of a different isotope for the positive ions in a metal was found to change the transition temperature by about one-half the percentage change of mass. The isotope effect was accounted for quantitatively in 1957, when the interaction in the fundamental BCS theory[2] of superconductivity was interpreted as arising from the phonon mechanism.

A recent experiment by Batlogg *et al.*[5] at AT&T Bell Laboratories now seems effectively to have eliminated the phonon mechanism in the high-T_c (90 K) superconductors $YBa_2Cu_3O_7$ and $EuBa_2Cu_3O_7$. By replacing 75% of the usual ^{16}O isotope by ^{18}O, they have found the Cu-O stretching frequency to change by the expected 4%, but the change in T_c is less than 0.25% — only about 0.3% of T_c. Although the isotope effect can exceptionally be less than the effect on phonon frequencies, it is unthinkable that the isotope effect can be 5% of that expected if the superconductivity is driven by phonon exchange.

As Sir Nevill Mott recently pointed out[6], there are almost as many theories of these superconductors as theorists. This result will eliminate many, but otherwise is not unexpected[7-10]. When transition temperatures above 15 K were first found, people asked whether the phonon mechanism could produce still higher T_cs and concluded[11-14] that values 30 K were not to be expected. Such arguments have recently been applied[8,9] to the newer materials: a generous estimate gives an upper limit of 40 K.

At least two experimental results had already indicated that conventional phonon pairing could not be responsible. Neutron diffraction measurements[15-18] in La_2CuO_4, which is antiferromagnetic but not superconducting, show atomic moments on Cu sites of almost 0.5 Bohr magneton. Magnetism in the *d*-transition series to which Cu belongs is invariably a result of strong interelectronic repulsive forces[19] — especially in insulating transition metal-oxides such as La_2CuO_4. Yet the material becomes superconducting when 10% of the La is replaced by, for example, Sr.

Unless there is a complete change in the fundamental electronic structure between the crystallographically identical La_2CuO_4 and $La_{1.8}Sr_{0.2}CuO_4$, no theory based simply on attractive forces between opposite-spin electrons is likely to be correct. So strong-coupling phonon mechanisms as in conventional BCS theory, as well as the single-site bipolaron mechanism[6] and other proposals which are conventional BCS theories with unconventional pairing are eliminated. But bipolaron mechanisms, whether single-site or not, driven as they are by electron–phonon coupling, are also now effectively eliminated by the absence of the isotope effect.

We argue that the antiferromagnetism of the parent compound indicates strong short-range interelectronic repulsion which must be taken into account when constructing a pairing theory for these superconductors. This force occurs in the heavy-fermion compounds which exhibit superconductivity and antiferromagnetism (at low temperatures). There, the pairing appears to be driven solely by electron–electron interaction and the effect of repulsion is to make the pairing anisotropic, an effect expected in single crystals of the new materials. In this framework, exchange mechanisms consistent with the repulsion, such as antiferromagnetic spin fluctuations[10] or localized charge transfer excitations[7], are not excluded. Nor is the resonating valence bond (RVB) theory[6], based entirely on short-range electron–electron repulsion.

The other set of data arguing against strong phonon coupling are those of Fleming *et al.*[20] and a number of other groups[21] on the high-temperature (300–500 K) crystallographic (tetragonal to orthorhombic) transition in the lanthanum compounds. Because the Fermi surface of these materials must surely 'nest'[22] very effectively, one would expect that, if there is strong electron–phonon coupling, the crystallographic transition would be accompanied by the appearance of an electronic charge density wave. But the crystallographic distortion that does occur has no effect whatever on the Fermi surface and appears to be almost irrelevant to the electronic structure. A mysterious force (the Princeton group actually feels it is not so mysterious[23]) prevents what electron–phonon coupling is present from being very effective.

Some experiments have not received the ballyhoo which seems now to accompany new results in this field — the observation of finite and rather large specific heats at low temperatures, suggestive of those of metals[24-28]. All the new materials studied so far, including the parent non-metallic La_2CuO_4, have this property. The oldest result of the quantum theory of metals is that the specific heat is given by γT, in which γ is the density of electron states near the Fermi surface. In superconductors, γ is characteristically absent because of the well-known BCS energy gap[2]; it is also very small, if not zero, in all insulators, again because an energy gap causes the absence of electron states at low excitation energy. But insulating La_2CuO_4, superconducting $(La,Sr)_2CuO_4$ and superconducting $YBa_2Cu_3O_7$ all have specific heats which are linearly dependent on temperature and which are greater than the equivalent molar amount of copper metal[19].

This linear behaviour in the superconducting samples, but not its magnitude, could be explained if the materials were 'gapless', but there is no other evidence of this. It is hard to avoid the conclusion that this pervasive behaviour of the specific heat is related to the superconductivity. This seems to eliminate most conventional theories and some unconventional versions of BCS. The linear behaviour is, on the other hand, predicted by the RVB theory of Anderson and collaborators[7] and this observation gives their ideas support.

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1. Bednorz, J.G. & Muller, K.A. *Z. Phys.* **B84**, 189 (1986).
2. Bardeen, J., Cooper, L.N. & Scrieffer, J.R. *Phys. Rev.* **108**, 1175 (1957).
3. Maxwell, E. *Phys. Rev.* **78**, 477 (1950).
4. Reynolds, C., Serin, B., Wright, W. & Nesbitt, L. *Phys. Rev.* **78**, 487 (1950).
5. Batlogg, B. *et al. Phys. Rev. Lett.* (in the press).
6. Mott, N.F. *Nature* **327**, 185 (1987).
7. Anderson, P.W. *Science* **235**, 1196 (1987).
8. Varma, C.M., Schmitt-Rink, S. & Abrahams, E. *Solid State Commun.* (in the press).
9. Ruvalds, J. preprint, Harvard Univ.
10. Lee, P.A. & Read, N. preprint, MIT.
11. McMillan, W.L. *Phys. Rev.* **167**, 3311 (1968).
12. Cohen, M.L. & Anderson, P.W. in *Superconductivity in d-and f-band Metals* (AIP, New York, 1972).
13. Allen, P.B. & Dynes, R.C. *Phys. Rev.* **B12**, 905 (1975).
14. Varma, C.M. in *Superconductivity in d- and f-band Metals* (Kernforschungzentrum, Karlsruhe, 1982).
15. Vaknin, D. *et al.*, preprint, Exxon.
16. Frelhoft, T. *et al.* Brookhaven, AT&T Bell, Exxon & Pennsylvania Univ. preprint.
17. Mitsuda, S. *et al.* Tokyo, Brookhaven & Exxon preprint.
18. Johnston, D.C. *et al.* Exxon preprint.
19. Anderson, P.W. *Solid State Physics*, vol. 14, Seitz-Turnbull, eds. **14**, 99 (Academic, New York, 1983).
20. Fleming, R.J. *et al. Phys. Rev.* **B35**, 7191 (1987).
21. Paul, D.McK. *et al. Phys. Rev. Lett.* **58**, 1976 (1987).
22. Mattheiss, L.F. *Phys. Rev. Lett.* **B58**, 1028 (1987).
23. Anderson, P.W., Baskaran, G., Zou, Z. & Hsu, T. *Phys. Rev. Lett.* (in the press).
24. Zirngiebl, E. *et al.* preprint, Los Alamos.
25. Reeves, M.E. *et al. Phys. Rev.* **B35**, 7207 (1987).
26. Phillips, N.E., personal communication.
27. Crow, J.E. (Temple), personal communication.
28. Ott, H.R. (ETH-Zurich), personal communication.