consisting of an array of superconducting niobium islands on a normal metallic gold substrate. By controlling the height, diameter and spacing of the islands, they were able to control the characteristics of the array. And because the individual islands were each composed of many different superconducting grains, the characteristics exhibited by their arrays are richer than those of similar but simpler arrays explored in previous studies — with surprising results.

At temperatures just above niobium's bulk superconducting transition temperature (9 K), the temperature dependence of the resistivity of the arrays was flat. But as the temperature was gradually lowered, at some point (T_1) below this temperature, the resistivity began to decrease slowly. In this state, one expects the electrical current to have been carried by Cooper pairs tunnelling from island to island (Josephson tunnelling), rather than by normal electrons. At this temperature, the multigrain nature of the superconducting islands gives rise to multiple incoherent Cooper pair states. This means that the interisland tunnelling is incoherent as well, analogous to the incoherent transport of electrons in a metal at finite temperature.

As the temperature is lowered further, the resistance of the system continues to fall slowly until, at some second temperature (T_2), it drops precipitously to zero. The authors explain this behaviour in terms of a gradual increase in the coherence of the Cooper pair condensate. Coherence first develops within each island and the Cooper pair states of its grains begin to coalesce. This then spreads as the temperature falls until, at T_2, the condensate in the array as a whole becomes coherent, or is as coherent as is allowed in two dimensions (following the model for 2D superfluidity[6]).

So how can it be said that this experiment suggests the existence of a putative 2D metal — particularly in light of the fact that it should be forbidden[4]? Eley *et al.* found that the temperature, T_2, changed considerably as the interisland spacing of their arrays was varied, falling monotonically with increasing separation. At the largest spacing investigated, the authors found T_2 to be as low as 1 K — well below the superconducting transition temperature of bulk niobium and tantalizingly close to 0 K. The results indicate that it might be possible to build an array with $T_2 = 0$. The resistance of such an array would never fall to zero — it would never become superconducting — but remain finite, even as it approached absolute zero. Such an array would, for all intents and purposes, represent the elusive 2D metal.

Figure 1 illustrates where this new metallic state lies in the phase diagram of a hypothetical 2D metal. The conventional metallic state exists only in total absence of disorder, W, and for sufficiently weak and positive Coulomb interaction, U. It is destroyed by the Mott transition for large positive U and for any level of W. On the other hand, for attractive effective interactions, described here by negative values of U, we would expect 2D superconductivity. For small values of U, this will be a Bardeen–Cooper–Schrieffer-type superconductor, whereas for stronger attractive interactions a Bose condensate of pre-formed pairs[7] might occur. The new metallic state proposed by Eley *et al.*[1] lies in a region where these pairs are mobile, but are not fully Bose–Einstein condensed into a superconducting state.

If it is possible to achieve, this zero-temperature metallic state would therefore be very different from a conventional metal, the properties of which are governed by electrons. Rather, it would be more accurate to describe it as a quantum liquid of bosons — as Cooper pairs behave like bosons. This therefore would be a realization of a gas of charged bosons, first investigated in 1955 by Schafroth as a model for superconductivity[7]. But just as a conventional metallic state encounters problems when it is taken from 3D to 2D, so too does a Bose gas, which is unable to manifest the equivalent of Bose–Einstein condensation in 2D. Such a state would be something that we have not yet encountered. Perhaps the most apt description of such a state is that of a quantum disordered phase of the condensate[1]. ❐

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References

1. Eley, S., Gopalakrishnan, S., Goldbart, P. M. & Mason, N. *Nature Phys.* **8,** 59–62 (2012).
2. Anderson, P. W. *Phys. Rev.* **109,** 1492–1505 (1958).
3. Mott, N. F. *Proc. Phys. Soc.* **A62,** 416 (1949).
4. Abrahams, E., Anderson, P.,W., Licardello, D. C. & Ramakrishnan, T. V. *Phys. Rev. Lett.* **42,** 673–676 (1979).
5. Haydock, R. & Te, R. *Phys. Rev. B.* **57,** 296–301 (1998).
6. Kosterlitz, J. M. & Thouless, D. J. *J. Phys. Condens. Matter* **6,** 1181–1203 (1973).
7. Schafroth, M. R. *Phys. Rev.* **100,** 463–475 (1955).

TOPOLOGICAL DEFECTS

Topology in superposition

Topological defects are encountered in fields ranging from condensed-matter physics to cosmology. These broken-symmetry objects are intrinsically local, but theoretical work now suggests that non-local quantum superpositions of such local defects might arise in a quantum phase transition.

K. Birgitta Whaley

Topological defects are local defects in otherwise ordered structures that can only be removed by some global deformation — no amount of local bending at or twisting around the defect can remove them from the structure. Such defects are well known in both classical and quantum settings; examples include domain walls and dislocations in crystals, vortices in two-dimensional superfluids and monopoles in liquid crystals[1]. Although a topological defect is local in structure, it is also intimately connected to the long-range ordering of the structure in which it is embedded. In a magnet, defects such as domain walls separate regions characterized by different magnetization or global spin order, resulting in discontinuous order parameters and different instances (or 'resolutions') of a broken symmetry. It is therefore natural to expect that the origins of topological defects should be related to the origins of broken symmetries and hence to the microscopic details of phase transitions. Such defects may also exist in the mathematical fields describing matter at high energies and temperatures, as a result of symmetry-breaking cosmological phase transitions in the early Universe. That insight has spurred much interest in the modelling of cosmological events by more commonplace phase transitions that can be studied in condensed-matter systems[2].

If topological defects are local, irremediable faults within a global structure, then what would it mean for the global system to be in a quantum superposition state of these defects?

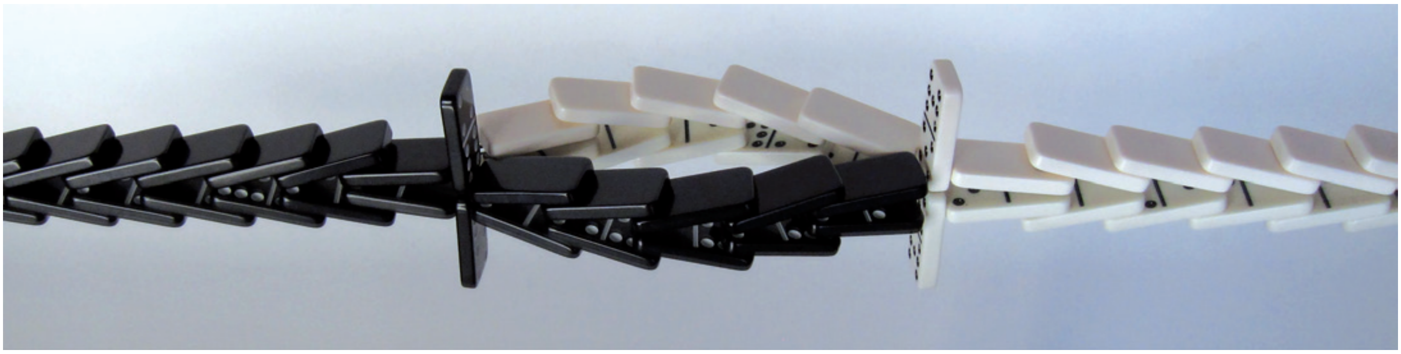

Figure 1 | Last domino standing. Topological defects, such as domain walls separating dominoes falling in opposite directions, are extremely stable. The domino domain wall is a kink between regions of different ordering. When this kink is put into a quantum superposition of two different position states, the entire region between the two locations is brought into quantum superposition, leading to the possibility of large-scale superposition states as these locations are taken farther apart.

Clearly, this has to be something very different from a quantum-superposition state of two spins localized at different points in space. As the defect is only defined relative to an underlying global symmetry, a superposition of defects seems to imply that this should be accompanied by a quantum superposition of the global symmetry states, or at least by some residual 'shadow' of the defect superposition on a much larger region beyond the defect. Writing in *Nature Physics*, Jacek Dziarmaga, Wojciech Zurek and Michael Zwolak propose a simple prototype for such a quantum-superposition state of topological defects, with an example drawn from the well-known one-dimensional quantum Ising model[3]. In this model, a chain of spin-half particles with ferromagnetic interactions is aligned along a longitudinal axis (such that the spins can point either 'up' or 'down'), and is subjected to a magnetic field in a transverse direction. A domain wall separating regions of up and down magnetization constitutes a kink, which also serves as a locator for the change from one ground state (all spins down) to another degenerate ground state (all spins up). Constructing a quantum state with superposed kink locations results in the domain walls being in superposition, but also ensures that all spins between these two locations are now also in superposition. Taking the defects farther apart then leads to a quantum superposition of the entire order parameter for the bulk-like regions between the two superposed kink locations (see the classical analogue shown in Fig. 1). Dziarmaga *et al.* demonstrate how these non-local superpositions might be generated from single kinks by modifying the spin–spin couplings at distinct locations and analyse the signatures of coherence that could be detected with interference measurements.

This intriguing analysis raises several questions with implications both for the meaning and realizability of macroscopic quantum superpositions and for the dynamics of symmetry breaking in phase transitions. First, if it were possible to make such a quantum superposition of topological defects that are separated by a macroscopic distance, what would the true size of this quantum superposition be? Is it trivially small on account of being a superposition of a single effective degree of freedom, that is, the order parameter? Or is it macroscopic, corresponding to the large number of spins between the two kinks that are in different spin states in each of the two branches of the superposition? This resembles the situation encountered for quantum superpositions of flux states of superconducting loops containing Josephson junctions, where very different answers are obtained using a macroscopic quantum circuit description and a microscopic all-electron theory[4]. The effective size of complex large-scale quantum superposition states depends on how many measurements are required to distinguish the two branches[5] and hence different answers might be expected from measurement of individual spins or of an order parameter. Second, just how large a superposition could one make? The question of a possible intrinsic size limitation to quantum mechanics has tantalized scientists since Erwin Schrödinger first presented his extreme paradox of a quantum superposition of a cat in live and dead states[6]. Even making this paradox more palatable by allowing only component states that might conceivably be interconverted in both directions (thereby removing any live–dead superposition) still leaves us with the classic questions of, on the one hand, how large and how complex a quantum superposition can be made, and, on the other hand, why we normally 'see' only one branch of such a superposition?

Dziarmaga *et al.*[3] do not consider the size and complexity of a quantum superposition, but provide an eloquent analysis of why we see only one branch. They show that environmentally induced decoherence will cause the kink-superposition state to decay at a rate proportional to the number of spins between the two kinks, generating a classical mixture of the two broken-symmetry ground states. Rapidly decohering non-local quantum superpositions of topological defects thereby provide a possible dynamical rationale for the 'collapse' into a single broken-symmetry state, analogous to the process of measurement on a quantum system. This leads to an appealing microscopic picture of the dynamics of the phase transition in the quantum Ising model. Initially, a single kink is formed by fluctuation of the interaction between two specific spins, followed by transformation of this local defect to a non-local kink-superposition state by the proliferation of further fluctuations. Finally, fast decoherence of the superposition leads to a single broken-symmetry state at the other side of the phase transition. Extending these ideas to cosmology will require a rationalization of decoherence in a quantum universe — a notoriously tricky problem — but the work of Dziarmaga *et al.* suggests a general scenario for the dynamics of symmetry breaking. ❐

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References

1. Sethna, J. P. *Statistical Mechanics: Entropy, Order Parameters and Complexity* (Oxford Univ. Press, 2006).
2. Kibble, T. *Phys. Today* **60,** 47–52 (September 2007).
3. Dziarmaga, J., Zurek, W. H. & Zwolak, M. *Nature Phys.* **8,** 49–53 (2012).
4. Korsbakken, J., Wilhelm, F. K. & Whaley, K. B. *Phys. Scripta* **T137,** 014022 (2009).
5. Korsbakken, J., Whaley, K. B., DuBois, J. & Cirac, J. I. *Phys. Rev. A* **75,** 042106 (2007).
6. Schrödinger, E. *Naturwissenschaften* **48,** 807–812 (1935).

Published online: 11 December 2011