much greater than the quantum resistance, that is, $Z_{chain} >> R_Q \equiv \Phi_0/2e = 6.45\ k\Omega$. This provides the necessary conditions for realizing the regime of intense quantum phase slips without dissipative elements[4]. This large impedance results from the large kinetic inductance of the condensate in a chain, which has a fundamentally different origin than electromagnetic inductance. Kinetic inductance expresses the finite kinetic energy in an electrical current and it is a result of the non-zero mass of current-carrying charges. This is in contrast to electromagnetic inductance, which results from their charge. The large kinetic inductance of a Josephson junction chain was recently used to control a quantum phase slip in a new type of superconducting qubit circuit[5].

When the condensate mass modifies the coupling between tunnelling charge and its environment, a picture of quantum electrodynamics (QED) emerges that is not bound to the conceptual foundations of atomic physics with its separate notions of charged massive particles and electromagnetic fields in a vacuum. In circuit QED, the quantum mechanic can work on systems in which fields and charged matter meld into one, strongly coupled, inseparable structure. This particularly captivating aspect of circuit QED promises experiments that challenge our basic understanding of quantum physics, and will hopefully lead us to a more precise measurement of the ampere. ❐

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DOPED MOTT INSULATORS

Breaking through to the other side

A superconductor that can be doped with elements that add electrons or take them away may finally lead to a clearer understanding of the transition from an insulator to a superconductor.

J. Orenstein and A. Vishwanath

Shortly after the recognition that insulators such as NiO were predicted to be metals by the newly developed band theory, Nevill Mott postulated that strong electron–electron repulsion could lead to a new type of insulator[1]. Fifty years later, Mott insulators went viral. Superconductors with the highest recorded transition temperatures were found when Mott insulators such as La_2CuO_4 were 'doped' by adding or removing a small fraction of their electrons. Understanding how a superconductor arises from a Mott insulator has proved to be a tricky problem — in large part because the connection between idealized theoretical models and real-world materials remains unclear. For example, to dissect a Mott insulator and examine whether it contains the seed to superconductivity, we would like to study what happens when a small number of electrons are either added or removed. Yet, until the discovery reported[2] by Kouji Segawa *et al.* in *Nature Physics*, there were no examples of a single Mott insulating material that could be made to conduct by both addition and removal of electrons (or equivalently, addition of holes). Segawa and co-workers report intriguing results at very low doping levels, where a marked difference in properties of electron- and hole-doped materials is manifest.

To appreciate the significance of these findings, consider doping a band insulator, as opposed to a Mott insulator. In a crystalline solid the electronic eigenstates organize themselves into bands: sets of levels with a continuous energy spectrum, separated by gaps. Band insulators such as diamond and pure silicon, where all the levels in the highest occupied (valence) band are filled, are electrically inert. An added electron occupies the next higher energy band. Removing an electron leads to an empty level in an otherwise filled band, which can also be thought of as a particle — a 'hole' — with the same spin as the electron but opposite charge. The states that result from these different routes to metallicity are expected to have rather different properties, as electrons and holes occupy distinct atomic orbitals.

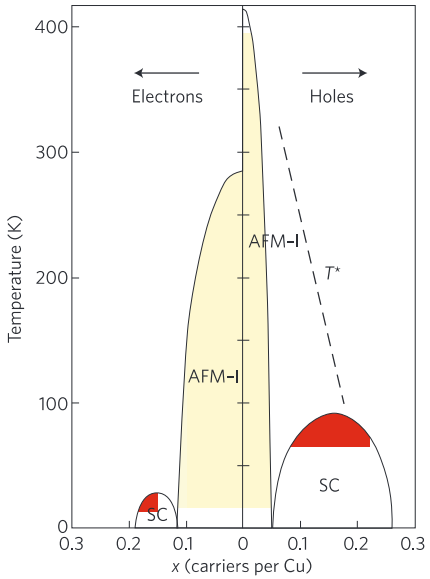

Figure 1 | Temperature–doping phase diagram. The 'parent' compound, which is an antiferromagnetic Mott insulator (AFM-I), must be doped with either holes (right) or electrons (left) to become a superconductor (SC). Hole-doped compounds have an extensive pseudogap region below T^* (dashed line) and more robust superconductivity.

However, what is meant by electrons and holes in Mott insulators is entirely different, and the question of electron–hole symmetry becomes significant. In a Mott insulator there is one electron per cell. Insulating behaviour arises because hopping from one cell to another generates double occupancy, which is strongly inhibited by electron–electron repulsion. When the band filling is slightly reduced, a small number of unoccupied states are created; similarly adding electrons creates doubly occupied sites. In either case, electron hopping does not change the number of doubly occupied cells, conduction is no longer prevented by the Coulomb interaction and an insulator-to-metal transition occurs.

Although removing electrons from a Mott insulator has come to be called hole-doping, the resulting metallic state is qualitatively different from that of the doped band insulator. In the case of the doped Mott insulator, conduction takes place in the same band, regardless of whether electrons have been added or removed. As we don't expect the metallic properties to depend on these small variations in band filling, a high degree

of electron–hole symmetry is expected. The high-temperature cuprates, certainly the most thoroughly studied doped Mott insulator, fail to live up to the expectation of electron–hole symmetry, as is clear from the phase diagram in temperature–doping (T–x) space shown in Fig. 1. On the hole-doped side, antiferromagnetism dies quickly, replaced by a high-temperature superconductor, and below a temperature T^*, by an extensive 'pseudogap' region whose origin is still debated. Electron-doped cuprates have much more robust antiferromagnetic order, lower superconducting critical temperatures and the mysterious pseudogap state is either weaker or non-existent[3].

Understanding these differences may hold important clues to the origin of superconductivity and the other puzzling phenomena in the cuprates. However, a careful comparison between electron and hole doping has, until now, been stymied by the lack of a single material in which both can be realized. The recent discovery of an 'ambipolar' cuprate, YLBLCO, where both electron- and hole-doped regimes can be accessed simply by altering the oxygen composition, provides an ideal platform to study this question.

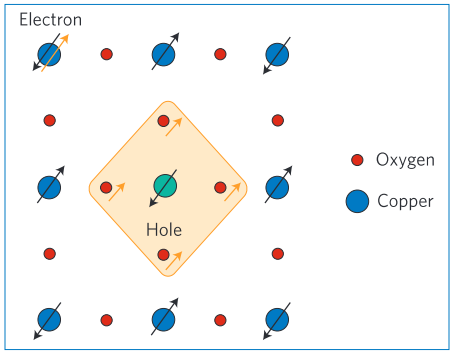

Figure 2 | Fundamental asymmetry in the CuO_2 planes. Electrons go to the copper sites, whereas holes tend to occupy the oxygen sites. Spins generated by doping are shown in yellow.

Segawa *et al.* report[2] that the properties of the electron- and hole-doped states of YLBLCO are very different — with perhaps the most striking difference being efficacy of carrier injection. Electrons are found to be much more effectively injected compared with holes. Thus, a change of oxygen concentration of 0.1 per formula unit leads to 10^5 times as many electrons as holes.

The origin of this difference is yet be clearly pinned down, although the authors speculate that this can be traced to the fact that the cuprates are charge-transfer Mott insulators. Whereas an extra electron is accommodated on the Cu atom, holes live predominantly on the oxygen sites (Fig. 2). They may ultimately be thought of as hole-like excitations on the Cu sites, by means of a mechanism called the Zhang–Rice singlet formation[4]. The resulting dressed object may be regarded as a hole, but with properties rather different from the doped electron. Future work on this remarkable material should help to answer these fundamental questions. ❐

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