mechanics directly. By solving the Schrödinger equation numerically, researchers can now simulate these extreme conditions with no empirical input.

### High-pressure surprise

This is precisely what Stan Bonev and collaborators at the Lawrence Livermore National Laboratory in California have done (*Nature* **431** 669). Their simulations show that the interactions between hydrogen molecules become stronger as the pressure increases – a well-known effect – but then, surprisingly, become weaker again at pressures above a million atmospheres. The melting temperature of the molecular crystal therefore decreases at these very high pressures, indicating that compressed molecular hydrogen may retain a fluid state down to very low temperatures where it could become a superfluid.

To complicate this state of affairs even further, one of the present authors (SS) has recently predicted, based on simulations, that fluid hydrogen should undergo a sharp phase transition at pressures slightly higher than those at which the intermolecular interactions become weaker. The transition involves the dissociation of the molecular insulating fluid into a non-molecular metallic fluid.

If fluid hydrogen were to retain a metallic character down to low temperatures, it is then conceivable that the electrons could collapse into a superconducting state at even lower temperatures. We may then be faced with a rather unusual and perhaps unique state of matter in which superfluidity and superconductivity coexist in the same substance. Such a state would provide an exciting benchmark for theories of quantum condensates.

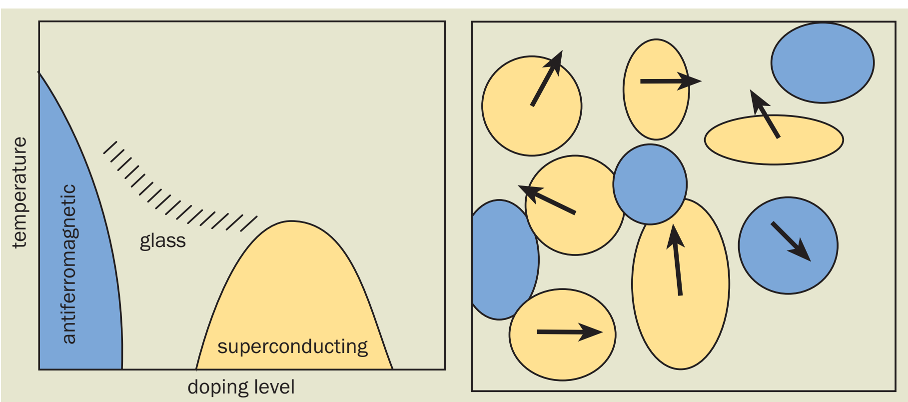
Exploring this possibility, Babaev and collaborators have developed a so-called Ginzburg–Landau theory that describes the superconductivity of the two-component (protons and electrons) quantum fluid as a function of temperature and magnetic field. Their analysis predicts an intriguing scenario of complicated phases that have no analogues in one-component superconductors based on Cooper pairs of electrons.

In particular, the theory predicts that at sufficiently low temperatures and low magnetic fields a remarkable state forms in which the dissipationless currents of the two oppositely charged carriers lead to an overall neutral "supercurrent". In other words, the superfluid state emerges as a result of charge cancellation. Such a superfluid could be turned into an electronic superconductor by, for instance, increasing the temperature until the protons became non-superconducting or "normal". At still higher temperatures, the electrons would also enter the normal state and the system would revert to the well-understood fluid metallic state.

Whether a superfluid and superconducting state of hydrogen exists in the real world remains to be seen. More importantly, no attempt has yet been made to provide quantitative estimates of the critical temperatures at which hydrogen becomes superfluid and superconducting. This makes it difficult to assess whether such effects can actually be seen in experiment. But the challenge is open, and even though the hydrogen atom will forever be at square one in the periodic table, there are good reasons to believe that research in this area will move on rather quickly.

# Superconductors go large

Giant proximity effect brings new puzzle for superconductivity




Superconducting puzzle – a recent experiment could force researchers to question whether the phase diagram of the high-temperature superconductors is the same for all cuprates. The phase diagram above for a disordered system (left) shows the antiferromagnetic and glassy regions plus the familiar superconducting "dome". The right part of the figure depicts the "clustered state" explanation for the glassy region, in which antiferromagnetic (blue) and superconducting (yellow) clusters coexist. The arrows represent the superconducting order parameter.

From **Gonzalo Alvarez** and **Elbio Dagotto** at the Oak Ridge National Laboratory and the University of Tennessee, US

Since it was discovered in 1986, high-temperature superconductivity has continued to surprise and fascinate condensed-matter physicists. Today, most researchers agree that there are several key features of these "cuprate" compounds – all of which contain layers of copper and oxygen atoms – that remain unexplained. These include the pairing mechanism that produces the exotic "*d*-wave" superconducting state, and the fact that the resistivity of the cuprates increases linearly with temperature above $T_c$, the temperature at which the material loses its electrical resistance.

Now Ivan Bozovic of the Brookhaven National Laboratory and co-workers have discovered another unexpected property of the cuprates. Using molecular beam epitaxy to prepare three-layer junctions with atomically smooth films, the team has observed a "giant proximity effect" in a high-temperature superconducting device for the first time (*Phys. Rev. Lett.* **93** 157002). The standard proximity effect, in which Cooper pairs drift from a superconductor to a metal when they are placed next to one another, is a common phenomenon. But the term "giant" in the new results arises from the abnormally large distance or coherence length over which this effect occurs.

### Close proximity

The three-layer device in which this giant effect was observed consists of a normal metal sandwiched between two superconducting lanthanum strontium copper oxide (LSCO) layers, which have a transition temperature of about 45 K. The normal metal was also made of lanthanum copper oxide, but with excess oxygen so that is has a lower transition temperature, $T_c'$.

The Brookhaven team found that the LSCO structure behaved as a Josephson junction – a device that exploits the proximity effect – for temperatures between $T_c'$ and $T_c$ for a barrier thickness as large as 20 nm. Standard theoretical arguments fail to provide a satisfactory explanation for this, since the superconducting coherence length in cuprates is widely believed to be very short – about the size of a Cooper pair, or a few ångströms.

Assuming that the material in the three-layer sandwich behaves as a standard metal, the coherence length should provide a natural limit to the thickness of the barrier required for a supercurrent to flow. But Bozovic and co-workers have found that a supercurrent flows in the junction across a barrier that is 100 times thicker than the coherence length. In other words, the normal metal in the three-layer sandwich is certainly not normal after all!

Previous experiments have also produced evidence for such giant effects in similar materials and geometries. However, these were met with scepticism because they could be explained by pinholes and other defects. The Brookhaven team has carefully addressed these concerns and concluded that the giant effects are real.

### Theoretical interpretation

There are at least two possible explanations for these fascinating results. Steve Kivelson and collaborators at the University of California at Los Angeles have proposed that strong phase fluctuations in the normal state of the cuprates – LCO in this case – prevent a superconducting state from forming. Here phase relates to the superconducting order parameter: this is a complex field that indicates whether or not a certain spatial point is superconducting. In other words, where there is a non-zero superconducting order parameter there is a condensation of Cooper pairs. This "phase fluctuating" state has incipient superconductivity, which could be responsible for the giant proximity effect (*Nature* **374** 434).

The other explanation, which has been proposed by the present authors and co-workers, suggests that the normal state is formed by a mixture of almost static nano-scale superconducting clusters that coexist with equally small antiferromagnetic clusters (arXiv.org/abs/cond-mat/0401474). The phases of the superconducting clusters are different for each cluster, and so the state is only superconducting on a local and not a global scale.

This "clustered state" emerges from the influence of disorder on the lattice, which is inevitable in chemically doped compounds that involve ions with different sizes and valences. A key qualitative difference with the phase-fluctuating state proposed by Kivelson and co-workers is that the clustered state is inhomogeneous, which means that a large number of Cooper pairs can be accommodated inside the superconducting clusters.

### Universal questions

Although no-one has yet calculated the Josephson currents in the Brookhaven team's three-layer geometry, it is conceivable that both the phase-fluctuating and superconducting clustered states may lead to a robust supercurrent, since they are both "almost" superconducting rather than being featureless metals.

Recent scanning-tunnelling-microscopy experiments in cuprates, such as those performed by Seamus Davis and co-workers at the Cornell University, clearly show nano-scale inhomogeneities – i.e. clusters – in high-temperature superconductors. But Nernst-effect experiments carried out by Phuang Ong and colleagues at Princeton University reveal vortices above the superconducting transition temperature that are best described in terms of uniform states, of which phase-fluctuating states are a special case.

Regardless of the details, evidence is clearly mounting that, in some temperature and doping regimes, cuprates form Cooper pairs that may be the origin of the giant proximity effect – even though they do not stabilize into a superconducting state. We now need additional experiments so that we can distinguish between the different theoretical scenarios.

In particular, these experiments might explore the nature of the fascinating glassy states of underdoped cuprates – in which the present authors argue that the superconducting order parameter is randomly oriented. The amount of doping in these materials is such that the superconducting transition temperature is lower than its maximum value.

The underdoped regime contains some interesting physics, of which the giant proximity effect is just one example, and it suggests another line of investigation that should be addressed in future experiments: is the phase diagram of the high-temperature cuprates truly universal? This question may sound absurd after the "universal" phase diagram has been published countless times (see figure), but is this really the phase diagram of other cuprates?

Investigations by the present authors suggest otherwise. For instance, it is unclear whether cuprates such as yttrium barium copper oxide (YBCO) have the same phase diagram as LSCO, since the amount of oxygen in the antiferromagnetic–superconducting crossover region is difficult to control. Moreover, organic superconductors – which are widely believed to be "cleaner" than the cuprates – do not display a glassy regime that separates the antiferromagnetic and superconducting states. Could it be that disorder plays a far more important role than previously anticipated and induces the exotic glassy regime of the cuprates? Clarifying these issues should be a high priority in the list of things to do in the fascinating arena of high-temperature superconductivity.

# Astrophysics in the lab

The effect that is thought to turn interstellar gas into planetary disks has been recreated in an experiment on Earth

From **Steven Balbus** in the Department of Astronomy, University of Virginia, Charlottesville, US

Magnetized gases are ubiquitous in astrophysics, and the universe would be a very different place without them. As they collapse under their own gravity, huge clouds of cold gas form rotating "accretion" disks that may ultimately form stars and planetary systems. Accretion disks are also crucial in observations of black holes and binary systems.

To understand the behaviour of accretion disks, it is therefore vital to study the properties of magnetic fields in rotating fluids. (Here the term fluid applies to a continuous medium, and not necessarily a liquid.) For many years, however, the theorists who studied accretion disks often avoided the complication of magnetic fields, focusing instead on the problems of turbulence and viscosity. This led to a major difficulty in explaining how the material in a disk could accrete onto a central object: why should a fluid element abandon its natural Keplerian orbit and spiral inwards?

According to Newton's laws of motion, the angular velocity of an orbiting object decreases as its orbital radius increases, while its angular momentum increases in the outward direction. However, in the 19th century Rayleigh worked out that in order for a rotating disk to be unstable – and therefore for accretion to occur – its angular momentum had to *decrease* in the outward direction.

We now know that this requirement is not necessary. Just a wisp of magnetic field is enough to destabilize the orbit of a rotating, electrically conducting gas. This "magnetorotational instability" was only finally understood in its entirety in 1991. Since then, supercomputers have allowed us to simulate the 3D behaviour of magnetized fluids numerically, and turbulent, unstable accretion disks have been studied intensively.

Despite its importance to astrophysics, however, the phenomenon has not been seen in an experiment until now. Dan Lathrop and colleagues at the University of Maryland have confirmed the existence of the instability by studying a magnetized fluid in the vicinity of a rotating metal sphere (D Sisan *et al.* 2004 *Phys. Rev. Lett.* **93** 114502).

### Unstable rotation

Magnetorotational instability is quite easy to understand in terms of the angular momentum of the disk, which is defined as the product of the angular velocity and the square of the orbital radius.

Fluid elements that are bound together by magnetic forces behave as if they are connected by loose, but very elastic, rubber bands. Since the outlying elements of an accretion disk are linked to the more rapidly rotating inner elements, they experience a positive torque with respect to the direction