Superconductivity - Quantum stripe search

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Zaanen, J. (2006). Superconductivity - Quantum stripe search. Retrieved from https://hdl.handle.net/1887/5123 into recognizing recursion, the analogous human capacity seems robust. Humans are quick to notice recursion and are able to do so without explicit reinforcement; perhaps most importantly, they can generalize recursive structures broadly. Starlings have thus far been shown to be able to extend A^nB^n only to new sequences of familiar sounds. Humans can clearly go further; once you recognize the pattern in *AABB* and *AAABBB*, it is a trivial matter to extend that pattern to new vocabulary (for example, *CCCDDD* or *JJJKKK*). Taken together with the tamarins, there actually seems to be a three-way split: some species may generalize recursion only to items that have already been instantiated in a given pattern; some species can generalize recursion freely to newly acquired vocabularies (arguably the essence of human language); and some species apparently cannot recognize recursion at all.

The "abstract computational capacity of language"[3] may consist not so much of a single innovation as a novel evolutionary reconfiguration of many (perhaps subtly[6] or even qualitatively[7] modified) ancestral cognitive components, genetically rejigged into a new whole. Contemporary research suggests that the human brain contains few if any unique neuronal types, and few if any genes lack a significant ancestral precedent[8]. At the same time, humans show much continuity with their non-speaking cousins in dozens of ways that might contribute to language, including mechanisms for representing time and space, for analysing sequences, for auditory analysis, for inhibiting inappropriate action, and for memory.

None of this challenges Chomsky's long-held conjecture[9] that children are innately endowed with a universal grammar — a set of mental machinery that would lead all human languages to have a similar abstract character. But that shared abstract character may have as much to do with our lineage as vertebrates as with our uniquely human innovations. In Charles Darwin's immortal words, "throughout nature almost every part of each living being has probably served, in a slightly modified condition" in some ancestor or another. ■

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SUPERCONDUCTIVITY

Quantum stripe search

Jan Zaanen

Do quantum stripes exist or not? Further indirect evidence for this controversial behaviour of electrons in high-temperature superconductors comes from measurements of atomic-lattice vibrations.

Since 1995, the 'stripe wars' have been raging in the demesne of high-temperature superconductivity. This fierce conflict, fought with the highest-calibre weapons of experimental physics, has its antecedent in a hotly contested claim about the way electrons behave in the copper oxide materials notoriously used as high-temperature superconductors. Supposedly, they form highly organized patterns called quantum stripes — but only on the picosecond timescale, so the patterns average away over longer periods through the electrons' constant quantum dance.

The dispute has lasted so long only because it has proved very hard to nail down such genuine quantum behaviour. In this issue, however, Reznik *et al.* (page 1170)[1] present further evidence in support of quantum stripes. They show that the collective vibrations of the atomic lattice of certain superconducting copper oxides behave in a manner that is hard to explain — unless one assumes that motions characteristic of the presence of quantum stripes are shaking the ion lattice. So is the end of hostilities in sight?

It is an everyday experience that, in a many-body system, collective behaviours emerge that are utterly unrelated to the behaviours of the objects that make it up. The evolution of a nation's economy over time, for example, is difficult to predict from the often conflicting motivations of the constituent human members. The same principles apply in quantum physics. But the exact rules that govern quantum emergence are poorly understood; uncovering them is a core business of modern physics.

Conventional superconductors — those operating only at temperatures very close to absolute zero — demonstrate only a minimal form of quantum emergence. In such materials, interactions between electrons diminish at low temperature, and the macroscopic electron system turns into a near-ideal (non-interacting) quantum gas of 'quasi'-electrons. A small residual attractive interaction binds these quasi-electrons in pairs, which in turn collapse to a single quantum state in the process known as Bose–Einstein condensation.

Although this theory of superconductivity, known as the Bardeen–Cooper–Schrieffer (BCS) model, gets everything right for conventional superconductors, it explains hardly anything in high-temperature superconductors. The discovery 20 years ago of this unusually sturdy form of superconductivity raised the curtain on a drama of wider relevance: the huge numbers of strongly interacting electrons in the copper oxide layers were plainly showing an unknown kind of collective quantum physics (for an overview, see ref. 2). In 1995, it was discovered[3] that small changes in the crystal structure of high-temperature superconductors can cause superconductivity to disappear, with a peculiar 'static stripe phase' taking over (Fig. 1). Here, strong interactions and quantum motions work together to form patterns of electrons moving in serried ranks. Domains in which the electrons come to a complete standstill separate these 'rivers of charge' (Fig. 1b).

The existence of static stripes, initially contentious, is now generally accepted. But quantum stripes are more radical and controversial. Members of the quantum-stripe faction hold that stripes are, in fact, always present. When a material superconducts, the stripes do not disappear; rather, a quantum-mechanical superposition of countless disordered stripe states forms (Fig. 1a), in such a way that the overall state corresponds to that of a superconducting quantum liquid (for a mathematical proof of principle, see ref. 4).

So how can we nail down quantum stripes experimentally? Consider Erwin Schrödinger's oft-cited cat hidden in a sealed box (Fig. 1c). Classically, the cat must be either dead or alive, but quantum mechanically it is in a superposition of dead and alive states. In the quantum state, the cat fluctuates back and forth between alive and dead states. This fluctuation takes a finite time. So, by taking snapshots quickly enough, one can see either a dead or a live cat. The same scheme works equally well with superpositions of countless many-electron configurations. Here, every quantum configuration takes the role of a classical 'dead or alive' state (Fig. 1c).

The fluctuation time of the quantum stripes is in the picosecond (10^{-12} second) range, and the problem for the experimentalist is how to grab a picture of complicated spatial electron patterns in so little time. One way to do this is to observe the change in kinetic energy of neutrons that scatter off the material inelastically. Since 1995, such neutron-scattering experiments have added to the body of evidence supporting the case for quantum stripes[5]. The drawback is that these studies relied on information about the direction of the electron spins that was open to alternative interpretations, including some compatible with the conventional BCS picture (see ref. 6 and references

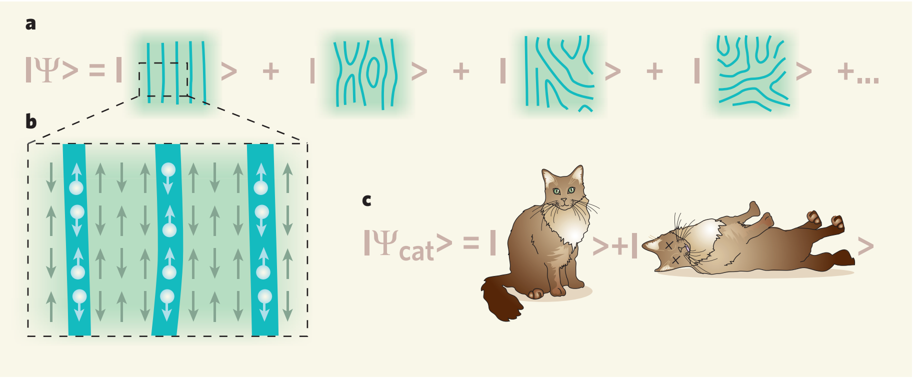

Figure 1 | Hunting the stripes. Electrons in the copper oxide planes of high-temperature superconductors sometimes form non-superconducting static stripe patterns. **a,** These stripes are believed to survive in the superconducting state as part of a quantum superposition of countless disordered stripe states that forms an overall featureless superconducting quantum liquid. **b,** Close up, the stripes are seen to consist of delocalized electrons ('rivers of charge') separated by domains of localized electrons showing a characteristic spin order. **c,** The principle of quantum superposition by which the stripe states are hidden from view in the superconducting phase is also the source of uncertainty over the fate of Schrödinger's infamous cat. Capturing the quantum cat or the quantum stripes in a definitive state requires snapshots taken on a timescale that is short compared with the timescale of quantum fluctuations between the superimposed states (dead or alive; stripy or non-stripy). By exploiting the coupling between high-frequency lattice and collective-stripe vibrations, Reznik *et al.*[1] provide a glimpse of quantum stripes.

therein). So, although taken seriously, quantum stripes have not been seen as a proven fact.

Reznik *et al.*[1] present a new indicator of quantum stripes by exploiting the motions of the ions that form the copper oxide lattice. These motions give rise to quantized lattice vibrations, known as phonons, that can be easily observed, again by inelastic neutron scattering. Electronic stripes must also undergo coherent vibrations, but these cannot be seen directly. When the phonons and the stripe vibrations enter resonance, however, they are expected to interact strongly and cause a characteristic anomaly in the spectrum of the phonons. Reznik and colleagues observe just such a phenomenon in a copper oxide with static stripes.

The key is that these anomalies will occur on a timescale that is shorter than the quantum fluctuation time of the delocalized quantum stripes. The quantum stripes will therefore seem to come to a standstill when viewed through the phonons, and the phonon anomaly should persist even when there is no sign of static stripes. This is exactly what Reznik *et al.* observe[1]: even in the best superconductors, which show no sign of static stripes, the anomaly is blurred, but it is still clearly discernible.

So is this the turning point in the stripe wars? Although quantum stripes are more elusive than nuclear submarines — all signals of them have so far been indirect — the strength of the idea is that this single hypothesis explains a world of strange behaviours. Viewed from that angle, the defenders of the conventional BCS model might seem like medieval defenders of a geocentric cosmos, forced by observations to add ever more epicycles to their already baroque universe. On the other hand, there is no a priori need for electrons in crystals to behave in aesthetically pleasing ways; the epicycles could still be the truth. For one side or the other to win the war, a way of sending a sortie for direct reconnaissance of quantum stripes must be found. ■

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BIOMATERIALS

Gripping stuff


Y. BRUN

The aquatic bacterium *Caulobacter crescentus* can come, quite literally, to a sticky end. As Peter H. Tsang and colleagues report (*Proc. Natl Acad. Sci. USA* **103,** 5764–5768; 2006), the bacterium's long, tail-like anchor sticks it so tightly to a supporting surface that it often tears apart when a detaching force is applied, rather than relinquishing its grip. The adhesion is thought to be the strongest of biological origin yet discovered.

When *C. crescentus* (two are pictured here, spawning clones) is in its non-motile (stuck) state, its anchor — appropriately named its 'holdfast' — binds the bacterium to the surface, and a stalk connects the holdfast to the cell body. The authors used atomic force microscopy to record the force needed to detach a non-motile cell from a micropipette by means of a suction pipette oriented perpendicular to the pulling direction. They measured the area of coverage of the holdfast and other dimensions of the bacterium, working out average geometries and finally applying a mathematical technique known as finite-element analysis to calculate the adhesion strength.

The holdfast enables the bacterium to remain stuck to the surface even in strong jets of water, and Tsang *et al.* calculate that, were it to cover an area of 1 cm^2, it could support a weight of 680 kg, even on a wet surface. That exceeds all other known cell-adhesion capabilities — including the sticking power of the much-studied gecko's foot. And because, owing to the geometry of *C. crescentus*, the adhesion often failed through fracture of the cell stalk rather than at the adhesion interface, the true adhesion strength at the interface could be still higher.

Polymers of a sugar-based molecule called *N*-acetylglucosamine are known to be present in the bacterium's adhesive plaque. The authors found that when they treated the polymers with an enzyme to break them down, the strength of the bacterial attachment was reduced. However, the detailed physical and chemical mechanisms of *C. crescentus*'s adhesive abilities remain to be revealed. Their elucidation could trigger the development of a new range of synthetic adhesives.

Rosamund Daw