

Cavity-altered superconductivity

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Is it feasible to alter the ground-state properties of a material by engineering its electromagnetic environment? Inspired by theoretical predictions^{1–12}, experimental realizations of such cavity-controlled properties without optical excitation are beginning to emerge^{13–19}. Here we devised and implemented a new platform to realize cavity-altered materials. Single crystals of hyperbolic van der Waals (vdW) compounds provide a resonant electromagnetic environment with enhanced density of photonic states and prominent mode confinement^{20–24}. We interfaced hexagonal boron nitride (hBN) with the molecular superconductor κ -(BEDT-TTF)₂Cu[N(CN)₂]Br (κ -ET). The frequencies of infrared hyperbolic modes (HMs) of hBN (refs. 25,26) match the infrared-active carbon–carbon (C=C) stretching molecular resonance of κ -ET implicated in superconductivity²⁷. Nano-optical data supported by first-principles molecular Langevin dynamics simulations confirm the presence of resonant coupling between the hBN hyperbolic cavity modes and the C=C stretching mode in κ -ET. Meissner-effect measurements using magnetic force microscopy (MFM) demonstrate a strong suppression of superfluid density near the hBN/ κ -ET interface. Non-resonant control heterostructures, including RuCl₃/ κ -ET and hBN/Bi₂Sr₂CaCu₂O_{8+x} (BSCCO), do not show the pronounced superfluid suppression. These observations suggest that hBN/ κ -ET realizes a cavity-altered superconducting ground state. Our work highlights the potential of dark cavities devoid of external photons for engineering electronic ground-state properties of complex quantum materials.

Some of the most exciting properties of solids arise from strong collective interactions among electrons, spins and the crystal lattice. The emergent effects born out of such strong interactions are abundant and drive the formation of varied electronic and magnetic phases. At the vanguard of present interest and debate is the question of whether the strong interaction of the quantum fluctuations of electromagnetic modes in photonic cavities or metastructures with elementary excitations in solids can also prompt phase transitions and lead to new quantum states of matter. A grand aspiration of cavity quantum materials research is to uncover fundamentally new routes for controlling properties of matter by judiciously tailoring the quantum electromagnetic environment^{1–12}. Experiments with dark cavities revealed modified transport properties in the integer and fractional quantum Hall states of a 2D electron gas^{13,17,19}, as well as cavity-assisted thermal control of the metal-to-insulator transition in charge-density-wave

systems¹⁵. Pioneering theoretical works on cavity control of superconductivity explored dark-cavity modification of phonon-mediated pairing through an increase in electron–phonon coupling by means of phonon polaritons^{1,8,9}, Amperean pairing directly mediated through dark-cavity photons^{28,29}, as well as the driven-cavity extension of the Eliashberg effect³⁰.

Here we have chosen to focus on superconductivity as a purely electronic phase transition, devoid of lattice reconstructions and charge or spin orderings. We work with κ -ET, a widely studied layered organic salt that superconducts below the transition temperature $T_c = 11.5$ K (refs. 31,32) (Supplementary Information Sections 1 and 2). We make use of an electromagnetic environment structured by the dipole-active phonons of a thin vdW hyperbolic material, hBN. Hyperbolicity occurs when the permittivity has opposite signs along different axes^{25,26} and results in a highly enhanced photonic density of states^{33–35}.

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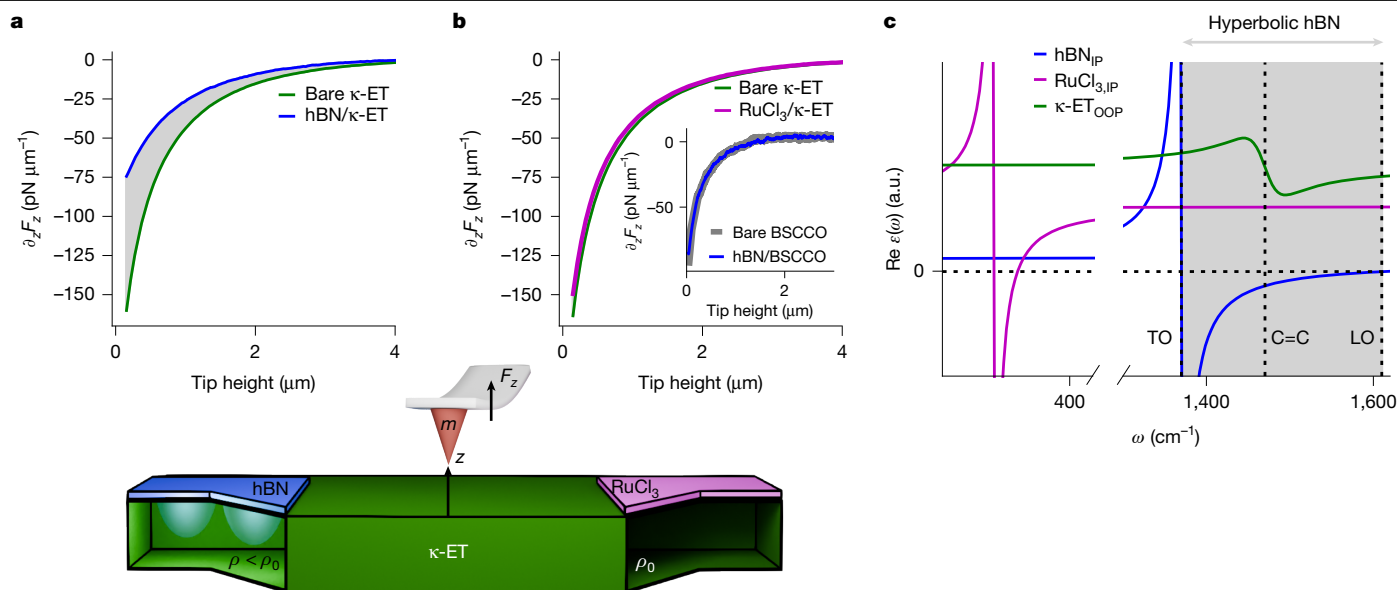


Fig. 1 | Electromagnetic environment alters the superfluid density at the interface between hBN and κ -ET. Schematic at the bottom depicts the Meissner force F_z experienced by the magnetic atomic force microscope tip above the surface of the κ -ET molecular superconductor. Exfoliated hBN and RuCl_3 microcrystals sit on the surface of a bulk κ -ET crystal (optical images in Supplementary Information Section 4). **a, b**, MFM data shown in the form of the derivative of the Meissner force $\partial_z F_z$ as a function of tip height on bare κ -ET (green), hBN/ κ -ET (blue) and RuCl_3 / κ -ET (magenta), taken at temperature 2 K. The κ -ET surface is at $z = 0$ and the grey shading highlights the difference between the two curves. The vertical axes in panels **a** and **b** are identical.

Notably, HMs of hBN overlap with the frequency of the C=C stretching mode of κ -ET at $1,470 \text{ cm}^{-1}$ (ref. 36) and the two modes hybridize at the hBN/ κ -ET interface. Effectively, the hBN slab acts as an electromagnetic cavity (Supplementary Information Section 3) resonantly tuned to the C=C stretching mode of κ -ET that is implicated in superconductivity²⁷. In this work, we examine how superconductivity is altered at the hBN/ κ -ET interface, using advanced scanning-probe-based techniques capable of analysis of electrostatics in buried interfaces.

Meissner effect at resonant interfaces

MFM examines the local superfluid density by means of the repulsive Meissner force experienced by a magnetized tip at the end of a cantilever oscillating above the surface of a superconductor³⁷. The force results from the supercurrent screening the stray magnetic field of the tip. Notably, the Meissner force is not affected when non-magnetic materials are inserted between the tip and the superconductor and the data in Fig. 1a,b confirm that MFM detects superconductors encapsulated by insulating layers. We measure the shift in the resonant frequency of the cantilever, which is proportional to the force gradient $\partial_z F_z$ (Methods). Analysis of $\partial_z F_z$ allows the extraction of the superfluid density ρ_0 (ref. 37) (Methods and Supplementary Information Section 5).

We examine the impact of hBN on superconductivity in a representative heterostructure composed of a 60-nm-thick hBN microcrystal on the surface of a bulk κ -ET single crystal (about $200 \mu\text{m}$ thick). We report $\partial_z F_z$ measured as a function of z , the separation between the tip and the κ -ET surface, in Fig. 1a. On a region of the κ -ET crystal unobscured by hBN (green), $\partial_z F_z(z)$ is negative at $T = 2 \text{ K}$, indicating a repulsive force. The magnitude of $\partial_z F_z(z)$ grows with reduced tip-sample surface separation. The $\partial_z F_z(z)$ signal collected above hBN (blue) shows a weakened $\partial_z F_z$, highlighted by the grey shading. As a control experiment, we placed a 55-nm-thick RuCl_3 microcrystal on top of the same κ -ET sample. RuCl_3 is an insulator with a static permittivity similar to

that of hBN (refs. 38,39). However, optical phonons of RuCl_3 all occur at much lower frequencies below 350 cm^{-1} (ref. 39) and therefore do not resonantly couple to the C=C stretching mode of κ -ET. Figure 1c schematically depicts the permittivities of hBN, κ -ET and RuCl_3 . Comparing measurements above RuCl_3 / κ -ET (Fig. 1b, magenta curve) and bare κ -ET (green curve, same as in Fig. 1a), we observe a much weaker (less than about 7%) effect than over hBN/ κ -ET.

The strong contrast between the RuCl_3 / κ -ET and hBN/ κ -ET interfaces indicates that the suppression of superfluid density under hBN is probably prompted by resonant coupling across the hBN/ κ -ET interface. We remark that the RuCl_3 control experiment rules out a prominent role of charge transfer owing to work-function disparity⁴⁰ in the suppression of the superfluid density in Fig. 1 (Supplementary Information Section 14) and similarly suggests that strain is unlikely to be important. We perform a second control measurement on a heterostructure of 8-nm hBN residing on a 28.5-nm-thick microcrystal of BSCCO with $T_c = 55 \text{ K}$. Crystals of BSCCO host phonons below 650 cm^{-1} (ref. 41), far below the HMs in hBN. MFM data plotted in the inset of Fig. 1b for hBN/BSCCO (blue) are indistinguishable from the data for bare BSCCO (dark grey; Supplementary Information Section 6). Thus, the marked suppression of the superfluid density is specific to the resonant nature of the hBN/ κ -ET interface.

Suppression of superfluid density

We now validate the association of reduced $\partial_z F_z$ (Fig. 1a) with suppressed superfluid density by studying the $\partial_z F_z$ temperature dependence. Over bare κ -ET, the large repulsive $\partial_z F_z$ arises from the Meissner effect (Supplementary Information Section 5), decreases with increasing temperature (Fig. 2a) and vanishes near T_c . Having confirmed that Meissner repulsion is the main contributor to $\partial_z F_z$ over bare κ -ET, we examine the effects at the heterostructure interfaces. We performed constant-height scans with the tip hovering above the κ -ET surface in

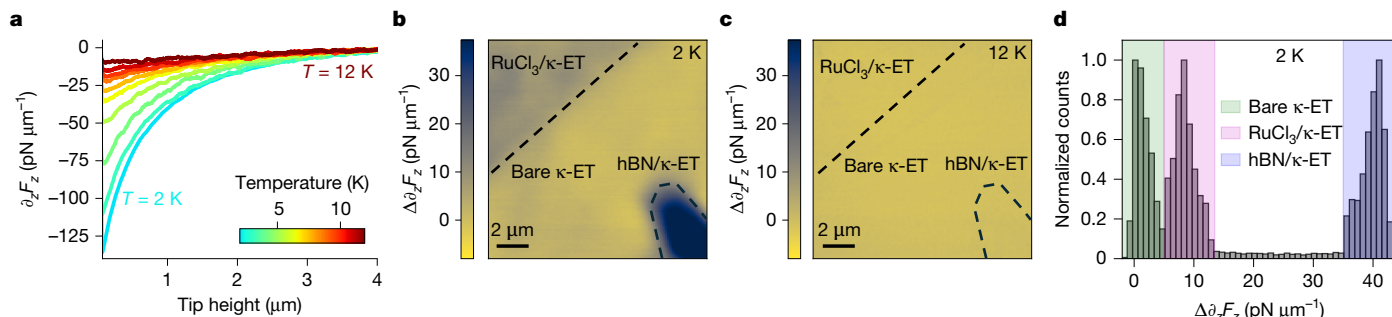


Fig. 2 | Meissner effect by MFM nano-imaging. **a**, $\partial_z F_z$ measured as a function of tip height at temperatures from 2 K to 12 K on bare κ -ET. The curves flatten as the temperature increases (colour scale). **b, c**, Constant-height MFM images over an area with hBN/ κ -ET, bare κ -ET and RuCl_3/κ -ET regions all within the same field of view, taken at a temperature of 2 K (below T_c) with a tip height of 300 nm above the κ -ET surface (**b**) and at 12 K (above T_c) with a tip height of 150 nm above

the κ -ET (**c**). The boundaries of the areas covered by hBN and RuCl_3 are marked by dashed black lines. The false-colour map represents the differential Meissner signal $\Delta\partial_z F_z$. **d**, Histogram of $\Delta\partial_z F_z$ values extracted from the image in panel **b**. Green, magenta and blue shading highlight typical $\Delta\partial_z F_z$ values measured over bare κ -ET, over the RuCl_3/κ -ET interface and over the hBN/ κ -ET interface, respectively.

a $16 \times 16\text{-}\mu\text{m}^2$ region that includes both hBN and RuCl_3 (Fig. 2b,c). To facilitate comparison between data collected at different temperatures, we focus on the differential signal $\Delta\partial_z F_z(x, y) = \partial_z F_z(x, y) - \partial_z F_z|_{\text{bare}}$, in which the latter term stands for $\partial_z F_z$ over bare κ -ET. At 2 K (Fig. 2b), $\Delta\partial_z F_z \approx 40 \text{ pN } \mu\text{m}^{-1}$ over hBN, indicating suppressed superfluid density. Over RuCl_3 , $\Delta\partial_z F_z$ is visibly much smaller. More quantitatively, in Fig. 2d, we show the histogram corresponding to the image of the $\Delta\partial_z F_z$ signal. We witness distinct distributions representing bare κ -ET, RuCl_3/κ -ET and hBN/ κ -ET. The hBN/ κ -ET peak is prominently separated from the other two, indicating the strong effect of hBN on the superfluid density of κ -ET. Supplementary Information Sections 7 and 8 discuss further effects, including possible scenarios for the minor difference between the MFM data registered at the RuCl_3/κ -ET interface and the bare κ -ET. On warming to 12 K, just above T_c , the image contrast disappears, giving $\Delta\partial_z F_z = 0$ everywhere (Fig. 2c). The vanishing $\Delta\partial_z F_z$ near T_c confirms that the weakened $\partial_z F_z$ signal observed at 2 K is associated with a reduction in the superfluid density.

We observe suppression of superfluid density under hBN in several hBN/ κ -ET heterostructures. The magnitude of suppression varies spatially (Supplementary Information Section 8); we focus on regions with the strongest effect. The results are summarized in Fig. 3. To model $\partial_z F_z$ analytically⁴², we make the grossly simplifying assumption that the suppression of the superfluid density is uniform in depth and evaluate the effective superfluid density under hBN, ρ_{eff} . In Fig. 3, we compile MFM data for several devices with hBN cavities and RuCl_3 dielectric layers of various thicknesses. We present data in the form of ρ_{eff}/ρ_0 , in which ρ_0 is the superfluid density in bare κ -ET. In all heterostructures, we observe at least 50% suppression of the superfluid density prompted by the hBN cavity. This result holds over a large variation in the hBN thickness, ranging from 25 nm to 110 nm. Accurate conversion between $\partial_z F_z$ and superfluid density would require knowledge of the depth profile (Supplementary Information Section 5). Although we expect the suppression of superfluid density to be strongest in the immediate vicinity of hBN and to decay into the κ -ET bulk, MFM measurements alone cannot differentiate among the possible depth profiles that all lead to similar $\partial_z F_z$. Nevertheless, the magnitude of the observed suppression of $\partial_z F_z$ implies that superconductivity in κ -ET is affected by the cavity to a substantial depth (Supplementary Information Section 9).

hBN/ κ -ET interface electrodynamics

Next we investigate resonant mode coupling across the hBN/ κ -ET interface. The hBN crystal hosts HMs that exhibit light-like dispersion near the transverse optical (TO) frequency and phonon-like dispersion near the longitudinal optical (LO) frequency²⁰. Here TO and LO refer specifically to the in-plane modes. In practice, the HMs manifest

as hyperbolic phonon polaritons (HPhPs) that can be visualized in nano-optical experiments as originally done in ref. 25. We examine the HPhP dispersion of hBN interfaced with κ -ET through the calculated imaginary part of the p -polarized Fresnel reflection $\text{Im}r_p$, as shown in Fig. 4a (Supplementary Information Section 10). For free-standing hBN, the HPhP dispersion shows a series of branches between the TO and LO phonon frequencies, each with a continuous dispersion²⁵. By contrast, for a hBN/ κ -ET heterostructure, the HPhP branches are interrupted near the C=C stretching frequency (dashed box in Fig. 4a). Avoided crossings are visible, yet the gaps in the HPhP dispersion are not fully developed because of broadening caused by dielectric loss associated with the in-plane response of κ -ET (ref. 43) (Supplementary Information Section 10).

To experimentally examine the mode coupling at the hBN/ κ -ET interface, we used scattering-type scanning near-field optical microscopy (s-SNOM)⁴⁴. Specifically, we evaluated the HPhP dispersion of hBN as its modes couple to the C=C stretching mode of κ -ET. We illuminated the metallized tip of an atomic force microscope with a frequency-tunable infrared laser. The strong electric field with high momentum achieved near the tip apex launches polaritonic waves. We performed nano-infrared measurements at $T = 50 \text{ K}$ on a region of

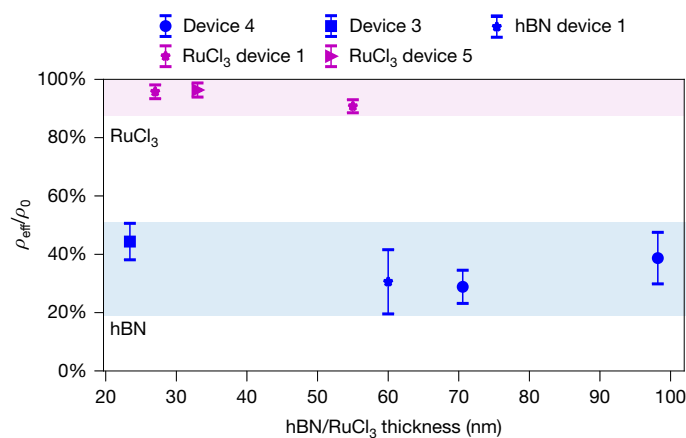


Fig. 3 | Quantifying superfluid density suppression. ρ_{eff}/ρ_0 (defined in the main text) shown as a function of cavity thickness. Measurements on hBN/ κ -ET and RuCl_3/κ -ET are shown in blue and magenta, respectively. Symbols distinguish different devices. The superfluid density is assumed to be uniformly suppressed underneath the hBN and RuCl_3 microcrystals. Error bars correspond to the error in local superfluid density from uncertainty in tip geometry (Supplementary Information Section 5) and exclude spatial variations of the hBN/ κ -ET interface (Supplementary Information Section 8).

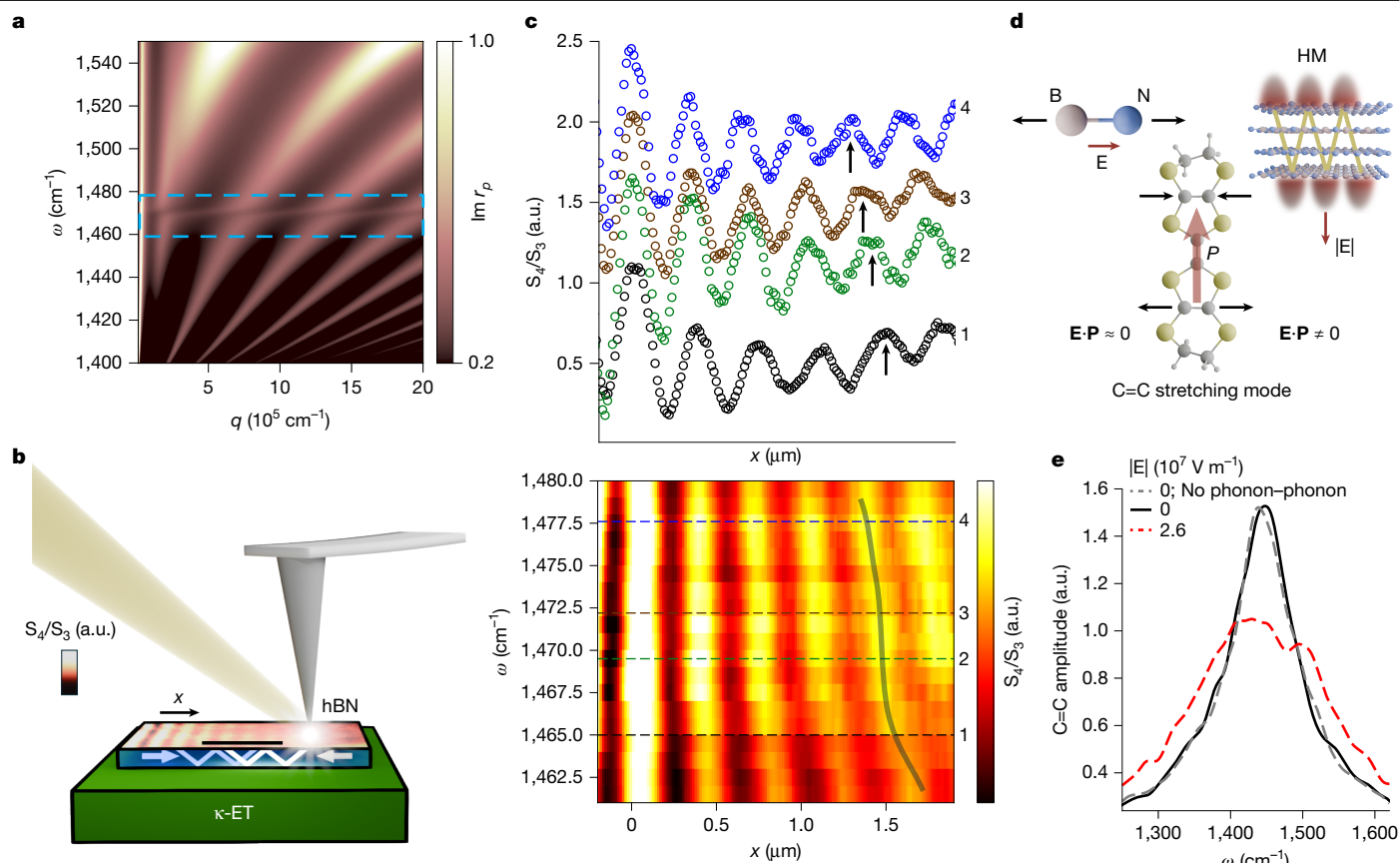


Fig. 4 | Mode coupling at the hBN/ κ -ET interface. **a**, Phonon-polariton dispersion for a hBN/ κ -ET interface (32-nm hBN, 100-nm κ -ET), represented by a false-colour map of the imaginary part of the Fresnel reflection coefficient r_p . See Methods for calculation details. **b**, s-SNOM experiment schematic on a hBN/ κ -ET heterostructure, showing continuous-wave light backscattered by an atomic force microscope tip. Phonon polaritons in hBN launched by the tip reflect off the hBN edge, forming interference patterns in the s-SNOM amplitude. The image shown was taken with incident light frequency $\omega = 1,477.6 \text{ cm}^{-1}$. The false-colour scale represents the normalized scattering amplitude S_4/S_3 , in which S_4 and S_3 are the near-field amplitude demodulated at the fourth and third harmonics of the tip-tapping frequency, respectively. Scale bar, $1 \mu\text{m}$. **c**, Bottom, hyperspectral image of S_4/S_3 at various illumination frequencies, for which x is along the phonon polariton propagation direction.

a hBN/ κ -ET heterostructure with 32-nm hBN on 100-nm κ -ET. Fringes arising from the interference of propagating HPhPs were observed in the nano-infrared images: representative results are shown in Fig. 4b for $\omega = 1,477.6 \text{ cm}^{-1}$. Line profiles from s-SNOM collected with varying incident light frequency show that the HPhP wavelength changes with photon energy (Fig. 4c). In free-standing hBN, the real-space fringes arising from HPhP interference evolve smoothly with the frequency⁴⁵. However, in our data on κ -ET-supported hBN, the fringe evolution exhibits an evident kink near the C=C frequency, indicated by the solid line tracking the fifth peak in Fig. 4c. These nano-infrared data attest to mode coupling across the hBN/ κ -ET interface.

To gain insight into the experimentally observed mode coupling, we take a closer look at the interplay between the zero-point fluctuations of the hBN HMs and the C=C stretching mode. First-principles molecular Langevin dynamics simulations indicate that the coupling arises from the interaction of the transverse component of the electric field of the HMs with the C=C stretching mode. The C=C stretching mode exhibits a dipole moment that is directed primarily out-of-plane (Fig. 4d and Supplementary Information Section 2). It is important to note that the electric field of the HMs has an out-of-plane component that can couple to the C=C mode (Fig. 4d). The combined contributions of

The overlay highlights the kink in the dispersion. Selected profiles are presented in the top panel. Black arrows mark the location of the fifth fringe. The profiles are vertically shifted for clarity. **d**, Schematic showing the coupling between the C=C stretching resonance and the HM of hBN enabled by the out-of-plane component of the electric field of the HMs discussed in the main text and further analysed in Supplementary Information Sections 2 and 3. **e**, The calculated spectrum of the C=C stretching mode amplitude for BEDT-TTF molecules on hBN (black curve). The grey curve has phonon-phonon scattering suppressed. The red curve is the spectrum in the presence of an oscillating out-of-plane electric field from the HMs of hBN, with field strength $2.6 \times 10^7 \text{ V m}^{-1}$. See Supplementary Information Section 11 for calculation details. a.u., arbitrary units.

many HM branches reaching high momenta make this field extend far beyond the hBN surface (Supplementary Information Section 3). We therefore calculate the C=C amplitude in the presence of an oscillating out-of-plane electric field with a frequency spectrum spanning the C=C frequency (fundamental frequency $\omega_0 = 1,440 \text{ cm}^{-1}$). Langevin molecular dynamics analysis carried out at $T = 2 \text{ K}$ (Supplementary Information Section 11) shows that the out-of-plane electric field induced by the zero-point HM fluctuations reduces the C=C amplitude and splits the peak in Fig. 4e. We therefore conclude that zero-point HM motion mediates the coupling between HMs and molecular vibrations without the need for external photons.

Hyperbolic cavity electrostatics

The data in Figs. 1–4 demonstrate that cavity electrostatics plays a pivotal role in suppressing the superfluid density—a hallmark equilibrium attribute of superconductivity. These experiments also establish a precedent for successfully altering the ground state thermodynamic property of a material through cavity engineering. Our specific implementation of the resonant structure exploits two notable features of hyperbolic cavity control. First, HMs entail both in-plane and

out-of-plane components of the fluctuating electromagnetic fields. The out-of-plane component is crucial for coupling to the primarily out-of-plane dipole moment of the C=C stretching mode in the κ -ET superconductor under investigation. Second, the numerous branches of the HMs enable interaction with the weakly dispersing C=C resonance at several intersections over a broad range of momenta, as shown in Fig. 4a. Future experiments need to evaluate the spatial extent of the mode coupling away from the hyperbolic interface; our earlier data for a similar resonant hBN/MoO₃ heterostructure suggest that the relevant length scale may exceed approximately 10² nm (ref. 46). Our data and modelling suggest a plausible pathway for cavity enhancement of superconductivity. As an illustrative example, we consider the scenario of an optical phonon in a superconductor coupled to a hBN cavity within the framework of Bardeen, Cooper and Schrieffer (BCS) theory (Supplementary Information Section 13). Electron–phonon coupling, quadratic in the phonon coordinate^{1,47}, results in a suppression of the superfluid density, whereas linear coupling results in enhancement. This analysis suggests that conventional superconductors may exhibit increased superfluid density through interactions with HMs. Here we pause to warn the reader: κ -ET studied in our work is an unconventional superconductor⁴⁸ and BCS-derived inferences can only guide our intuition. A rigorous description of the physics involved in cavity-coupled κ -ET awaits further investigation. We conclude by highlighting that the concept of using readily reconfigurable vdW hyperbolic cavities for resonant manipulation of material properties is rather general. HMs of phononic, plasmonic and excitonic origin are hosted in many vdW materials including insulators and semiconductors, as well as a variety of emerging materials²⁴. These modes span the range from THz to visible⁴⁹, thus offering limitless options for hypercavity engineering.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41586-025-10062-6>.

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Methods

Device fabrication

The heterostructures were fabricated by placing vdW materials of thicknesses on the order of 10–120 nm on large flat surfaces of κ -ET single crystals (a - c crystallographic plane; Supplementary Information Section 2). Measurements were performed on six devices (Supplementary Information Section 4). Data in Fig. 1 are from device 1, in Fig. 4 from device 2, in Fig. 2b–d from device 1 and in Fig. 2a from device 6. The data in Fig. 3 represent a compilation of results from devices 1, 3, 4 and 5.

The κ -ET crystal surfaces were as-grown (devices 1, 4 and 5), exposed by cleaving bulk crystals (devices 3 and 6) or exposed by exfoliating single crystals (device 2). For bulk samples, the κ -ET single crystal was fixed onto a silicon substrate using either epoxy or silver paint. For devices 3 and 6, the crystal was then cleaved to expose new surfaces. Large atomically flat surfaces were then selected by optical and atomic force microscopy. As-grown surfaces were regularly found to be atomically flat. Cleaved surfaces showed larger variations in surface roughness. For each device, MFM measurements spanned time periods ranging from weeks to months and, in general, included several thermal cycles. For all devices, no sign of degradation was found.

Both hBN and RuCl_3 microcrystals were exfoliated using a standard scotch-tape technique onto a polydimethylsiloxane (PDMS) stamp and identified through optical and atomic force microscopy. The stacking process was performed using a commercial transfer stage with temperature control. The PDMS stamp was gently pressed onto the κ -ET surface and then slowly retracted. The hBN microcrystals were released at approximately 60 °C, whereas the RuCl_3 microcrystals in devices 1 and 5 were released at around 110 °C and 130 °C, respectively. Isotopically pure hBN (^{10}B) was used to achieve a narrow linewidth for the TO phonon. The narrow linewidth makes HPhPs visible in s-SNOM.

hBN/BSCCO samples were prepared by exfoliating and assembling BSCCO and hBN crystals in a glovebox filled with inert gas ($\text{O}_2 < 0.1$ ppm; $\text{H}_2\text{O} < 0.1$ ppm). BSCCO was first exfoliated on SiO_2 substrates. hBN microcrystals were then exfoliated on a PDMS stamp and transferred onto BSCCO at room temperature.

s-SNOM

The nano-infrared scattering experiments were performed using a home-built cryogenic scattering-type scanning near-field optical microscope (s-SNOM) housed in an ultrahigh-vacuum chamber with a base pressure of about 7×10^{-11} torr.

The s-SNOM is based on a tapping-mode atomic force microscope with the tapping frequency and amplitude of the atomic force microscope set to approximately 285 kHz and 70 nm, respectively. The s-SNOM operates by scattering tightly focused laser light from a sharp atomic force microscope tip, enabling near-field interactions to be investigated with nanometre-scale resolution. The laser source is a tunable quantum cascade laser from Daylight Solutions. The laser beam was focused onto the metallized atomic force microscope tip using a parabolic mirror with a 12-mm focal length.

The backscattered light was registered by a mercury cadmium telluride detector and demodulated following a pseudoheterodyne scheme. The signal was demodulated at the n th harmonic of the tip-tapping frequency, yielding a background-free near-field signal. In this work, we selected $n = 3$ and 4 to eliminate the far-field background⁵¹.

MFM

MFM measurements were performed in an Attocube cantilever-based cryogenic atomic force microscope (attoAFM I with attoLIQUID2000 cryostat), in which the microscope sits in a helium exchange gas at low temperature. Nanosensors PPP-MFMR probes with hard magnetic coatings and force constants near $k = 2.8 \text{ N m}^{-1}$ were used for all measurements. Measurements were taken on different samples using different tips, all with resonance frequencies ranging from 75.5 kHz to 79.4 kHz.

Measurements recorded the resonant frequency shift of the probe cantilever (Δf) and were converted to $\partial_z F_z$ through $\partial_z F_z = -2k/f_0 \times \Delta f$ (ref. 52), using the force constant k provided by the manufacturer for each cantilever and the measured resonant frequency far from the sample surface, f_0 . The tip oscillation amplitude was typically 50–70 nm. hBN is non-magnetic and therefore has no impact on the detection of the Meissner effect over hBN/ κ -ET. RuCl_3 is antiferromagnetic at low temperature but has a low susceptibility.

To minimize noise and instrument drift, $\Delta f(z)$ was typically averaged over several measurements repeated at each point and taken with high z resolution (typically 1–2 nm to define the surface accurately). During the measurements, the tip was electrically biased to compensate for the local contact potential difference and thus minimize electrostatic forces. The average curves were then smoothed with a uniform filter with width 30–50 pixels to reduce the appearance of noise. For the κ -ET heterostructures, a linear background was subtracted by fitting the data far from the sample surface at which the $\partial_z F_z$ is negligible. For the BSCCO sample, a background measured on the silicon substrate was subtracted (Supplementary Information Section 6). For proper comparison in Fig. 1, we have compensated for the thickness of the hBN and RuCl_3 microcrystals such that the measurements for hBN/ κ -ET, bare κ -ET and RuCl_3/κ -ET all have the κ -ET surface at zero. The analysis of penetration depth and superfluid density from MFM data followed previous works referenced in the main text, as well as further works^{42,53}, and is described in full in the Supplementary Information.

Constant-height MFM images were taken with the tip at a fixed height above the plane of the κ -ET surface. The images shown are raw data, except for the linear conversion from Δf to $\partial_z F_z$ and an overall constant offset to calculate $\Delta \partial_z F_z$. During the measurements, the tip was held at a fixed electric bias to compensate for the contact potential difference at one point in the field of view.

The data points in Fig. 3 were obtained either by fitting $\partial_z F_z(z)$ curves or by converting constant-height MFM images to maps of the local λ_{in} , the decay length for currents running parallel to the surface. λ_{in} was converted to superfluid density through the proportionality to $1/\lambda^2$, as described in Supplementary Information Section 5.

HPhP dispersion simulation

The HPhP dispersion was calculated using the transfer-matrix method. The dispersion is represented by peaks in the imaginary part of the Fresnel reflectivity of the device for p -polarized light, r_p . In the dispersion calculation, we consider the real-valued frequencies and momentum. For coupling analysis, the eigenmodes are found by determining the poles of r_p , for which the complex frequencies and real momentum are considered.

Data availability

The data that support the findings of this study are present in the paper and its Supplementary Information. Further data are available from the corresponding authors on request. Source data are provided with this paper.

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Author contributions I.K., T.A.W., J.X. and G.P. collected and analysed MFM data. I.K. and T.A.W. wrote the manuscript. S.Z. and S.S.Z. collected SNOM measurements. S.Z. and J.Z. analysed SNOM data. S.Z. simulated the HPhP dispersion for hBN on κ -ET. D. Sun and B.S.Y.K. fabricated the heterostructures, with input from C.R.D. G.P. performed scanning electron microscopy imaging

of the MFM tips. J.Y. and Q.L. performed SQUID magnetometry measurements. T.O. provided simulations of the electric field for a z -dependent superfluid density and an oscillating dipole above hBN. J.H.E. grew the hBN. M.J., R.P.P. and S.W. provided discussion and interpretation of the data, as well as formulation of the idea. K.M. and K.K. grew the κ -ET crystals. G.G. grew the BSCCO crystal. D.M. and M.C. grew the RuCl_3 crystal. M.B., A.C. and A.J.M. provided discussion and interpretation of the data. D.M.K. provided guidance on fitting and participated in the discussion on mechanisms. M.H.M. computed the quantum electric field fluctuations from a thin film of hBN. D. Shin performed the ab initio calculations under the supervision of A.R., D. Shin, M.H.M. and A.R. analysed the ab initio results and developed a microscopic model for the quenching of superconductivity. E.V.B. developed the analytical model for BCS–HM coupling. M.A.S. provided theoretical input on the interpretation of results and contributed to the manuscript. A.N.P. advised on measurements and data interpretation. D.N.B. advised and supervised the project. All authors discussed the results and contributed to the final paper.

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Additional information

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