Major progress has been made in recent years in identifying new topological states of matter; however, the extent to which topological protection is manifested in realistic systems and the microscopic mechanisms that lead to its apparent breakdown remain poorly understood. The quantum Hall effect is a prime example of a topologically protected state that exhibits quantized dissipationless electron transport. Although an extremely high degree of conductance quantization has been achieved in engineered systems in gallium arsenide (GaAs) heterostructures and in graphene, quantum Hall devices commonly exhibit small but fundamentally important deviations from the ideal quantized conductance. Various mechanisms that undermine the topological protection have been explored, including imperfect contacts, current-induced breakdown, absence of edge equilibration and edge reconstruction. Nonetheless, exactly how the dissipation in the quantum Hall regime occurs on a microscopic level has not been directly identified. Here we provide nanoscale imaging of the dissipation processes in the quantum Hall state in graphene and reveal the intricate mechanisms that compromise the apparent global topological protection.

A superconducting quantum interference device—SQUID-on-tip (SOT)\(^1\), which acts as a nanothermometer (tSOT) with microkelvin sensitivity\(^3\) and has an effective diameter of around 50 nm—was scanned approximately 50 nm above the surface of high-mobility hexagonal boron nitride (hBN)-encapsulated graphene devices (see Methods) at \(T = 4.2\) K. Three modalities were used simultaneously (Fig. 1a, see Methods): (i) d.c. thermal imaging, which maps the local temperature variations \(T_{\text{dc}}(\mathbf{r})\) induced by an externally applied current \(I_{\text{dc}}\). The current was chopped at around 94 Hz and \(T_{\text{dc}}(\mathbf{r})\) was recorded using a lock-in amplifier. (ii) a.c. thermal imaging, in which the tSOT is mounted on a quartz tuning fork and vibrates parallel to the sample surface at a frequency of around 35 kHz with an amplitude \(x_{\text{ac}}\) of around 8 nm. The resulting \(T_{\text{ac}}(\mathbf{r}) = x_{\text{ac}} \partial T_{\text{dc}}(\mathbf{r})/\partial x\) provides a high-sensitivity map of the local temperature gradients. (iii) Scanning gate mode\(^3\), in which a voltage \(V_{\text{gs}}\) is applied to the tip and the induced variations in the two-probe, \(R_{\text{xy}}(\mathbf{r})\), or four-probe, \(R_{\text{xy}}(\mathbf{r})\), sample resistance is imaged.

Topological protection in an idealized integer quantum Hall system is manifested by three guiding principles\(^5\). First, the quantum Hall plateau the current flows along ballistic chiral edge channels with no backscattering and no dissipation except at the current contacts. Second, in the plateau transition regions, dissipation sets in through Joule heating, however, the dissipation mechanism comprises two distinct and spatially separated processes. The work-generating process that we image directly, which involves elastic tunnelling of charge carriers between the quantum channels, determines the transport properties but does not generate local heat. By contrast, the heat and entropy generation process—which we visualize independently—occurs nonlocally upon resonant inelastic scattering from single atomic defects at graphene edges, and does not affect transport. Our findings provide an insight into the mechanisms that conceal the true topological protection, and suggest routes towards engineering more robust quantum states for device applications.
corresponding quantized conductance is robust against local perturbations and is determined by the bulk Chern number and the bulk-edge correspondence.

Global transport measurements of our devices show common quantum Hall characteristics—including conductance quantization (see Methods and Extended Data Fig. 4) — which are qualitatively consistent with the above principles. However, when inspected microscopically, we find these principles to be largely violated. A d.c. current, $I_{dc}$, is driven through the narrow bottom constrictions and drained at the top-right contact (arrows) in presence of an applied field $B_{app} = 1.0$ T at $4.2$ K. At lower filling factors (Fig. 1d) the dissipation is greatly enhanced in both downstream and upstream directions with no visible chirality, and extends over the entire length of the edges with no apparent decay (Supplementary Information section 1).

Finally, an example of violation of the third principle is demonstrated in Fig. 1e. Topologically protected states should be robust against local perturbations, and hence positive $V_{bg}$ — which depletes holes on a scale much smaller than the sample size — should not affect global transport properties. However, contrary to this, the two-probe resistance $R_{pp}$ of a 30-µm sample is profoundly affected by a perturbation on a scale of about 50 nm (the tip size). The large increase in $R_{pp}$ occurs only along the graphene boundaries and is observed over a wide range of $V_{bg}$ both at quantum Hall plateaus (Supplementary Video 2) and at plateau transitions (Fig. 1e). It is also of note that the $R_{pp}$ signal is visible along the entire length of the boundaries.

For a closer inspection, we focus on the dashed rectangle in Fig. 1b with a square-shaped protrusion in the top-left corner. The higher-resolution $T_{ac}(r)$ image (Fig. 2a) reveals a disordered heat signal concentrated along two separate contours. The outer contour consists of a series of thermal rings centred along the physical edge of graphene (dashed line). The inner contour, with arc-shaped features, is visible further inside the sample. Critically, the simultaneously acquired scanning gate image of $R_{sg}(r)$ signal (Fig. 2b) mimics precisely the $T_{ac}(r)$ signal along the inner contour, while showing no response along the outer contour or elsewhere. This difference indicates that the inner and outer contours arise from fundamentally different mechanisms.

To decipher the different mechanisms, we consider a diffusive system in steady state with strong electron–phonon coupling. In this system, dissipation is described by local Joule heating $P(r) = W = J(r) \cdot E(r) = Q(r)$, where power $P$ is the rate of work $W$ per unit volume, performed by current density $J$ driven by an electric
field \( \mathbf{E} \). In this case, the work \( W \) is transformed into heat \( Q \) locally, and hence \( W(r) = Q(r) \). Conversely, dissipation in a ballistic system can be highly nonlocal, resulting in \( W(r) = Q(r) \), as illustrated in Fig. 2c for elastic tunnelling through a potential barrier. The work generation \( W(r) \) occurs only where the carriers are accelerated by \( \mathbf{E} \) within the barrier. Meanwhile, processes that generate heat, \( Q(r) \), or entropy, \( Q/T \), occur nonlocally as carriers lose their excess kinetic energy remotely via inelastic scattering of phonons far from the initial barrier.

In general, one should consider three main stages: work generation, equilibration through electron–electron scattering, and heat transfer to the environment through phonon emission. The equilibration process due to electron–electron scattering in the quantum Hall channels has been extensively studied by spectroscopic transport measurements\(^\text{12–14} \). Such electron–electron scattering results in energy redistribution within the electronic bath, which is undetectable by our technique because no energy is transferred to the phonon bath. In the following, we focus on the first stage of \( W \) generation and the last stage of \( Q \)-release into the phonon bath under steady-state conditions, in which the details of the intermediate electron–electron scattering process have no substantial effect. In other words, we address the question of where and how the work is generated and where and how the heat is transferred to the environment.

In an ideal current-carrying ballistic channel, no work-generating processes can take place because there is no potential drop along the channel, \( E(r) = 0 \), and hence \( W(r) = 0 \). Paradoxically, however, heat can still be generated by the entropy-generating processes, \( Q(r) \). This is the situation at higher \( v \), in which analogous to the tunnel barrier in Fig. 2c—work \( W(r) \) is performed at the bottom constriction in Fig. 1c by injecting energetic charge carriers into the quantum Hall edge channels. These chiral carriers flow downstream ballistically and cause nonlocal heating by losing their excess energy to phonons. At low temperatures and in the absence of disorder, electron–phonon coupling is very weak, and as such, phonon emission occurs predominantly through resonant inelastic scattering off single atomic defects along the graphene edges\(^\text{15} \). These defects form quasi-bound states with sharp energy levels that mediate electron–phonon coupling when in resonance with the incoming charge carriers\(^\text{15,16} \), giving rise to the \( Q \) rings observed in Figs. 1c, 2a. Because only forward carrier scattering is allowed in chiral quantum Hall channels, phonon scattering does not affect conductivity and is thus invisible in the \( R_{\text{hg}}(r) \) image in Fig. 2b and can coexist with full conductance quantization.

At lower fillings, however, markedly different behaviour is observed (Supplementary Information section 1 and Supplementary Video 1). The \( Q \) rings along the graphene boundaries in Figs. 1d, 2a still reflect nonlocal dissipation, but they are apparently not ‘powered’ by the work generated at the constriction, as evidenced by a lack of observable chirality and of signal decay. Instead, the \( W \) process occurs along the inner contour in Fig. 2b, where carriers tunnel elastically between neighbouring quantum Hall channels with different electrochemical potential \( \mu \), as illustrated schematically in Fig. 2d. The tip positioned at \( r \) modifies the local separation between the channels by its potential \( V_{\text{tg}} \). When channels are brought closer together, the tunnelling rate increases and the corresponding backscattering current increases by \( \delta b_{\text{tg}}(r) \), which in turn increases \( R_{\text{tg}}(r) \) and generates excess local work at a rate of \( \delta W(r) \times \delta b_{\text{tg}}(r)(\mu_+(r) - \mu_-(r)) \). However, this \( W(r) \) process is elastic and therefore does not generate local \( Q(r) \), and no phonons are emitted locally (see Methods and Extended Data Fig. 9). Instead,
the backscattered carriers release their excess energy \( \mu_b(r) - \mu_i(r) \) to phonons elsewhere, predominantly at atomic defects on graphene boundaries. The emitted phonons propagate ballistically, which increases the overall sample temperature—including at the instantaneous position of the tip, \( r \). Because the resulting overall increase in \( \delta T \) and the increase in \( R_{xx}(r) \) are both proportional to the tip-induced \( \delta W(r) \), increases the overall sample temperature—including at the instantaneous position of the tip, \( r \).
the $T_{er}(r)$ signal in Fig. 2a along the inner contour accurately mimics the $R_{er}(r)$ signal in Fig. 2b, even though no local $Q(r)$ is generated (see Methods and Extended Data Fig. 9).

The above picture, however, raises yet another question. In conventional integer quantum Hall regime, backscattering is prohibited by chirality unless in the presence of counterpropagating channels. Such counterpropagating channels are typically only present at the opposite sample edges, whereas the described $W(r)$ process requires proximity between them (Fig. 2d). Our findings, therefore, provide microscopic evidence for the presence of edge reconstruction induced by charge (holes) accumulation along the graphene edges, as has been suggested previously$^{17–20}$.

To control this edge reconstruction and investigate its origin, we incorporated plunger gates as described in Fig. 3a–c and Extended Data Figs. 2, 3. As detailed in Fig. 3d, e, band bending due to charge accumulation along the edges creates pairs of counterpropagating quantum Hall channels, which are not topologically protected and exist in addition to the standard topological channels dictated by the bulk-edge correspondence$^{26–29}$.

These ‘nontopological’ channels provide the means for $W(r)$ backscattering and work generation along the entire edge of the sample, as evidenced in Fig. 1d, e, 2h, 3f–h. The presence of band-bending-induced nontopological channels is largely insensitive to the bulk $V$, and therefore the backscattering $W(r)$ occurs for both compressible and incompressible bulk (Supplementary Information section 2, Supplementary Video 2). Moreover, as the nontopological pairs are present at both edges of the sample, the $W(r)$ and the resulting nonlocal $Q(r)$ show no chiral directionality (Fig. 1d, e). The backscattering rate is determined by the separation between the counterpropagating channels, which we can tune by the plunger-gate potential $V_{pg}$. Notably, by increasing the hole accumulation the separation between the channels is increased (Fig. 3i, j), which leads to elimination of $W(r)$ (Fig. 3k) and of the associated nonlocal heating (Fig. 3l, m) in the region of the plunger gate. Upon further accumulation of holes (see Supplementary Information sections 3, 6 and Supplementary Video 3 for the full sequence) the $W(r)$ unexpectedly reappears, but at the bulk side of the plunger gate (Fig. 3n–r), where two copropagating channels (blue and green in Fig. 3o) are formed and hence no backscattering is naively expected. The green channel, however, creates a closed loop and therefore serves as a backscattering mediator between the downstream $\mu_l$ (red) and upstream $\mu_r$ (blue) channels. Because the green and red channels copropagate along a longer path and are in close proximity due to the steep edge potential (Fig. 3n), the electrochemical potential of the green channel will be close to $\mu_l$. As a result, the overall backscattering rate will be determined by the tunnelling rate between the green and blue channels, explaining the dominant $W(r)$ signal along this segment. Note that the patterns along this segment (Fig. 3p–r and Supplementary Fig. 2h, i) are smoother, emphasizing the dominant role of edge disorder in the formation of the complex $W(r)$ arc-like patterns along the graphene edges (Figs. 1d, 2a, b). Also, because there are almost no atomic defects in the bulk of graphene$^1$, no $Q(r)$ rings are observed along this segment (Supplementary Video 3).

The $Q(r)$ rings are resolved only along the graphene boundaries (Supplementary Fig. 2), powered by the remote $W(r)$, which is consistent with the observed separation of $Q(r)$ and $W(r)$ contours in Fig. 2.

Even though the plunger gate affects a small region, it considerably influences the global transport (see Methods). A positive (hole-depleting) $V_{pg}$ cuts off the nontopological pairs, increasing $R_{er}$ (Extended Data Fig. 5d) and forcing the current to bypass the plunger-gate region through the bulk (see Methods and Extended Data Fig. 6). A large tip potential $V_{tt}$ can also cut off the nontopological pairs, as described in Methods, Extended Data Fig. 8, Supplementary Information section 5 and Supplementary Video 5. Note also that the measured $R_{er}(r)$ is essentially independent of the current (Supplementary Information section 4 and Supplementary Video 4), which rules out possible current-induced quantum Hall breakdown$^4$.

The edge reconstruction explains the previously reported discrepancies in the quantum Hall state of graphene$^4$ and in other two-dimensional electron gas systems$^{12,13}$. Although several mechanisms have been proposed$^{14–17}$, edge accumulation has been mainly ascribed to electrostatic gating$^{18,19}$, which should lead to symmetric edge accumulation of holes and electrons for $p$ and $n$ doping respectively. We find that at charge neutrality and for both dopings, the accumulation remains hole-type (see Methods and Extended Data Fig. 7), which indicates that the accumulation is predominantly governed by negatively charged impurities. We observe hole-accumulation for both etched and native edges (dashed line in Fig. 1b), despite no chemical exposure for the latter, suggesting that broken bonds at graphene edges become naturally negatively charged. Similar edge accumulation was recently reported in an InAs two-dimensional electron gas$^{20}$. Notably, in proximity-induced superconductivity in graphene and InAs two-dimensional electron gases, the supercurrent was observed to flow preferentially along the edges$^{21–23}$. Our results may shed light on the underlying mechanism, which is in turn important for studies of topological superconductivity and Majorana physics$^{24–26}$. Note that the upstream edge channels can undermine the apparent topological protection only if the channels are not well equilibrated$^6$. We observe the equilibration length of the upstream channels to be in excess of our sample size of 30 µm (Supplementary Information section 3), which provides a possible explanation for the difficulty in achieving precise quantum Hall quantization in exfoliated graphene devices. Our findings suggest that the detrimental edge reconstruction can be mitigated by passivation or edge-potential engineering$^{27,28}$. The developed concept of simultaneous work and dissipation imaging, combined with their nanoscale control and spectroscopic analysis, provides a tool for the investigation of microscopic mechanisms of energy loss and scattering in various quantum and topological systems and in operational electronic nanodevices.

Online content

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Methods

Device fabrication
Monolayer graphene heterostructures were fabricated by exfoliating natural graphite and hBN flakes onto oxidized silicon wafers (290 nm of SiO₂) and stacking via a polymer stamping method. This method can achieve contamination-free areas limited only by the size of the hBN. Our devices comprised a relatively thick bottom hBN crystal (>30 nm) with a thinner (10–20 nm) crystal covering the monolayer graphene. We intentionally misaligned the graphene edges with respect to either hBN (>5°) to avoid any superlattice effects. For samples B and C incorporating a plunger gate, the bottom gate structures were first patterned and metallized with Cr/Au (1 nm/9 nm), followed by transferring of the annealed hBN/graphene/hBN heterostructure.

We used electron beam lithography (Raith EBPG5200) with a bilayer (A3 495K, A3 950K) polymethyl methacrylate (PMMA) mask to define both the contact location and sample geometry. To improve either contact resistance or edge sharpness, we incorporated two different CHF₃ and O₂ reactive ion etching (RIE) recipes for each of the contacts and mesa definition. Contacts were defined by mixed chemical/physical etching (5 W RIE, 150 W inductively-coupled plasma (ICP)) to improve selectivity for hBN over PMMA, and thus allowing etching and metallization in a single step. Mesa etching incorporated a physical RIE process (20 W RIE, 0 W ICP), followed by a weak Ar/O₂ RIE etch to remove the residual exposed graphene step at the edges. Contact metallization was achieved via e-beam evaporation of Cr/Au (1 nm/70 nm) and standard lift-off procedure. Finally, before scanning, the samples were soaked in a tetramethylammonium hydroxide (TMAH)-based alkaline developer (MIF-319) to remove residual PMMA resist from the surface of the heterostructure. These fabrication procedures are known to produce samples with high electron mobility and ballistic transport, with a momentum-relaxing free path limited by the sample dimensions.

Sample A had a main chamber of 30 × 10 μm² (Fig. 1b, Extended Data Fig. 1). Constrictions of 300 and 200 nm width at the bottom and top-left edges were designed to allow injection of energetic carriers into the quantum Hall edge channels. We also etched a series of 1.5 × 1.5 μm² holes in the centre of the main chamber in order to visualize dissipation in the centre of the device by detecting holes in the centre of the main chamber in order to visualize dissipation of the sample contacts is measured using a lock-in amplifier locked to the second harmonic of the d.c. current, a sinusoidal a.c. current Iₜₛₒₜ which is acquired by a lock-in amplifier locked to the second harmonic frequency 2f.

d.c. thermal imaging Tₑₑₑ(rijk). A current Iₑₑₑ is applied to the sample and chopped by a square wave at a frequency of 94 Hz and the corresponding thermal map Tₑₑₑ(rijk) of the sample is acquired using lock-in amplifier locked to the chopping frequency. As a result, the Tₑₑₑ(rijk) image provides a map of the current-induced local temperature increase in the sample.

Second harmonic thermal imaging Tₑₑₑ(rijk). Similar to the Tₑₑₑ(rijk), instead of the d.c. current, a sinusoidal a.c. current Iₑₑₑ is applied to the sample at frequency f and the corresponding thermal map Tₑₑₑ(rijk) of the sample is acquired by a lock-in amplifier locked to the second harmonic frequency 2f.

a.c. thermal imaging Tₑₑₑ(rijk) at tuning fork frequency. Using the fact that the tSOT is mounted on the tuning fork, we also measure Tₑₑₑ(rijk) and the corresponding thermal map Tₑₑₑ(rijk) of the sample is acquired using lock-in amplifier locked to the second harmonic frequency 2f.

Scanning gate imaging R(rijk). By applying a voltage Vₕ between the tSOT and the sample we carry out scanning gate imaging using a method similar to those reported previously simultaneously with the thermal imaging. In particular, the voltage difference V between a pair of sample contacts is measured using a lock-in amplifier locked to the chopping frequency of the current Iₑₑₑ, and then R(rijk) = V(rijk)/Iₑₑₑ(rijk) is plotted against the tip location r. In this manner either two-probe, Rₑₑₑ(rijk), or four-probe, Rₑₑₑ(rijk), tip-position dependent resistance values are attained.
Transport characteristics

Four-point transport characterization measurements were performed using standard lock-in techniques at 5.4 Hz. Extended Data Fig. 4 shows the Landau fans of samples B and C. From the slopes of the resistance minima we extract the capacitance $C = \frac{\varepsilon \varepsilon_0}{\rho_0 W} = \frac{1}{2, 1.6, 1.0, 0.7, \ldots} \times 10^2 \text{ F cm}^2 = 6.27 \times 10^2 \text{ eV}^2 \text{ cm}^2 \text{ V}^{-1}$ for sample B and $0.85 \times 10^2 \text{ eV}^2 \text{ cm}^2$ for sample C, where $e$ is the elementary charge. Using the zero field resistivity data $\rho_n$, we derive the mobility $\mu = \frac{1}{\rho_n e v_F} = 7.0 \times 10^9 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and the mean free path $l_m = \frac{1}{2k_B T_0 e^2} = 4.5 \mu\text{m}$ at $n_s = 2.8 \times 10^4 \text{ cm}^{-2}$ for sample B, and $\mu = 2.13 \times 10^9 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $l_m = 1.19 \mu\text{m}$ at $n_s = 2.4 \times 10^4 \text{ cm}^{-2}$ for sample C; $h$ is Planck’s constant. Here $n_s = C (\rho_n - \rho_{bg})/e$ is the carrier density, $\nu = n_s e g_B/B$ is the filling factor, $\rho_{bg} = -0.6 \text{ V}$ is the charge neutrality point ($-1.85 \text{ V}$ for sample C), $v_F = \sqrt{\mu e n_s}$ is the graphene Fermi wavevector, and $g_B = h/e$. Because of its unconventional geometry and limited working contacts, we could not properly measure the Landau fan diagram of sample A to extract its mobility and mean free path. However, $R_n$ measurements show a similar behaviour, from which we extract $\rho_{bg}$ and the approximate filling factors. Note that Figs. 1 and 2 were acquired at different cool downs, resulting in a shift in $\rho_{bg}$.

Extended Data Fig. 5 describes the effect of plunger gate on the global transport. Because the size of the plunger gate is much smaller than the sample, it should naively have no measurable effect in a topologically protected state. Extended Data Fig. 5b shows that, when analysed on a linear scale, the variations in $\alpha_n$ and $R_n$ with $V_{pg}$ may not appear to be very substantial; however, on a logarithmic scale (Extended Data Fig. 5c) variations of up to two orders of magnitude in $R_n$ are visible, in particular around $v = 2$ plateaus. Extended Data Fig. 5d shows $R_n$ at $V_{bg} = -1 \text{ V}$ in the vicinity of the $v = 2$ plateau plotted against $V_{pg}$ displaying a stepwise increase from $R_n = 100 \Omega$ to over $4 \Omega k$ for $V_{pg} > -0.23 \text{ V}$. Hole edge accumulation creates additional pairs of counterpropagating nontopological channels that reduce the sample resistivity. When the hole accumulation is depleted by applying a positive $V_{pg}$, the highly conductive nontopological channels are cut off (Extended Data Fig. 6a), leading to the observed sharp increase in $R_n$. Hole edge accumulation is present also for n-doping of graphene and is visible in Extended Data Fig. 5c up to $V_{bg} = -2.3 \text{ V}$, above which the $\rho_{bg}$ dependence decreases considerably, indicating the dominant contribution of negatively charged impurities to the hole edge accumulation (see Methods).

Cutting off the non-topological edge channels by plunger gate $V_{pg}$

The enhanced conductivity of the nontopological pairs of channels due to hole accumulation provides low resistance paths for the current flow. This accumulation, however, can be locally depleted by the plunger gate with $V_{pg} = -0.23 \text{ V}$, as indicated by transport measurements in Extended Data Fig. 5d. In this case, the nontopological pairs are cut off (Extended Data Fig. 6a), causing a pronounced increase in the global $R_n$. Notably, in this situation the current that is carried by the nontopological channels is partially forced to flow through the bulk in the cut off segment. A depleting $V_{pg}$ increases the local bulk resistivity under the tip, therefore enhancing $R_n(r)$ (as observed by the diffused red blob in Extended Data Fig. 6b and Supplementary Video 3), revealing the current path through the bulk. Note that the topologically protected channel remaining in the depleted region (red in Extended Data Fig. 6a) still carries current; however, the resulting potential drop that develops across the plunger gate region imposes a parallel partial conduction through the bulk. The current that flows in the topological channel, however, cannot be visualized by $R_n(r)$ because the downstream flowing carriers there cannot backscatter to another channel and do not perform work. However, these carriers can still lose their excess energy by phonon emission at the atomic defects, giving rise to the $Q$ rings along the graphene boundaries as observed in Extended Data Fig. 6c.

Because the nontopological channels are cut off, this case provides an insight into work and dissipation that should occur in their absence. Extended Data Fig. 6b shows that the carriers tunnel between the edge states through the bulk as expected in the quantum Hall plateau transition regions. When the nontopological edges are present, however, they shunt the bulk by providing low-resistance paths for carrier backscattering and hence hardly any work and dissipation are observed in the bulk of the sample even in the plateau transition regions.

Hole accumulation at the graphene edges for n-doped bulk

Edge charge accumulation causes the formation of nontopological pairs of channels that provide a low-resistance path for current flow. These nontopological pairs can be cut off by a depleting plunger gate leading to an increase in $R_n$. In the case of hole accumulation this is demonstrated by applying a positive $V_{pg}$ while a negative $V_{pg}$ does not affect $R_n$ substantially because increasing local accumulation only lowers the local resistance, which is already relatively low (Extended Data Fig. 5d). Extended Data Fig. 5c shows that for negative $V_{pg}$ (p-doped bulk) a depleting (positive) $V_{pg}$ increases $R_n$. If the edge accumulation would be solely caused by backgate electrostatics $\nu = 2$ and 6 plateaus would be visible, whereas a negative $V_{pg}$ would deplete the electron accumulation along the edges thus increasing $R_n$. However, Extended Data Fig. 5c shows that it is not the case and $R_n$ is increased by a positive $V_{pg}$ even in the n-doped region ($V_{pg} \lesssim 2.3 \text{ V}$). This implies that for moderate n-doping of the bulk, the edges still remain p-doped, as confirmed microscopically in Extended Data Fig. 7. Here the $R_n(r)$ scans for n-doped bulk show that—similarly to the case of p-doped bulk—a positive, rather than a negative, $V_{pg}$ increases the resistance along the edges. This hole edge accumulation is clearly resolved in the vicinity of $v = 2$ and 6 plateaus as shown in Extended Data Fig. 7a, b.

Demonstration of the elastic $W(r)$ scattering and nonlocal heating

We present here a more detailed evidence that the $W(r)$ process is predominantly elastic. For this we first summarize the effect of the tip potential $V_{tg}$ which is crucial for revealing the described phenomena. At flat band conditions $V_{tg} = 1.45 \text{ V}$ the tip has no influence on the sample. In this case $R_n(r)$ is fixed independent of the tip position (Extended Data Fig. 8a) and therefore the $W(r)$ processes cannot be imaged (Extended Data Fig. 9a). Nonetheless, the $T_n(r)$ signal due to $Q(r)$ processes is present, but the phonons—even though they are being emitted predominantly at resonant states at atomic defects—propagate ballistically throughout the sample. As a result, the $T_n(r)$ profiles are smooth (Extended Data Fig. 9b) and hence the atomic-scale $Q(r)$ sources cannot be resolved individually.

Upon applying a finite $V_{tg}$, however, both the $Q(r)$ and $W(r)$ processes can be clearly identified. The individual $Q(r)$ sources are revealed through the formation of the temperature rings around them (for example, Supplementary Fig. 2), which reflect the loci of the tip positions at which the tSOT potential $V_{tg}$ brings the localized resonant electronic states of the defects to the Fermi energy. Similarly, applying a small positive $V_{bg}$ allows imaging of the locations at which $W(r)$ is present and hence revealing the locations of the nontopological channels by shifting them slightly closer to each other (Extended Data Fig. 8b), thus enhancing the local elastic tunnelling rates between them by $\delta W(r)$ and increasing the $R_n(r)$. The observed rich patterns of $\delta W(r)$ reflect the intricate trajectories of the quantum Hall channels and the variations in the local separation between them due to electrostatic disorder. In particular, it reveals the nontopological channels at the inner edge of the plunger gate in Extended Data Fig. 9c. A further increase of the depleting $V_{pg}$ can entirely cut off the nontopological pairs (Extended Data Fig. 8c) and even induce an n-doped region under the tip (Extended Data Fig. 8d).

Because the nontopological channels are cut off, this case provides an insight into work and dissipation that should occur in their absence. Extended Data Fig. 6b shows that the carriers tunnel between the edge states through the bulk as expected in the quantum Hall plateau transition regions. When the nontopological edges are present, however, they shunt the bulk by providing low-resistance paths for carrier backscattering and hence hardly any work and dissipation are observed in the bulk of the sample even in the plateau transition regions.

Hole accumulation at the graphene edges for n-doped bulk

Edge charge accumulation causes the formation of nontopological pairs of channels that provide a low-resistance path for current flow. These nontopological pairs can be cut off by a depleting plunger gate leading to an increase in $R_n$. In the case of hole accumulation this is demonstrated by applying a positive $V_{pg}$ while a negative $V_{pg}$ does not affect $R_n$ substantially because increasing local accumulation only lowers the local resistance, which is already relatively low (Extended Data Fig. 5d). Extended Data Fig. 5c shows that for negative $V_{pg}$ (p-doped bulk) a depleting (positive) $V_{pg}$ increases $R_n$. If the edge accumulation would be solely caused by backgate electrostatics the situation would be inverted for n-doped bulk; namely, a negative $V_{pg}$ would deplete the electron accumulation along the edges thus increasing $R_n$. However, Extended Data Fig. 5c shows that it is not the case and $R_n$ is increased by a positive $V_{pg}$ even in the n-doped region ($V_{pg} < 2.3 \text{ V}$). This implies that for moderate n-doping of the bulk, the edges still remain p-doped, as confirmed microscopically in Extended Data Fig. 7. Here the $R_n(r)$ scans for n-doped bulk show that—similarly to the case of p-doped bulk—a positive, rather than a negative, $V_{pg}$ increases the resistance along the edges. This hole edge accumulation is clearly resolved in the vicinity of $v = 2$ and 6 plateaus as shown in Extended Data Fig. 7a, b.
Throughout the paper we refer to the $W$ process of carrier tunnelling between the channels as a purely elastic process with no local phonon emission, in which case all the $Q$ processes are nonlocal (Fig. 2d). One can also consider a higher-order inelastic tunnelling between the channels, in which a phonon is emitted concurrently with tunnelling, resulting in a local $Q$ at the tunnelling location. We can discern the two cases by considering the perturbation induced by the tip potential. A weakly perturbing tip has two effects: enhancing backscattering $\delta W(\mathbf{r})$, thus revealing the locations of $W(\mathbf{r})$ processes through $R_n(\mathbf{r})$ imaging (Extended Data Fig. 9c); and enhancing heating (either local or nonlocal) as a result of the enhanced $\delta W(\mathbf{r})$. Figure 2, Supplementary Fig. 2 and Supplementary Video 3 clearly demonstrate that the $Q$ rings at atomic defects along the graphene boundaries reflect nonlocal heating. However, the observed enhanced temperature signal along the quantum Hall channels (for example, on the bulk-side edge of the plunger gates in Extended Data Fig. 9d) could reflect either local heating due to higher-order inelastic carrier tunnelling between the quantum Hall channels or a nonlocal heating due to phonons emitted at remote locations causing overall temperature increase detected as an enhanced $T_{\text{dc}}(\mathbf{r})$ at the instantaneous position of the tip $\mathbf{r}$. These two possibilities are hard to distinguish by inspecting only the tip-perturbing images such as those in Extended Data Fig. 9d. A non-perturbing tip, by contrast, performs only one function: imaging the unperturbed temperature distribution. If the tunnelling between quantum Hall channels is elastic then the heating is nonlocal and thus the maximum of $T_{\text{dc}}(\mathbf{r})$ should occur along the graphene boundaries where the phonons are emitted at the atomic defects regardless of where $W(\mathbf{r})$ occurs. If, on the other hand, the tunnelling is inelastic, a peak in $T_{\text{dc}}(\mathbf{r})$ should occur along the $W(\mathbf{r})$ contours. Usually the $W(\mathbf{r})$ contours are located close to the graphene boundaries, but near the sample corners they can be considerably shifted towards the bulk (Fig. 2a, b) or, alternatively, we can shift them in a controllable manner using the plunger gate (Extended Data Fig. 9).

Extended Data Fig. 9e, f presents three $T_{\text{dc}}(\mathbf{r})$ profiles along the colour lines in Extended Data Fig. 9b for the case of a non-perturbing tip. The green profile shows that $T_{\text{dc}}(\mathbf{r})$ is maximal along the graphene boundaries with a slowly decaying tail into the bulk of the sample due to ballistic phonon propagation. The red and blue profiles show that the slow tails of $T_{\text{dc}}(\mathbf{r})$ originating from the three boundaries overlap, resulting in a plateau-like profile in the sample protrusion region. The key observation, however, is that the blue profile in Extended Data Fig. 9e shows no peak in $T_{\text{dc}}(\mathbf{r})$ at the location of the $W(\mathbf{r})$ contour on the bulk side of the plunger gate as revealed in Extended Data Fig. 9c. d. These results demonstrate that the $W(\mathbf{r})$ scattering is predominantly elastic and that the $Q(\mathbf{r})$ dissipation is predominantly nonlocal occurring at the atomic defects at graphene boundaries.

Data availability

Data supporting the findings of this study are available within the article and its Supplementary Information files and from the corresponding authors upon reasonable request.

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Additional information

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Extended Data Fig. 1 | Optical image of sample A. Shown are the hBN/graphene/hBN heterostructure (green), the etched regions exposing the SiO₂/Si substrate (dark) and the metal contacts (yellow). The dashed rectangles mark the regions shown in Fig. 2 (red) and Supplementary Video 2 (blue). The current is applied to the bottom constriction and drained at the top contact, and the corresponding voltages $V_{xx}$ and $V_{z}$ are measured in the scanning-gate mode. The dashed line on the right shows the native edge of graphene encapsulated in hBN.
Extended Data Fig. 2 | Optical and scanning electron microscopy images of sample B. 

**a**, Optical image showing the hBN/graphene/hBN heterostructure (light green), etched trenches exposing the SiO$_2$/Si substrate (light blue), bottom plunger gates (light brown) and the metal contacts (dark). The dashed rectangle marks the region shown in Fig. 3, Extended Data Figs. 6, 7, 9, Supplementary Fig. 2 and with variable voltage $V_{pg}$ applied to the plunger gates.

**b**, Scanning electron micrograph of a twin sample of device B showing (from bright to dark) the metal contacts, four plunger gates, hBN/graphene/hBN, and the etched trenches.

The current is applied to the top contact and drained at the bottom contact and the corresponding voltages $V_{xx}$ and $V_{sg}$ are measured in the scanning gate mode.
Extended Data Fig. 3 | Optical image of sample C. Shown are the hBN/graphene/hBN heterostructure (light brown), etched trenches exposing the SiO₂/Si substrate (light cyan) and the metal contacts (yellow). The bottom plunger gates are difficult to distinguish in the optical image and are artificially highlighted in a dark orange colour. The dashed rectangle marks the region shown in Supplementary Fig. 2. The current is applied to the top contact and drained at the bottom, and the corresponding voltages $V_{xx}$ and $V_{pp}$ are measured in the scanning gate mode.
Extended Data Fig. 4 | Transport measurements of samples B and C. a, b, Colour rendering of $R_{xx}$ of samples B (a) and C (b) as a function of the back-gate voltage $V_{bg}$ and the applied perpendicular magnetic field $B_z$. 
Extended Data Fig. 5 | Effect of the plunger gate on transport characteristics. 

**a**, An optical image of device B with the measurement circuit shown. 

**b**, Four-probe measurements of Hall conductance $\sigma_{xy}$ and $R_{xx}$ against back-gate voltage $V_{bg}$ for different $V_{pg}$ values at $B_z = 0.9$ T and $I_{ac} = 50$ nA at 93.72 Hz. A voltage of 3 V was applied to the two plunger gates on the right edge and -3 V was applied to the top plunger gate on the left edge. In this configuration the nontopological quantum Hall channels on the right edge of the sample are cut off, giving rise to enhanced $R_{xx}$ response on the left edge upon varying $V_{pg}$. 

**c**, $R_{xx}$ plotted against $V_{bg}$ from **b** plotted on a logarithmic scale. 

**d**, Values from the four-probe measurement of $R_{xx}$ plotted against $V_{pg}$ at $V_{bg} = -1$ V (dashed line in c).
Extended Data Fig. 6 | Visualization of bulk current flow upon cutting off nontopological channels. a, Schematic trajectories of quantum Hall edge channels with the nontopological pair of channels cut off by the hole-depleting plunger gate. b, Scanning gate $R_{xx}(r)$ image in sample B at $V_{bg} = -1.2\, \text{V}$, $V_{tg} = 3\, \text{V}$, $V_{pg} = -0.1\, \text{V}$ and $I_{dc} = 1.75\, \mu\text{A}$, revealing current flowing through the bulk in the cut-off region (diffuse red blob). c, $T_{ac}(r)$ acquired simultaneously with $R_{xx}(r)$ showing Q rings along the graphene boundaries due to nonlocal dissipation. The images were acquired in the dashed red area in Extended Data Fig. 2.
Extended Data Fig. 7 | Demonstration of hole edge accumulation in n-doped bulk. 

**a.** Scanning gate $R_{xx}(r)$ imaging of sample B (in the red dashed area in Extended Data Fig. 2) in the vicinity of n-doped $\nu = 2$ plateau ($V_{bg} = 0.12$ V, $\nu = 2.07$, $V_{pg} = -2$ V, see Extended Data Fig. 5c for transport) using a positive $V_{tg}$ of 6 V. The depletion of the hole accumulated edges by the positive $V_{tg}$ cases increase in $R_{xx}(r)$ similar to the case of the p-doped bulk. 

**b.** Same as **a** in the vicinity of the $\nu = 6$ plateau ($V_{bg} = 1.475$ V, $\nu = 5.98$). In both images, $I_{dc} = 1.75 \mu$A.
Extended Data Fig. 8 | Effect of the tip potential $V_{tg}$ on the quantum Hall channels with p-doped edge accumulation. 

**a–d.** Schematic trajectories of the edge channels upon increasing $V_{tg}$. 

**a.** Non-perturbing tip at flat band conditions $V_{tg} \approx 0\text{V}$. 

**b.** Application of a weakly perturbing $V_{tg}$ slightly reduces the edge hole accumulation and shifts the nontopological quantum Hall channels closer to each other. 

**c.** A stronger depleting $V_{tg}$ cuts off the nontopological pair of channels. 

**d.** A higher $V_{tg}$ forms an n-doped region under the tip.
Extended Data Fig. 9 | See next page for caption.
Extended Data Fig. 9 | Demonstration of elastic tunnelling by comparing perturbing and non-perturbing tip potential in sample B. a, Two probe $R_{2p}(r)$ in the case of non-perturbing $V_{bg} = 0.05\, V$ showing essentially constant $R_{2p}(r)$. b, The corresponding $T_{dc}(r)$ shows the current-induced temperature variation in the sample unperturbed by the tip at $V_{bg} = -1.1\, V$ ($\nu = -1.44$), $V_{bg} = -2\, V$ and $I_{dc} = 1.75\, \mu A$. The increased temperature at the bottom-right corner is caused by heat diffusion from the hot spot at the nearby current contact. c, $R_{2p}(r)$ for $V_{bg} = 3\, V$ revealing the location of $W(r)$ processes by perturbing the local work by $\delta W(r)$ through enhanced backscattering. d, The corresponding $T_{dc}(r)$ showing the temperature map mimicking the $R_{2p}(r)$ signal caused by the enhanced nonlocal heat release $Q$ due to tip-induced $\delta W(r)$. e, Horizontal line cuts of $T_{dc}(r)$ along the green and blue lines in b. The green data show a peak at the graphene boundary (dashed yellow line in b) followed by a slowly decaying tail into the bulk, whereas the blue data display no peak at the inner edge of the plunger gates, showing that the $W(r)$ process there is elastic. f, Vertical line cut through the protrusion region showing peaks at the graphene boundaries with overlapping tails in the middle. The coloured dots are the intersection points of the lines.