This example is simply intended to illustrate that even in the reduced symmetry, with intrinsic anisotropies, an interpretation based on collective effects is not too far-fetched. In reality, there are many sample- and material-specific details that may prove to be significant. Apart from the aforementioned sample geometry, these include the strong coupling of the electrons' spin to their orbital motion in bismuth; the relative weakness of interactions owing to a large dielectric constant ($\varepsilon \approx 100$); and the Dirac dispersion underlying the small Fermi surface. Details aside, it seems likely that resolving the nature of the anisotropic phase will involve a careful re-examination of several tenets of solid state theory — and some fascinating new physics. ❐

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2D ELECTRON SYSTEMS

Metals in flatland

Is it possible for a metal to exist in a strictly two-dimensional system? This may seem trivial, but it is actually a longstanding problem. The electrical characteristics of an array of superconducting islands on a normal metal suggests that the answer could be 'yes'.

James F. Annett

Every undergraduate physics student learns that a metal is a material whose valence electrons occupy a finite density of quantum states at the Fermi energy (or chemical potential). Consequently, these electrons are free to move through the metal, to conduct electricity and heat more easily than they could in an insulator. This distinction becomes absolute in the limit of absolute zero temperature, at which the electrical resistivity of a metal remains finite and an insulator becomes infinite. One might expect that such behaviour is independent of the dimensionality of a system. Yet it turns out that the question of whether it is even possible for a conventional metallic state to exist in two dimensions is one that has eluded a definitive answer for decades. Now, in *Nature Physics*, Eley and colleagues[1] report a study that comes the closest yet to an answer, and suggests that the answer could be 'yes'.

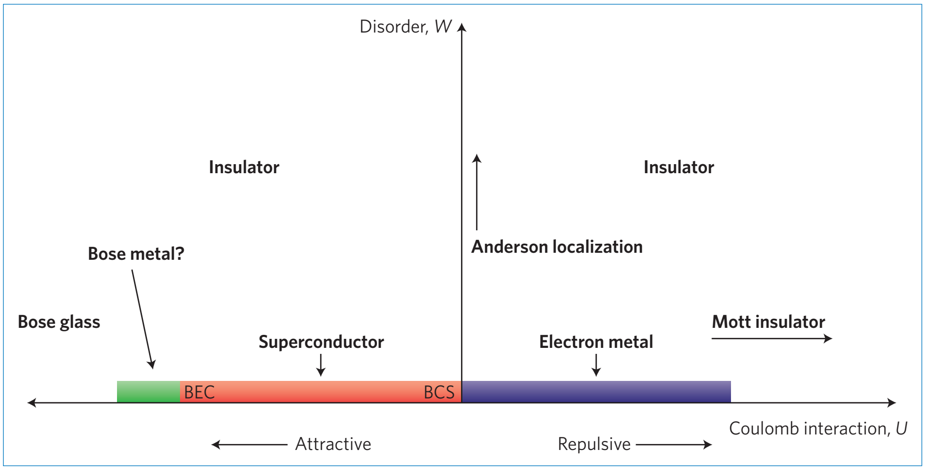

Figure 1 | Phase diagram of a 2D metal. It is believed that metals are unable to exist in two dimensions in the presence of disorder, W, as they would become insulating. If there are strong repulsive interactions between the electrons (U), the metal (blue) is also destroyed and becomes a Mott insulator. Weak attractive interactions lead to a Bardeen–Cooper–Schrieffer (BCS)-type superconductor (red). If the interactions are strong, this crosses over into a superconductor of pre-formed pairs — a Bose–Einstein condensate (BEC) of charged bosons. Conventionally, we would expect that even stronger attractive interactions would lead to instability of this BEC towards localization of the pairs, forming a Bose glass phase, which would be an insulator. In the structured systems described by Eley *et al.*[1], there appears to be a possibility of a new metallic phase (green), which would be a metal of charged bosons (Cooper pairs), rather than a conventional electron metal.

The two main factors that have frustrated attempts to realize an 'ideal' two-dimensional (2D) metal are disorder and Coulomb repulsion. Conventional Bloch theory begins by assuming that all materials are perfect crystals, and that the electrons moving through a given material only ever see the potential that is created by the ions of its crystal lattice — that is, the Coulomb interaction between electrons is negligible. But, in reality no crystal is perfect, and the effects of even a small Coulomb interaction can be important if there is also disorder. Moreover, in work that won them a share in the 1977 Nobel Prize for Physics, Philip Anderson and Neville Mott respectively showed that the introduction of disorder[2] or strong Coulomb interactions[3] can cause a metal to become an insulator. In a 3D metal, this only occurs when the disorder (or strength of the Coulomb interaction) exceeds a certain critical point. But in a 2D metal, it has been shown that the presence of any amount of disorder, not matter how weak, will always induce an insulating state[4]. This represents just one of the remarkable differences that can arise between 2D and 3D materials — a fact that surprises even specialists in condensed-matter physics. And although this conclusion[4] is widely accepted, there are still issues of controversy[5].

Eley *et al.* take an unconventional approach to the question[1]. Rather than attempting to grow a perfect 2D metal film, they constructed an artificial analogue 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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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?