DISORDERED ELECTRONS

When silicon is like a cuprate

Recent advances in spectroscopy give access to the decay time of excitations in disordered insulating silicon close to the metal–insulator transition, revealing similarities to high-temperature cuprate superconductors.

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The computer chips at the heart of modern technology are made from doped semiconductors containing deliberate impurities, which are crucial to the electronic properties of these materials. For example, pristine silicon or silicon with a low doping concentration is insulating, whereas silicon with an impurity density above a critical value becomes conducting. Doped semiconductors therefore also present one of the most fundamental problems in condensed-matter physics — the metal–insulator transition. Although we can explain this phenomenon to some extent by assuming electrons do not repel each other, this approximation misses many important details. Understanding the role of electronic interactions in this context is one of the most important open problems of the field. Writing in *Nature Physics*, Fahad Mahmood and co-workers report that they have now demonstrated that electronic excitations in insulating doped silicon are strongly correlated, with surprising similarities to those of cuprate superconductors[1].

The fact that doped impurities end up at random positions in the otherwise ordered structure of the silicon lattice is key. Sufficiently large randomness or low enough dopant density leads to Anderson localization[2]: the quantum states electrons can occupy become confined to small regions of space, electrons can no longer wander freely through the material and the metal becomes an insulator. This transition is well understood if electronic interactions are not important, but a lot of attention has been devoted to the case where they do matter, on both the metallic and the insulating side of the transition[3].

To guide our understanding, we can use the theory of clean metals such as copper. A useful way to think about these so-called Fermi liquids[4] is to start from non-interacting electrons, whose behaviour we understand very well, and 'turn on' electron–electron interactions very slowly. If no phase transition intervenes, the interacting system should behave in a fashion that is similar to the non-interacting one — at least if one looks only at very low temperatures. This concept of 'adiabatic continuity' is like changing the shape and size of an object while still keeping it recognizable.

However, for this approximation to work, the electrons must satisfy a crucial condition: when they gain only a small amount of energy, they must take a very long time to give up this energy to other electrons. This can be quantified by observing how the decay time of excited electrons depends on the gained energy. In normal metals, the relaxation rate of excited electrons vanishes quadratically as the gained energy is reduced, satisfying the conditions for adiabatic continuity. This is why interacting electrons in metals closely resemble their non-interacting counterparts. If the relaxation rate is instead linearly proportional to the gained energy, the decay is not slow enough and the condition underlying the Fermi liquid description breaks down. This fast decay of excited electrons is one of the most puzzling features of some strongly correlated metals, of which high-temperature cuprate superconductors are the most notorious examples[5]. Electronic systems with this phenomenology have been dubbed marginal Fermi liquids[6].

The validity of adiabatic continuity can be verified in clean metals by inferring decay times from measurements of the electrical conductivity. In insulating doped semiconductors, this indirect method is unfortunately not detailed enough to obtain the necessary information. Mahmood and co-workers overcame this limitation using a technique called terahertz two-dimensional coherent spectroscopy[7]. It consists of sending a sequence of two or more short pulses of electromagnetic radiation with frequencies in the terahertz range and measuring the transmitted radiation. Through a clever choice of pulse sequences, it allows one to directly extract the decay times of excitations. One useful feature of this technique is its ability to weed out the effects of spatial inhomogeneities, which is necessary in very disordered insulators such as doped silicon. Furthermore, it enables the separate determination of two different decay times: the relaxation timescale over which an excitation gives up its energy, and the decoherence time that measures how fast an excitation loses its quantum phase coherence.

Mahmood and co-workers' main finding is that excitations of the disordered insulator have relaxation rates that are proportional to the excitation energy. In analogy to the marginal Fermi liquid behaviour of high-temperature superconductors, they called this insulating phase a marginal Fermi glass. This observation is an indication that the idea of adiabatic continuity does not apply to these systems. Moreover, the relaxation time lengthens with increasing temperature, whereas the decoherence time remains unchanged. One would expect decay times to instead decrease with increasing temperatures, because more pathways become available through which to lose energy or phase coherence.

But can this odd phenomenology be rationalized somehow? Mahmood and co-workers argue that it can. Excitations created by the incident terahertz radiation involve the transfer of a negatively charged electron from one localized state to another, leaving a positively charged hole behind. These electron–hole pairs interact with each other via long-ranged dipolar interactions, which play a crucial role in the team's argument. At the same time, there is a finite density of created pairs at small excitation energies owing to unscreened electron–electron interactions. These pairs can coherently hop quantum mechanically from one place to another[8] and provide just the right decay channels to produce the observed energy dependence of the decay times. It is a delicate balance because the specific forms of the dipolar and electron–electron interactions are crucial for the argument to work and be consistent with the experimental results.

The temperature dependence is also consistent with this theoretical picture. Increasing the temperature destroys the quantum-mechanical coherence of the hopping and leads to longer decay times,

although why this does not reduce the measured decoherence time remains an open question. However, this explanation assumes conditions that are applicable only at doping densities far lower than the critical value at the metal–insulator transition. Why these assumptions should remain valid so close to the transition is unclear.

Unfortunately, other poorly understood aspects of doped semiconductors, such as the behaviour of magnetic excitations across the transition[9,10], appear to lie beyond the present scope of the technique. But Mahmood and co-workers have demonstrated the value of terahertz two-dimensional coherent spectroscopy for understanding an important problem in condensed-matter physics. New light sources have only recently made this technique more widely available, and further development may allow it to tackle other challenging problems in doped semiconductors and other strongly correlated systems. ❐

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Competing interests

The author declares no competing interests.