

COPPER-OXIDE SUPERCONDUCTIVITY

The mystery and the mystique

'Mottness' or a reconstructed Fermi surface? Nodes and arcs, or pockets? Both approaches to the pseudogap state of cuprate superconductors receive some support from specific heat data obtained up to 45 T. Can the two be reconciled?

Zlatko Tesanovic

The recent discovery of high-temperature superconductivity (HTS) in iron-based compounds set off a stampede of worldwide activity, as seemingly everyone who ever held Tinkham's *Introduction to Superconductivity*, and then some, rushed to join in the festivities. For those old enough to remember, 2008 brought memories of the original — and still unsurpassed — 'Woodstock' era of physics, when HTS meant one and only one thing: the cuprates.

Speaking of which, as iron HTS was in the midst of its 'Sturm und Drang' period, the cuprates — now settled into a more mature and introspective mode — were undergoing a quiet revolution themselves. Observations of quantum oscillations in the high-field magnetization of underdoped YBCO crystals^{1,2} — within the so-called pseudogap state — reoriented the focus of the field. It is reasonable to assume that refs 1 and 2 attest to the presence of a Fermi surface, apparently multiply connected, containing electron- and hole-like pockets, all much smaller than the Fermi surface inferred from band-structure calculations. In turn, this is suggestive of a Fermi-surface reconstruction occasioned by an underlying density-wave order of some kind³. This perspective calls into question the need for the correlated electron exotica hurled at the cuprates in their headiest days.

Since its inception, the field of cuprate HTS has been a battleground — an appropriate metaphor, incidentally — between two important paradigms. At the risk of oversimplification, one offered hope that the cuprates can be understood along the logical lines that triumphed in ³He: a correlated normal state, atop of which rises HTS, by means of a *d*-wave BCS-like instability driven by antiferromagnetic spin fluctuations⁴. The other called for change: cuprate HTS is something entirely new, a manifestation of strong electron correlations, or 'Mottness' — the most famous illustration being the resonating valence bond state⁵. Over the years, as experiments came and

went and casualties fell on both sides, the rival armies congregated on the pseudogap region as the most mysterious in the phase diagram. Is the pseudogap another form of order, or near-order, and a density-wave competitor^{3,6–8} of superconductivity? Or is the pseudogap a remnant of superconductivity, with robust *d*-wave Cooper pairs — phase incoherent and lacking long-range order — still around, the product not of attraction but of their aptitude for benefitting from kinetic energy while simultaneously reducing the strong Mott repulsion that rules the underdoped regime^{9–11}? Quantum oscillations^{1,2} tipped the balance to the former while flagging the latter for 'unnecessary Mottness'.

Enter Riggs *et al.*¹². They report specific heat data on those same high-quality YBCO crystals¹ measured over a wide window of magnetic fields, from zero all the way to 45 T, a range that just a few short years ago seemed beyond reach. The results are remarkable: first, there are quantum oscillations, above 28 T or so, in agreement with the magnetization^{1,2}. Good; the specific heat is pure thermodynamics and therefore the quantum oscillations are real and part of the full picture.

However, there is more to the data of Riggs *et al.* The oscillations ride on a \sqrt{H} background specific heat, which, as $T \rightarrow 0$, is frozen into place from the lowest to the highest fields. At low H , deep in the superconducting state, the \sqrt{H} behaviour is commonly attributed to the presence of nodes in the *d*-wave gap function Δ_d . But, as H increases, the \sqrt{H} background sails right through $H_{irr} \sim 23$ T, paying no heed whatsoever to the superconducting transition. Now, the natural interpretation of this behaviour is a quantum vortex 'solid-to-liquid' transition, yielding a resistive state far below some 'mean-field' critical field $H_{c2}(0)$ (ref. 10). Throughout, the large pairing *d*-wave (pseudo)gap Δ_d seems unaffected. This squarely points back to the Mott camp, as strong correlations are the only way of maintaining large Δ_d in a state lacking superconducting order⁹.

But wait, there is more: Riggs and co-workers also extract the absolute value for the specific heat and there is just not enough of it to go around. A typical density-wave-reconstructed Fermi-surface scenario will produce too much specific heat per YBCO unit cell bilayer, an argument carefully laid down in the paper¹². Such excess specific heat will warm up the heart of any Mottness enthusiast and is a challenge for the 'pockets' picture³.

So, much to no one's surprise, the cuprates remain a mystery. Is it pockets or nodes? Nodes or pockets? Or both? The \sqrt{H} background naturally arises within the picture of a quantum-phase-disordered strongly correlated *d*-wave superconductor but generating oscillations can be a struggle. Conversely, within the density-wave-reconstructed Fermi-surface scenario the quantum oscillations are a natural outcome, but a large \sqrt{H} background and small absolute value of specific heat are real hurdles. One possible scenario is the formation of pockets as H increases beyond some critical value. At low fields, an incipient density wave loses to a large Δ_d and an electron attempting to move along the reconstructed orbits associated with a density wave order is repeatedly turned back by a sequence of Andreev reflections. At higher fields, however, as quantum fluctuations exact their toll, Δ_d is reduced in the nodal neighbourhood of the magnetic Brillouin zone, sufficiently so for the electron to manage to quantum tunnel its way to a full Landau orbit stemming from what in effect is a field-induced density wave. Another explanation, an 'intruder' Fermi surface only loosely coupled to HTS, is discussed by Riggs *et al.* themselves¹².

In the end, perhaps the most valuable aspect of the specific heat measurements¹² is the wealth of information revealed by Fig. 1. Cuprate HTS was never a field in which anyone was speechless or in doubt for more than a second — this indeed is an integral part of the field's charm (or disrepute, some would insist). But, as one contemplates Fig. 1, one can hardly resist the urge to be quiet for a while, and to ponder its implications across the cuprate landscape.

As the field reflects on Riggs *et al.*, I beg its indulgence for this brief intrusion, and for the reminder: a quarter of a century later, the cuprates still retain their mystique. And their preeminence at the frontier of condensed-matter physics. □

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References

1. Doiron-Leyraud, N. *et al.* *Nature* **447**, 565–568 (2007).
2. Sebastian, S. E. *et al.* *Nature* **454**, 200–203 (2008).
3. Chakravarty, S. *Rep. Prog. Phys.* **74**, 022501 (2011).
4. Scalapino, D. J., Loh, E. & Hirsch, J. E. *Phys. Rev. B* **34**, 8190–8192 (1986).

5. Anderson, P. W. *Science* **22**, 1705–1707 (2007).
6. Metlitski, M. A. & Sachdev, S. *Phys. Rev. B* **82**, 075128 (2010).
7. Berg, E., Fradkin, E. & Kivelson, S. A. *Phys. Rev. B* **79**, 064515 (2009).
8. Millis, A. J. & Norman, M. R. *Phys. Rev. B* **76**, 220503(R) (2007).
9. Tesanovic, Z. *Nature Phys.* **4**, 408–414 (2008).
10. Li, L. *et al.* *Nature Phys.* **3**, 311–314 (2007).
11. Chatterjee, U. *et al.* *Nature Phys.* **6**, 99–103 (2010).
12. Riggs, S. C. *et al.* *Nature Phys.* **7**, 332–335 (2011).

SIMON VAN DER MEER

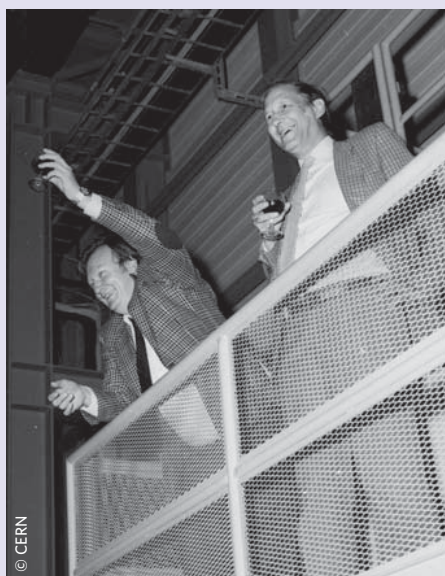
Stochastic success

Simon van der Meer, who died on 4 March 2011 at the age of 85, followed a path to Stockholm that was perhaps less orthodox than most. A native of The Hague in the Netherlands, he finished his high-school science studies in 1943 but was unable to progress to university for two years, owing to the closure of the Dutch universities under the German occupation. At the end of the war, he entered the University of Technology at Delft to study ‘technical physics’, a subject more akin to engineering. “I have often felt regrets”, he wrote at the time of the award of his Nobel Prize in Physics in 1984, “at not having had the intensive physics training that many of my colleagues enjoyed.”

Nevertheless, van der Meer was building a successful career, first at the Philips Research Laboratory in Eindhoven and then, from 1956, at a recently founded laboratory in Geneva, Switzerland — CERN. His work was technical in nature, mostly concerned with magnets and power supplies for CERN’s 28 GeV synchrotron, but interaction with accelerator and experimental physicists at the laboratory led him to develop an interest in particles, and how to handle them in an accelerator.

By the early 1960s, he had devised the ‘horn’ that, by enabling the focusing of neutrinos into beams of sufficient intensity, became a crucial component of most neutrino experiments — particularly those present-day experiments in which neutrino beams are fired through the Earth over distances of hundreds of kilometres to explore the tendency of these particles to oscillate from one type of neutrino to another.

In 1968, in a meeting at CERN, van der Meer first raised his notion of ‘stochastic



cooling’ for particles in an accelerator, but did not pursue it with any great urgency. In a way, it was a solution looking for a problem — but that problem soon appeared, with Carlo Rubbia’s proposal to use CERN’s Super Proton Synchrotron (SPS) to create high-energy proton-antiproton collisions, in which might be found definitive proof of the standard model.

The standard model of particle physics was being pieced together in the 1970s: disparate strands of evidence, once-confusing observations, the infamous ‘zoo’ of particles were all woven into a magnificent theoretical framework. The theory hinged on the existence of two types of massive boson, the *W* and the *Z*, mediators of the weak force. Rubbia’s idea was to build an accelerator of sufficient reach in energy to observe, in the debris of the proton-antiproton collisions, evidence of the production of *W* and *Z* bosons.

The problem lay in accumulating a sufficient number of particles, nestled tightly together in the accelerator beams, to achieve a high-enough rate of collisions to find the bosons. Van der Meer’s stochastic cooling was the solution, and he proved its efficacy in the Initial Cooling Experiment before it was deployed in the SPS.

Stochastic cooling works by reducing the spread in the momentum of the particles within each of the ‘bunches’ that make up an accelerator beam. As the bunches circulate in the accelerator, electrical signals are picked up from individual particles within a bunch and used to activate an electrical ‘kicker’ that pushes the particle’s momentum back into line. According to a statement from CERN Director General Rolf-Dieter Heuer and Director of Accelerators Steve Myers, stochastic cooling is “deceptively simple at first sight, but to anyone who truly understands accelerators it was nothing less than a stroke of genius.”

Van der Meer’s genius coupled with Rubbia’s drive was a winning formula. In 1981 the SPS began generating proton-antiproton collisions, using stochastic cooling; in 1983, the existence of the *W* and *Z* bosons was confirmed; and in 1984, the Nobel Prize was shared, and celebrated, by van der Meer and Rubbia (pictured right and left, respectively). Despite the Nobel, modesty always prevailed for van der Meer: “If I have at times been able to make original contributions in the accelerator field, I cannot help feeling that to a certain extent my slightly amateur approach in physics, combined with much practical experience, was an asset.”

ALISON WRIGHT