The discovery of charge-density-wave order in the high-temperature superconductor YBa$_2$Cu$_3$O$_{6+x}$ places charge order centre stage with superconductivity, suggesting that they are intertwined rather than competing.

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Ineluctable complexity

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electronic order, including charge- and spin-density-wave orders and nematic charge order, has (mostly) been dismissed as being an uninteresting sideshow, a material-dependent complication or even a disease. However, in recent years increasingly extensive but largely indirect experimental evidence that these other types of order are ubiquitous in HTSC materials has led to a slowly spreading realization that they may have to be included in the ‘irreducible minimum’ to understand HTSC. The direct observation — by X-ray diffraction — of an incipient charge density wave (CDW) in high-quality (ortho-VII) crystals of YBa$_2$Cu$_3$O$_{6.9}$ (YBCO) has now been independently reported by Johan Chang et al. in Nature Physics and Giacomo Ghirrighelli et al. in Science. This is an important discovery, with the broad implication that other forms of charge order are intricately intertwined with HTSC.

YBCO is the most studied HTSC compound. It is a quasi-two-dimensional material, as all the superconducting copper oxides are, in which the mobile electrons are largely confined to move in layers made of copper and oxygen, forming a liquid of strongly correlated degrees of freedom carrying charge and spin quantum numbers. A schematic phase diagram of YBCO as a function of the temperature $T$ and the doping level $y$ (that parameterizes the oxygen content of its chemical composition) is shown in Fig. 1. Near $y = 0$, and below the (Néel) temperature $T_N \sim 400$ K, YBCO is an antiferromagnet and an electrical (Mott) insulator. As $y$ increases, a superconducting phase with the shape of a rather distorted dome (red curve) is found, which has its maximum at the value of $T_c \sim 90$ K at the optimal doping level of $y = 0.93$. For doping levels $y < 0.93$, the material is considered ‘underdoped’. At temperatures well above the maximum $T_c$ is a strange or ‘bad metal’ regime with many anomalous properties that are strikingly different from those of familiar ‘good’ metals. One of the most mysterious regions of the phase diagram is referred to as the ‘pseudogap regime’, which lies below a not very sharply defined crossover temperature $T^*$, marking the boundary between the ‘bad metal’ and an even more anomalous regime.

What Chang and co-workers discovered were pronounced peaks in the X-ray structure factor corresponding to substantially correlated CDW fluctuations that emerge below a temperature, $T_{CDW} \approx 140$ K, which is lower than, but of order $T^* \approx 250$ K, at the same level of doping. YBCO has a crystal structure consisting of stacked Cu–O bilayers, and

length of the peak in the structure factor when $T < T_c$. Presumably, this enhanced CDW order is an indirect consequence of the field-induced suppression of the superconducting order.

Fluctuating and static charge- and spin-density-wave (SDW) orders (in the form of stripes) have been seen in La$_{2−x}$Sr$_x$CuO$_4$ and La$_{2−x}$Ba$_x$CuO$_4$, but were regarded as special to the lanthanum ‘214’ family. Moreover, charge nematic order — a melted CDW/SDW state with broken rotational invariance — has been seen in neutron scattering in highly underdoped YBCO (with $y = 0.45$) and also in Nernst-effect experiments above the superconducting dome throughout much of the pseudogap regime. The case of La$_{2−x}$Ba$_x$CuO$_4$ is particularly significant as it has a pronounced suppression of $T_c$ near $x = 1/8$ where static CDW and SDW (stripe) phases are seen, as well as a state above $T^*$ in which the Cu–O layers are superconducting and effectively decoupled. More directly relevant to the findings of Chang et al. (and to those of refs 3,4) is the comparison with the other evidence for charge order in YBCO. Exquisitely detailed quantum-oscillation experiments in magnetic fields larger than 30 T (sufficient to suppress superconductivity in YBCO) provided evidence that the competing state is a density wave. Subsequent NMR experiments in magnetic fields in the range 15–35 T have shown that a sharp thermodynamic phase transition occurs at the onset of the CDW phase (although the ordering wave vector does not seem to agree with the X-ray results). Recent ultrasound experiments have found a thermodynamic transition at $T^*$ and a peak in the attenuation rate at $T_{CDW}$. Finally, possible evidence of time-reversal symmetry-breaking has been reported in YBCO with the Kerr effect and in neutron scattering.

Clear evidence of incipient CDW order in YBCO is an important advance in the field. As the ‘cleanest’ of the cuprate materials, any ordering tendencies observed in YBCO are probably intrinsic. Nonetheless, the results raise many questions. Is the incipient CDW order in YBCO a material-specific property of this family of cuprates in a narrow range of doping, or is it more ubiquitous? Is it a close relative of the fully formed CDW
order seen in the same materials (by NMR) at higher fields and low temperatures? Is it closely related to the well-developed stripe order seen in the lanthanum ‘214’ family and/or the short-range CDW correlations seen on the surface of BSCCO? On a more basic level, is the incipient CDW order always correlated with pseudogap formation? Is local CDW ordering the cause of the pseudogap or a derivative phenomenon that can, at times, arise once the essential pseudogap correlations have developed? Is there more to the interplay between CDW order and HTSC than just competition?

Although there is no direct X-ray evidence of any unidirectional (stripe) character of the incipient CDW order in YBCO, the fact that it occurs in a similar location in the phase diagram and has such similar energy and temperature scales, suggests a single, unifying physical significance of the CDW tendencies in YBCO and other cuprates. In particular, the comparable magnitudes of the temperatures of the observed phases (other than antiferromagnetism) suggest that all these orders arise together from one ‘parent’ state and that the various order parameters are ‘intertwined’ rather than simply competing with each other. HTSC in the cuprates occurs on doping an insulating antiferromagnet. In the process of adding delocalized charge carriers to such a strongly correlated insulating state there is an inherent tendency of the charge degrees of freedom (holes in this case) to undergo electronic phase separation\(^\text{18}\). The combined effects of the long-range repulsive (Coulomb) interactions and the electronic zero-point (quantum) kinetic energy compete with this tendency, leading to complex phase diagrams involving several generally inhomogeneous and anisotropic states\(^\text{19}\).

From this perspective, a dynamically fluctuating, mesoscopically inhomogeneous mixture of antiferromagnetic and conducting (delocalized) regions may play the role of the ‘parent’ state out of which the many phases, including HTSC, emerge.

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References
1. Bednorz, J. G. & Müller, K. A. Z. Phys. B 64, 189–193 (1986).
2. Chang, J. et al. Nature Phys. 8, 871–876 (2012).
3. Ghiringhelli, G. et al. Science 337, 821–825 (2012).
4. Kivelson, S. A. et al. Rev. Mod. Phys. 75, 1201–1241 (2003).
5. Tranquada, J. M. in Handbook of High-Temperature Superconductivity (eds Schrieffer, J. R. & Brooks, J.) Ch. 6 (Springer, 2007).
6. HÜcker, M. et al. Phys. Rev. B 83, 104506 (2011).
7. Hinkov, V. et al. Science 319, 597–600 (2008).
8. Daua, R. et al. Nature 463, 519–522 (2010).
9. Li, Q. et al. Phys. Rev. Lett. 99, 067001 (2007).
10. Berg, E. et al. New J. Phys. 11, 115004 (2009).
11. Lawler, M. J. et al. Nature 466, 347–351 (2010).
12. Parker, C. V. et al. Nature 466, 677–680 (2010).
13. Doiron-Leyraud, N. et al. Nature 447, 565–568 (2007).
14. Wu, T. et al. Nature 477, 191–194 (2011).
15. Shekhter, A. et al. Preprint available at http://arxiv.org/abs/1208.5810 (2012).
16. Xia, J. et al. Phys. Rev. Lett. 100, 127002 (2008).
17. Fauqué, B. et al. Phys. Rev. Lett. 96, 197001 (2006).
18. Emery, V. J. & Kivelson, S. A. Physica C 209, 597–621 (1993).
19. Kivelson, S. A., Fradkin, E. & Emery, V. J. Nature 393, 550–553 (1998).