EMERGENT PHENOMENA

Light-induced superconductivity

Intense light pulses irradiating a sample of K_3C_{60} result in dramatic changes of its high-frequency (terahertz) conductivity. Could these be signatures of fleeting superconductivity at 100 K and beyond?

Jure Demsar

Superconductivity is a phenomenon that occurs in certain materials below their (equilibrium) critical temperatures, T_c. Below T_c, the conduction electrons form a concerted state of electron pairs that propagate through the crystal without experiencing scattering — forming a state of zero electrical resistance. By stimulating the superconductor with excitations (photons and phonons) with energies exceeding the pair-binding energy, 2Δ, paired electrons can be split apart and superconductivity destroyed.

Preparing materials with the highest possible T_c has been one of the driving forces of materials science for over a century. Indeed, the discovery of high-T_c superconductivity in copper-oxide compounds (cuprates) in the late 1980s provided materials that, under ambient pressure, superconduct below 134 K (−139 °C). Alternatively, in addition to tuning the properties by varying chemical structure, superconducting properties can be tuned externally, for instance, by applying pressure or by irradiating with light. Whereas pressure changes can give rise to an increase in T_c by changing the lattice constants and interaction strengths, irradiation normally suppresses superconductivity by breaking pairs when the driving frequency is higher than the gap frequency, $2\Delta/h$, where h is Planck's constant. Indeed, given that 2Δ is of the order of millielectronvolts ($2\Delta = 4.14$ meV corresponds to a gap frequency $2\Delta/h = 1$ THz), superconductors are used as sensitive far-infrared detectors. However, the latest experiments by Matteo Mitrano and colleagues[1] suggest that in K_3C_{60}, a short-lived superconductivity can be induced at temperatures up to 100 K when excited with intense mid-infrared optical pulses.

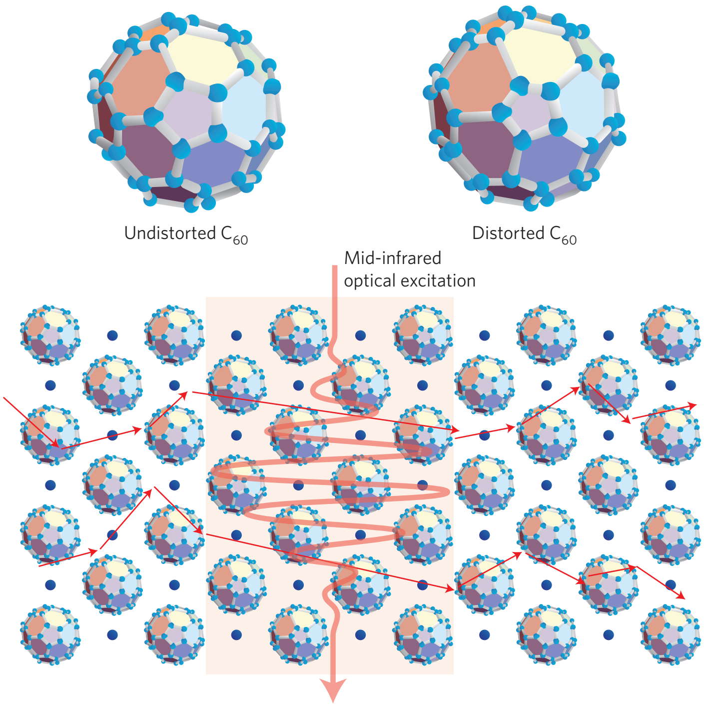

Figure 1 | The proposed[1] mechanism for light-induced superconductivity in K_3C_{60}. Intense mid-infrared pulses (light pink) at 43 THz resonantly drive the T_{1u} molecular vibrations of C_{60} (molecules shown above, where the undistorted is on the left and the distorted is on the right). Large vibrational amplitudes and nonlinear phonon effects result in sizeable, quasistatic (lifetime of ~1 ps) distortions of C_{60} molecules in the K_3C_{60} crystal (represented here by one K_3C_{60} layer, with K^+ ions represented by dark blue spheres). The electron–phonon coupling is enhanced, thereby promoting superconductivity for temperatures greater than T_c. Red arrows denote electron trajectories between scattering events; superconductivity (or enhanced conductivity) in the excited (shaded) region is represented by the lack of electron scattering.

Non-equilibrium superconductivity[2,3] — when a material is exposed to a continuous or a time-varying stimulus — has been studied since the 1960s. One of the most fascinating observations was that the critical current, the superconducting gap 2Δ, and even the critical temperature, were enhanced in thin films of metallic aluminium and tin when illuminated with electromagnetic radiation at sub-gap frequencies[4] (below $2\Delta/h$). Although the superconducting enhancement effects were small (typical changes in T_c on the order of a per cent were demonstrated[2,3]), thus of little practical significance, these puzzling results contradicted all intuitive hypotheses. The first theoretical explanation[5] of these emergent phenomena focused on the interaction of light with low-energy quasiparticles (broken pairs present at all finite temperatures). Sub-gap excitation can excite these quasiparticles away from the edge of the superconducting gap. Because it is these low-energy quasiparticles that interfere most effectively with the pairs, the superconducting gap (and the pair density) can be enhanced when being pushed to higher energies. Following these ideas, enhancement of the superconducting gap was demonstrated using sound waves[6], and — using intense narrow-band terahertz pulses — even in a short mean-free-path superconductor NbN (ref. 7) and for pumping frequencies exceeding $2\Delta/h$.

The alternative route, followed by Mitrano *et al.*[1], is to transiently induce large-amplitude structural distortions and thereby modulate the strength of the pairing glue that binds the electrons together. To do so, they chose fulleride K_3C_{60}, a known superconductor with $T_c \approx 20$ K, in which several models suggest the electron pairing to be mediated by intramolecular vibrations of A_g and H_g symmetry and/or on-site correlations[8]. Although these modes cannot be optically excited directly, the authors argue[1] that molecular distortions along the normal mode coordinates of the H_g symmetry phonons could be externally driven (Fig. 1). They suggest that large amplitude vibrations of the infrared active T_{1u} symmetry mode could be induced, resulting in a quasistatic distortion of H_g symmetry through phonon–phonon (anharmonic) interactions[1]. The emanating distortions could enhance electron–phonon coupling strength and/or on-site correlations to promote superconductivity; the lifetime of such a transient superconducting state would be limited by the phonon lifetime to ~1 ps.

Following this approach, intense 300 fs mid-infrared optical pulses at the central frequency $\nu_{\mathrm{MIR}} \approx 43$ THz (180 meV) were used to (resonantly) excite the T_{1u} phonon of the C_{60} molecule. The resulting changes in the electronic properties were recorded by appropriately delayed phase-stable terahertz pulses, providing access to the complex optical conductivity $\sigma(\omega)$ in the frequency range (0.75–2.5 THz) relevant to the superconductivity fingerprints of K_3C_{60} (in equilibrium $2\Delta/h \approx 1.5$ THz for $T << T_c$). Indeed, for base temperatures far above T_c, the $\sigma(\omega)$ recorded at time 1 ps after optical excitation displays features that are consistent with photoinduced superconductivity: a gap in the real part of conductivity, $\sigma_1(\omega)$, and an enhancement of the imaginary part of conductivity, $\sigma_2(\omega)$, indicative of the inductive response of the condensate. Similarly, the theoretical estimates of the driven quasistatic distortions and their effect on electron–phonon coupling strength and electronic correlations[1] seem to support this idea.

If the results are indeed consistent with the light-induced superconductivity driven by distortions of C_{60} molecules, what are the reasons for the word 'possible' used in the title of the manuscript[1]? Principally, terahertz pulses can neither provide evidence of infinite conductivity at zero frequency, nor can the expulsion of the magnetic field (another hallmark of superconductivity) be determined within the 1 ps time window. But this is an academic argument.

More nontrivial is the fact that experiments performed at temperatures below T_c show a photoinduced suppression of superconductivity. Note that 2Δ, deduced from $\sigma_1(\omega)$ in the photoinduced state at 25 K, is twice the size of the superconducting gap in equilibrium. Following the presented line of thought, where amplification of superconductivity is a result of an increase in pairing strength, one would expect massive gap enhancement also at low temperatures.

Finally, as pointed out by the authors[1], there are several alternative interpretations that could account for the observed $\sigma(\omega)$ in the photoinduced state; for example, a photoinduced sliding charge density wave seems viable. Indeed, taking K^+-ion optical phonons as being responsible for the pairing of carriers in C_{60} molecules, it was shown[9] that a charge density wave state may be stabilized in K_3C_{60}. In a highly non-equilibrium state as here, such a scenario seems equally plausible.

Clearly further experiments and theoretical modelling are required to determine the nature of the observed transient state. Regardless, the presented results are striking, presenting fascinating emergent phenomena far away from equilibrium. ❐

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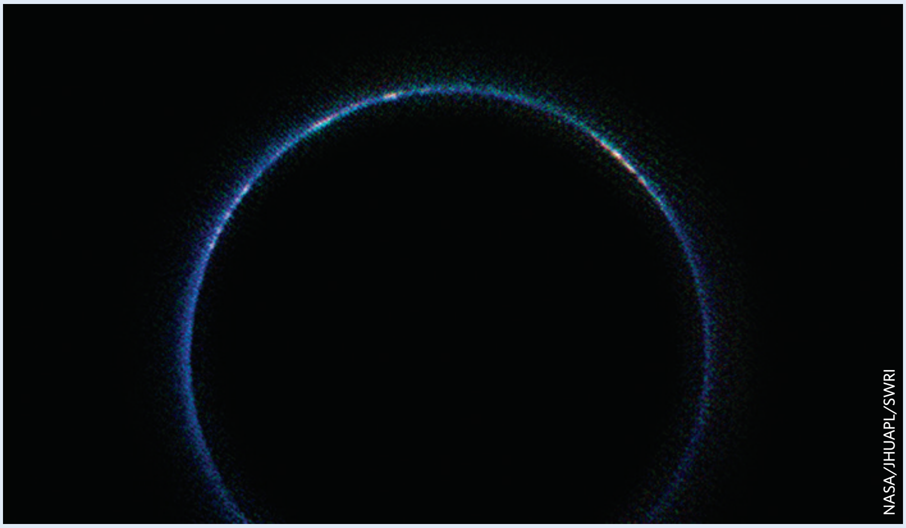
NEW HORIZONS

Small but still special

Pluto may be a planet no longer, but it still has an atmosphere (unlike Mercury). This image, taken by infrared cameras aboard the New Horizons spacecraft on 14 July 2015, shows Pluto's atmosphere at a distance of 180,000 km. It is a true-colour image captured while Pluto was backlit by the Sun, with New Horizons in its shadow (known as occultation). The blue colour comes from sunlight scattering off particles in the haze — a smog consisting of mostly nitrogen gas and particles of mixed hydrocarbons such as acetylene and ethylene.

Given Pluto's distance from Earth, 7.5 billion km at its greatest, the atmosphere was not detected, even indirectly, until 1976. Its surface is mainly nitrogen ice, with frozen methane and carbon monoxide. Incoming cosmic rays vaporize the surface ices to replenish the atmosphere. As the gravity (0.66 m s^{-2}) and atmospheric pressure (1 Pa) are weak, the gases escape at a rate of 10^{27}–10^{28} molecules of nitrogen per second, or at least several hundred metres of surface material over the lifetime of the Solar System. New Horizons will be able to quantify the surface loss so we can gain a better understanding of Pluto's surface evolution.



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