

Landau Velocity for Collective Quantum Hall Breakdown in Bilayer Graphene

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Breakdown of the quantum Hall effect (QHE) is commonly associated with an electric field approaching the inter-Landau-level (LL) Zener field, the ratio of the Landau gap and the cyclotron radius. Eluded in semiconducting heterostructures, in spite of extensive investigation, the intrinsic Zener limit is reported here using high-mobility bilayer graphene and high-frequency current noise. We show that collective excitations arising from electron-electron interactions are essential. Beyond a noiseless ballistic QHE regime a large super-Poissonian shot noise signals the breakdown via inter-LL scattering. The breakdown is ultimately limited by collective excitations in a regime where phonon and impurity scattering are quenched. The breakdown mechanism can be described by a Landau critical velocity as it bears strong similarities with the roton mechanism of superfluids. In addition, we show that breakdown is a precursor of an electric-field induced QHE-metal transition.

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The Fermi sea of a 2D electronic system (2DES) is unstable at high magnetic field (B field) toward the formation of discrete Landau levels, giving rise to the quantum Hall effect (QHE) [1], where the bulk is a quantum Hall insulator. The QHE has led to many developments in metrology [2,3] and quantum electronics [4]. The fate of the QHE at high electric field (E field) remains an open question, as well as the nature of the phase reached when the drift velocity $\mathbf{v}_D = \mathbf{E} \times \mathbf{B}/B^2$ approaches the cyclotron velocity $R_c\omega_c$, where R_c and ω_c are the cyclotron radius and frequency, resulting in cyclotron orbit breaking. A precursor of the transition is the quantum Hall breakdown reported soon after the discovery of QHE [5–7]. The breakdown field E_{bd} marks the onset of longitudinal resistance and dissipation. Its natural scale is the Zener field, $E_c \sim \hbar\omega_c/eR_c$, with $\omega_c = eB/m^*$ and $R_c \sim \sqrt{N}l_B$, where m^* is the effective mass, N the number of occupied Landau levels (LLs), and $l_B = \sqrt{\hbar/eB}$ the magnetic length [8]. The relevance of the Zener mechanism was soon questioned as E_c exceeds experimental E_{bd} . Besides, genuine inter-LL tunneling suffers from a strong

momentum mismatch at finite doping, $\Delta k = 2k_F$, where $k_F = \sqrt{2N}/l_B$ is the Fermi wave vector [9]. It can be circumvented assuming impurity-assisted or phonon-mediated quasielastic inter-LL scattering (QUILLS) [8,10].

Breakdown was extensively investigated in semiconductors [6,7,11–16] and graphene [17–20], but mainly in Hall bars. Few experiments used constrictions [7,11], or Corbino geometries [21–24], with the purpose of achieving homogeneous current, or E -field, distributions. In all cases $E_{bd} < E_c$ and critical Hall current densities $J \lesssim 50$ A/m [18]. The leading explanation thus shifted to a thermal instability, driven by the imbalance between dissipation and phonon relaxation [25]; its threshold is smaller and material dependent [17,18,26,27]. According to low-frequency noise measurements, the thermal instability eventually gives rise to electron avalanches [11,21,22]. On comparing breakdown ($v_{bd} = J_{bd}/ne$) and Zener ($v_c = E_c/B$) velocities one finds $v_{bd}/v_c \sim 0.01$ in Hall bars and $v_{bd}/v_c \lesssim 0.5$ in constrictions, presumably due to electrostatic inhomogeneities.

We propose a scenario where breakdown stems from the spontaneous generation of collective excitations at the

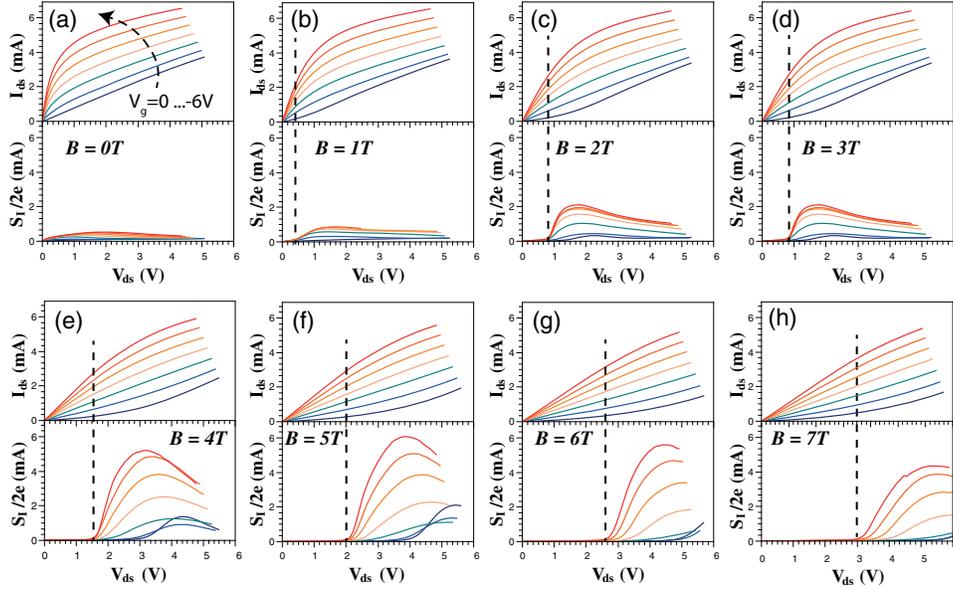


FIG. 1. High electric-field magnetotransport and 5 GHz shot noise in bilayer graphene of dimensions $L \times W = 4 \times 3 \mu\text{m}$ at $T = 4 \text{ K}$. (a)–(h) High-bias transport current $I_{\text{ds}}(V_{\text{ds}})$ and shot-noise current $S_I/2e(V_{\text{ds}})$ in the hole doping QHE regime $|n| = 0\text{--}4.3 \times 10^{12} \text{ cm}^{-2}$ corresponding to $V_g = 0 \rightarrow -6 \text{ V}$. In quantizing fields ($B \gtrsim 2 \text{ T}$) shot noise is suppressed at low bias where $G_{\text{ds}} = |n|e/B$, rises up abruptly at a breakdown voltage (dashed black lines), peaks to a large value eventually reaching the full shot-noise limit $S_I \approx 2eI_{\text{ds}}$ ($B = 5 \text{ T}$), and vanishes as conductance saturates to a field-independent value $G_{\text{sat}} \simeq 0.6 \text{ mS}$.

magnetoexciton (ME) minimum [28]. Similar excitations exist in fractional QHE [29] that are longitudinal and called magnetorotons in reference to the roton minimum in superfluids [30]. Elusive in spectroscopy, high-momentum excitations can be probed by measuring the critical drift velocity (Landau velocity v_L), when their excitation gap, $\omega(q) - v_L q$ in the laboratory frame of reference, vanishes. Recent examples are given by superfluid helium-3 [31] and quantum gases [32]. The case of MEs is generically similar with, however, a transverse polarization, and a series of N minima in the dispersion relation with a spectral weight vanishing for $q \gtrsim k_F$ [33]. With $q_{\text{ME}} \sim k_F$ and $\omega(q_{\text{ME}}) \sim \omega_c$, MEs yield $v_L \sim \omega_c/k_F$ identical to the Zener velocity $v_c = E_c/B \sim \omega_c l_B/\sqrt{N}$. We note that a similar mechanism was proposed in Ref. [40] to explain the steplike breakdown in GaAs/AlGaAs heterostructures [6,41]. We report on QHE measurements in a clean bilayer graphene (BLG) micro-sample, a two-terminal rectangular sample of dimensions $L \times W = 4 \times 3 \mu\text{m}$ [33], chosen here as a prototypical massive 2DES ($m^*/m_0 \simeq 0.03$). The QHE regime persists up to large velocities, $v_{\text{bd}} \lesssim 1.7 \times 10^5 \text{ m/s}$ [Fig. 2(a)], approaching the intrinsic limit $v_{\text{bd}} \simeq v_c$. We reveal the collective nature of breakdown using shot noise. We report on large Fano factors $\mathcal{F} \lesssim 20$ and highlight the scaling of shot noise with the Zener field and Landau energy.

A representative set of the current and noise measurements is presented in Figs. 1(a)–1(h). The bias-induced QHE breakdown is signaled by a strong uprise of noise, widely exceeding the zero B -field value, and eventually approaching a full shot noise limit $S_I \approx 2eI_{\text{ds}}$. The contrast

with the ballistic QHE regime, where noise is essentially suppressed [42], is striking with a peak noise ($E \lesssim 2E_{\text{bd}}$) highlighting a tumultuous breakdown. The onset of noise provides an unambiguous determination of breakdown, because it signals the departure from ballistic transport associated to well-defined LLs. The breakdown voltage $V_{\text{bd}}(B) = E_{\text{bd}}W$ is indicated by dashed lines in Figs. 1(a)–1(h). As seen in the figure, it corresponds to a deviation from the dissipationless Hall transport regime $I_{\text{ds}} = G_H V_{\text{ds}}$ with $G_H = |n|e/B$ [43]. In this sample the breakdown currents, $J_{\text{bd}} \simeq 1200 \text{ A/m}$ ($B = 7 \text{ T}$, $V_g = -6 \text{ V}$), exceed previously reported values ($J_{\text{bd}} \lesssim 50 \text{ A/m}$). The decrease of noise at $E \gg E_{\text{bd}}$ is different in nature; it signals the ignition of energy relaxation restricting the electronic temperature $k_B T_e \simeq S_I/4G_{\text{ds}}$ below a hot-electron limit $k_B T_e \sim eV_{\text{ds}}/2$, indicating the recovery of a metallic behavior. Conversely, the fact that a full shot noise can be reached at intermediate bias is direct evidence of the quenching of phonon relaxation mechanisms. This observation is consistent with the $q = 2k_F$ resonant electron-phonon coupling reported in phonon-induced resistance oscillations [9], implying a suppression of conventional phonon relaxation mechanisms at low temperature and high electron density, i.e., in the Bloch-Grüneisen (BG) regime [44]. It also excludes significant contribution from impurity-assisted supercollisions [45], intrinsic optical phonon cooling [46], and demonstrates *in situ* the quenching of hyperbolic phonon cooling under quantizing magnetic fields [37]. Importantly for the interpretation of breakdown, this observation rules out the

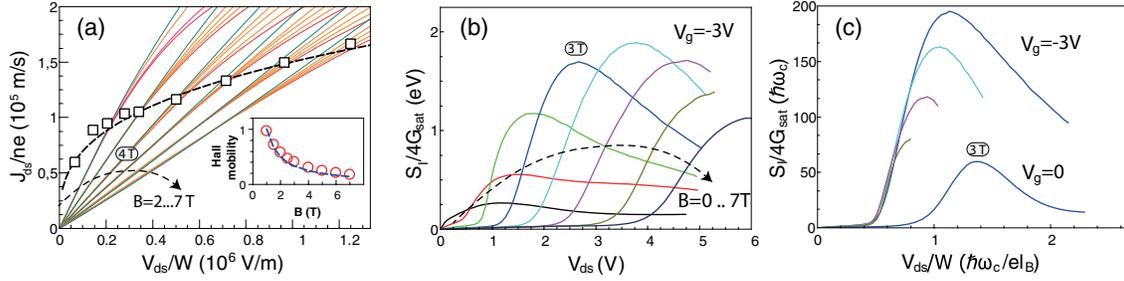


FIG. 2. Scaling behavior of current and noise in the QHE regime. (a) Bias dependence of the drift velocity $v_D = J_{ds}/|n|e$ deduced from current data in Fig. 1. The $B = 2 \rightarrow 7$ T data of different densities bunch in the QHE regime and stray above the breakdown field. The slopes, represented as a Hall mobility in the inset, obey the expected law $\mu = 1/B$ (blue dashed line in m^2/Vs). Black squares correspond to a typical breakdown voltage deduced from the onset of noise [dashed lines in Figs. 1(a)–1(h)]. They can be fitted to the Zener tunneling limit $v_c = (E_c \hbar e / N m^* 2)^{1/3}$ (black dashed line) by taking a constant Landau level $N = 5$ corresponding to the median experimental value [dashed yellow line in Figs. 1(b)]. (b) Bias dependence of $|n| = 2.15 \times 10^{12} \text{ cm}^{-2}$ shot-noise data [from Figs. 1(a)–1(h)] in increasing magnetic fields $B = 0 \rightarrow 7$ T. Ballistic transport is characterized by a suppression of noise below a critical voltage ranging from $V_c \simeq 0.6$ (at $B = 2$) to $V_c \simeq 4$ V (at $B = 7$ T). Current noise is scaled by the constant saturation conductance $G_{\text{sat}} = 0.6$ mS to be expressed as a noise temperature. (c) The above noise data obey a quantum Hall scaling at breakdown where Hall voltage and noise temperature are scaled to the maximum Zener field $E_c = \hbar \omega_c / e l_B$ and cyclotron energy $\hbar \omega_c$, respectively.

thermal scenario of Refs. [18,26,27] or phonon-assisted QUILLS in our experiment, which is performed below the BG temperature. The fact that supercollisions are not seen at zero field in Ref. [37] is a strong indication that impurity-assisted QUILLS should be very weak. Finally, another feature of transport in Figs. 1(a)–1(h) is the saturation of the differential conductance at high bias to a $G_{\text{sat}} \simeq 0.6$ mS that is independent of doping and magnetic field, suggesting that transport becomes metallic.

Signatures of QHE breakdown in transport are best captured by the drift velocity $v_D = J_{ds}/ne$ as function of the Hall field $E = V_{ds}/W$ in Fig. 2(a). It shows a universal Hall mobility, pictured by the bunching of constant B -field data along $v_D = E/B = \mu E$ lines. Breakdown is signaled by fanning out of the drift velocity at different densities above E_{bd} . The noise determinations of breakdown are more clear cut, they are added in Fig. 2(a) as black squares, in qualitative agreement with the velocity determination [47]. Focusing on the median values corresponding to $N = 5$ (out of the experimental window $N = 1 \rightarrow 10$), the noise data can be accurately fitted by the Zener tunneling limit $v_c = E_c/B = \omega_c l_B / \sqrt{N}$ (black dashed line) as shown in Fig. 2(a). The strong effect of LL quantization on noise is evidenced in Fig. 2(b), which gathers data of Fig. 1 taken in the doped regime ($V_g = -3$ V), where noise is expressed in terms of a noise temperature $k_B T_e = S_I / 4G_{\text{sat}}$. G_{sat} being constant, this representation conveniently interpolates between quantum shot noise at $E \gtrsim E_{\text{bd}}$ and thermal noise at $E \gg E_{\text{bd}}$. The figure captures (i) the suppression of shot noise below E_{bd} , (ii) the proliferation of inter-LL excitations above E_{bd} , with $k_B T_e \sim eV_{ds}/2$, and (iii) their relaxation at ultimate bias. As seen in Fig. 2(c), the noise data themselves obey a QHE scaling where the E field is scaled to the maximum Zener field, $\tilde{E} = E/E_c$ ($N = 1$), and the noise temperature to the

Landau gap. One retrieves the Zener-like critical field with $\tilde{E}_{\text{bd}} \simeq 1/\sqrt{5}$ in agreement with the theoretical fit in Fig. 2(a). In this plot, we have added $V_g = 0$ data showing that $\tilde{E}_{\text{bd}} \rightarrow 1$ at neutrality as expected. The above QHE scaling supports the fundamental physics origin of shot noise and highlights the fact that the Fermi sea is sprayed over a very large number of LLs [$\gtrsim 100$ in Fig. 2(c)] under the combined effects of LL quantization and QHE breakdown, and that noise itself scales like the cyclotron energy with $S_I(k_F, B, E) \propto \hbar \omega_c \times f(k_F l_B, \tilde{E})$ at ($E_{\text{bd}} \lesssim E \lesssim 2E_{\text{bd}}$).

To gain a deeper insight into the breakdown mechanism, we compare in Fig. 3(a) the noise current with the backscattering current defined as the deviation from ballistic Hall transport, $I_{\text{bs}} = G_H V_{ds} - I_{\text{ds}}$. At $E \gtrsim E_{\text{bd}}$ the backscattering current identifies with the inter-LL tunneling current which is drained back to the source via a dense array of counterpropagating edge states. Both S_I and I_{bs} vanish in the QHE regime $E < E_{\text{bd}}$ and grow exponentially at $E \sim E_{\text{bd}}$. As $S_I(V_g) \propto I_{\text{bs}}(V_g)$, we can define an E -field and doping independent backscattering Fano factor $\mathcal{F}(B) = S_I / 2eI_{\text{bs}}$. At $B = 3$ T the large $\mathcal{F} \simeq 7.5$ in Fig. 3(a) points to a collective mechanism and rules out the single electron Zener interpretation. The inset of Fig. 3(a) shows the linear dependence $\mathcal{F}(B) \propto B$ which supports the QHE scaling of noise in Fig. 2(c). It introduces a constant energy scale, $\epsilon_c = \hbar \omega_c / \mathcal{F} \simeq 1.4$ meV, the origin of which remains to be clarified.

From a theoretical point of view, single-electron Zener tunneling is also excluded based on the necessary conservation of the wave vector in the direction perpendicular to the electric field, and one would need to appeal to impurities that break translation invariance or to electron-electron interactions. The latter give rise to collective excitations such as magnetoexcitons [28] with a dispersion

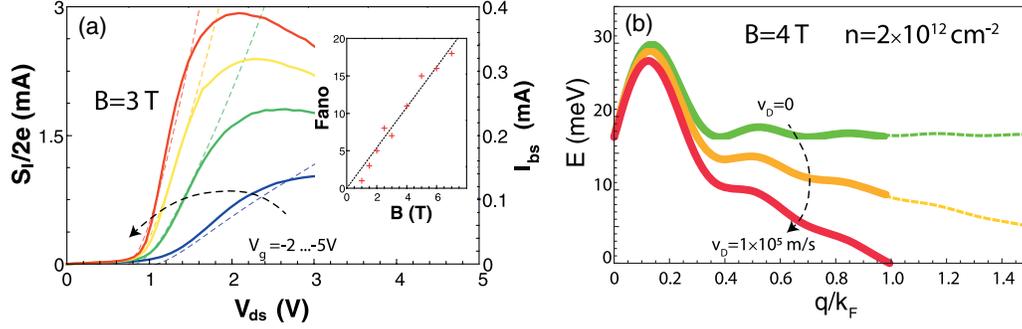


FIG. 3. Super-Poissonian inter-Landau level tunneling and a sketch of the magnetoexciton instability scenario of QHE breakdown. (a) Shot noise (solid lines, left axis) and backscattering current $I_{bs} = G_H V_{ds} - I_{ds}$ (dashed lines, right axis) at $B = 3$ T for $V_g = -2 \rightarrow -5$ V (blue, green, orange, red) obey a similar bias dependence at breakdown yielding a doping independent Fano factor $\mathcal{F} = S_I/2eI_{bs} \simeq 7.5$. Inset $\mathcal{F}(B) \simeq (2.7T^{-1})B \approx \hbar\omega_c/\epsilon_c$ obeys a linear law with $\epsilon_c = 1.4$ meV. (b) ME spectrum according to Eq. (1), at rest ($v_D = 0$), for a subcritical ($v_D = 0.5 \times 10^5$ m/s) and the critical ($v_D = 1 \times 10^5$ m/s) drift velocities. For clarity we have chosen a large $r_s \simeq 4$, $B = 4$ T and $|n| = 2 \times 10^{12}$ cm $^{-2}$ ($N = 5$), corresponding to the $V_g = -3$ V median working point in (Fig. SM1 [33]). The line thickness illustrates the spectral weight which, according to Ref. [48], vanishes at $q \sim k_F$. The Landau critical velocity $v_c = 1 \times 10^5$ m/s is estimated by the vanishing of the ME gap at $q/k_F \sim 1$. It agrees with the noise determination of breakdown, $v_{bd} = 1.1 \times 10^5$ m/s [$B = 4$ T square in Fig. 2(a)].

$$\omega_{ME}^E(q) \simeq \omega_c \left(1 + \frac{r_s k_F}{2\pi q} [J_1(2Nq/k_F)]^2 \right) - \mathbf{v}_D \cdot \mathbf{q}, \quad (1)$$

in terms of the Bessel function $J_1(x)$ [33]. Here, the doping-dependent Seitz radius, $r_s = 1/a_B^* k_F \simeq 0.5 \dots 1$, is given by the effective Bohr radius $a_B^* = 0.5 \text{ \AA} \times (m_e/m^*)\epsilon$, with $\epsilon = 3.2$ for BN. While magnetoexcitons are always gapped [$\omega_{ME}^{E=0}(q) \geq \omega_c$] in the absence of an electric field ($E = 0$), the latter tilts the dispersion by $-\mathbf{v}_D \cdot \mathbf{q}$. One immediately notices that the system becomes unstable towards proliferation of MEs because parts of the dispersion become negative at large wave vectors. However, in order to have a true instability, the excitation must have a nonzero spectral weight at the wave vectors where the dispersion vanishes. The spectral weight of the MEs is restricted to a wave-vector range $1/\sqrt{2N}l_B \leq q \leq 2\sqrt{2N}/l_B = 2k_F$ [38,39,48], and the instability thus occurs when $\omega_{ME}^E(q \simeq 2\sqrt{2N}/l_B) \simeq \omega_c \simeq 2v_D\sqrt{2N}/l_B$. This yields the above-mentioned scaling law $v_c = E_c/B \sim \omega_c l_B/\sqrt{N}$ for the critical velocity, and establishes the equivalence of the Zener and ME instability critical fields.

Figure 3(b) is a sketch of the low energy ME spectrum $\omega_{ME}(q) - v_D q$ in increasing drift velocities $v_D = 0, 0.5$, and 1×10^5 m/s for our typical experimental parameters $|n| = 2 \times 10^{12}$ cm $^{-2}$ ($V_g = -3$ V), $B = 4$ T ($N = 5$). Line thickness sketches ME's spectral weight, which vanishes for $q \gtrsim k_F$ as mentioned above. The ME instability occurs at a Landau critical velocity $v_L \sim \omega_c/k_F \simeq 1 \times 10^5$ m/s in agreement with the experimental (4 T) value in Fig. 2(a), where $v_{bd} = 1.1 \times 10^5$ m/s.

We conclude from the above analysis that the single-electron Zener tunneling and the collective ME instability mechanisms cannot be distinguished by their critical

velocity, and that an independent diagnosis of their excitation yield is needed, such as the current noise in Figs. 1(a)–1(h). A first evidence is the large Fano factor observed at $E \gtrsim E_{bd}$. In contrast with the Zener mechanism, the proliferation of inter-LL collective excitations is naturally explained by the ME instability. However, a quantitative determination of the number $N_{\text{bunch}} = \mathcal{F} \lesssim 20$ of excitation bunches remains beyond the scope of the present argument. In the Supplemental Material [33] we propose a tentative explanation that estimates a $N_{\text{bunch}} = \mathcal{F} \sim \hbar\omega_c/\epsilon_c$ from the interedge charging energy $\epsilon_c \sim e^2/(\epsilon W) \simeq 2$ meV. A second evidence of the collective nature of breakdown comes from the current noise peak itself at $\mathcal{E} \gtrsim 2\mathcal{E}_{bd}$. Its large amplitude, $S_I/2e \sim I_{ds}$ in Figs. 1(a)–1(h) or $k_B T_N = S_I/4G_{\text{sat}} \sim 100\hbar\omega_c \sim eV_{ds}/2$ in Figs. 2(b), 2(c) suggests an alteration of occupation numbers in the full LL spectrum consistently with a ME instability. By contrast a Zener mechanism, which affects mostly LLs at Fermi energy leaving deep LLs unaffected, should lead to $S_I/2e < I_{ds}$. It is further supported by the hint of a QHE-metal transition at very high electric fields ($E \gg E_{bd}$), characterized by a constant differential conductance $G_{ds} \rightarrow G_{\text{sat}} \simeq 0.6$ mS in Figs. 1(a)–1(h) and a decrease of thermal noise $S_I(B, E) \rightarrow S_I(0, E)$ in Fig. 2(c). This trend is a natural consequence of the field-induced melting of LLs. Remarkably, it is accompanied by the ignition of hyperbolic substrate-phonon cooling, an efficient mechanism recently demonstrated using the same sample [37]. The suppression of phonon relaxation in quantizing fields, also reported in magneto-optic experiments [49], and its restoring upon LL merging, are experimental illustrations of the importance of the plane-wave nature of electrons in electron-phonon coupling.

In conclusion, the old problem of quantum Hall breakdown has been revisited in the light of high-frequency shot-noise measurements performed in high-mobility

bilayer graphene. A new mechanism has been proposed that involves an electric-field driven bulk magnetoexciton instability. It explains the observed critical velocity and noise phenomenology as well as their scaling with the Zener field and the Landau energy. The mechanism makes a bridge between quantum-Hall and superfluid breakdowns by introducing a Landau critical drift velocity to the quantum Hall insulator state. This new approach will stimulate further theoretical and experimental works, aiming at modeling the E -field-induced QHE to metal transition or checking its universality, e.g., in single-layer graphene where Lorentzian invariance substitutes Galilean invariance, in ultraclean semiconducting heterostructures, or in the fractional quantum Hall effect.

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- [1] K. von Klitzing, G. Dorda, and M. Pepper, New Method for High-Accuracy Determination of the Fine-Structure Constant based on Quantized Hall Resistance, *Phys. Rev. Lett.* **45**, 494 (1980).
- [2] A. Tzalenchuk, S. Lara-Avila, A. Kalaboukhov, S. Paolillo, M. Syvajarvi, R. Yakimova, O. Kazakova, T. J. B. M. Janssen, V. Fal’ko, and S. Kubatkin, Towards a quantum resistance standard based on epitaxial graphene, *Nat. Nanotechnol.* **5**, 186 (2010).
- [3] R. Ribeiro-Palau, F. Lafont, J. Brun-Picard, D. Kazazis, A. Michon, F. Cheynis, O. Couturaud, C. Consejo, B. Jouault, W. Poirier, and F. Schopfer, Quantum Hall resistance standard in graphene devices under relaxed experimental conditions, *Nat. Nanotechnol.* **10**, 965 (2015).
- [4] E. Bocquillon, V. Freulon, F. D. Parmentier, J.-M. Berroir, B. Plaçais, C. Wahl, J. Rech, T. Jonckheere, T. Martin, C. Grenier, D. Ferraro, P. Degiovanni, and G. Fève, Electron quantum optics in ballistic chiral conductors, *Ann. Phys. (Berlin)* **526**, 1 (2014).
- [5] P. Streda and K. von Klitzing, Critical non-dissipative current of the quantum Hall regime, *J. Phys. C* **17**, L483 (1984).
- [6] M. E. Cage, R. F. Dziuba, B. F. Field, E. R. Williams, S. M. Girvin, A. C. Gossard, D. C. Tsui, and R. J. Wagner, Dissipation and Dynamic Nonlinear Behavior in the Quantum Hall Regime, *Phys. Rev. Lett.* **51**, 1374 (1983).
- [7] L. Bliiek, E. Braun, G. Hein, V. Kose, J. Niemeyer, G. Weimann, and W. Schlapp, Critical current density for the dissipationless quantum Hall effect, *Semicond. Sci. Technol.* **1**, 110 (1986).
- [8] L. Eaves and F. W. Sheard, Size-dependent quantised breakdown of the dissipationless quantum Hall effect in narrow channels, *Semicond. Sci. Technol.* **1**, 346 (1986).
- [9] I. A. Dmitriev, A. D. Mirlin, D. G. Polyakov, and M. A. Zudov, Nonequilibrium phenomena in high Landau levels, *Rev. Mod. Phys.* **84**, 1709 (2012).
- [10] C. Chaubet and F. Geniet, Nonequilibrium occupation of Landau levels and universal critical field in the quantum-Hall-effect breakdown, *Phys. Rev. B* **58**, 13015 (1998).
- [11] K. Chida, T. Arakawa, S. Matsuo, Y. Nishihara, T. Tanaka, D. Chiba, T. Ono, T. Hata, K. Kobayashi, and T. Machida, Nonequilibrium occupation of Landau levels and universal critical field in the quantum-Hall-effect breakdown, *Phys. Rev. B* **87**, 155313 (2013).
- [12] M.-Y. Li, T. Nakajima, K.-T. Lin, C. C. Chi, J. C. Chen, and S. Komiyama, Transition dynamics in the electrical breakdown of the quantum Hall effect, *Phys. Rev. B* **85**, 245315 (2012).
- [13] K. Panos, R. R. Gerhardts, J. Weis, and K. von Klitzing, Current distribution and Hall potential landscape towards breakdown of the quantum Hall effect: A scanning force microscopy investigation, *New J. Phys.* **16**, 113071 (2014).
- [14] B. E. Kane, D. C. Tsui, and G. Weimann, Evidence of Inter-Landau-Level Tunneling in the Integral Quantum Hall Effect, *Phys. Rev. Lett.* **61**, 1123 (1988).
- [15] I. I. Kaya, G. Nachtwei, K. von Klitzing, and K. Eberl, Spatially resolved monitoring of the evolution of the breakdown of the quantum Hall effect: Direct observation of inter-Landau-level tunneling, *Europhys. Lett.* **46**, 62 (1999).
- [16] J. A. Alexander-Webber, A. M. R. Baker, P. D. Buckle, T. Ashley, and R. J. Nicholas, High-current breakdown of the quantum Hall effect and electron heating in InSb/AlInSb, *Phys. Rev. B* **86**, 045404 (2012).
- [17] J. Guignard, D. Leprat, D. C. Glatli, F. Schopfer, and W. Poirier, Quantum Hall effect in exfoliated graphene affected by charged impurities: Metrological measurements, *Phys. Rev. B* **85**, 165420 (2012).
- [18] J. A. Alexander-Webber, A. M. R. Baker, T. J. B. M. Janssen, A. Tzalenchuk, S. Lara-Avila, S. Kubatkin, R. Yakimova, B. A. Piot, D. K. Maude, and R. J. Nicholas, Phase Space for the Breakdown of the Quantum Hall Effect in Epitaxial Graphene, *Phys. Rev. Lett.* **111**, 096601 (2013).
- [19] A. M. R. Baker, J. A. Alexander-Webber, T. Altbauer, and R. J. Nicholas, Energy relaxation for hot Dirac fermions in graphene and breakdown of the quantum Hall effect, *Phys. Rev. B* **85**, 115403 (2012).
- [20] S. Tian, P. Wang, X. Liu, J. Zhu, H. Fu, T. Taniguchi, K. Watanabe, J.-H. Chen, and X. Lin, Nonlinear transport of graphene in the quantum Hall regime, *2D Mater.* **4**, 015003 (2017).
- [21] K. Chida, T. Hata, T. Arakawa, S. Matsuo, Y. Nishihara, T. Tanaka, T. Ono, and K. Kobayashi, Avalanche electron bunching in a Corbino disk in the quantum Hall effect breakdown regime, *Phys. Rev. B* **89**, 235318 (2014).
- [22] T. Hata, T. Arakawa, K. Chida, S. Matsuo, and K. Kobayashi, Giant Fano factor and bistability in a Corbino

- disk in the quantum Hall effect breakdown regime, *J. Phys. Condens. Matter* **28**, 055801 (2016).
- [23] A. Laitinen, M. Kumar, T. Elo, Y. Liu, T. S. Abhilash, and P. J. Hakonen, Breakdown of zero-energy quantum Hall state in Graphene in the light of current fluctuations and shot noise, *J. Low Temp. Phys.* **191**, 272 (2018).
- [24] A. Laitinen, M. Kumar, P. J. Hakonen, and E. B. Sonin, Gyrotropic Zener tunneling and nonlinear IV curves in the zero-energy Landau level of graphene in a strong magnetic field, *Sci. Rep.* **8**, 594 (2018).
- [25] S. Komiyama, T. Takamasu, S. Hiyamizu, and S. Sasa, Breakdown of the quantum Hall effect due to electron heating, *Solid State Commun.* **54**, 479 (1985).
- [26] G. Nachtwei, Breakdown of the quantum Hall effect, *Physica (Amsterdam)* **4E**, 79 (1999).
- [27] S. Komiyama and Y. Kawaguchi, Heat instability of quantum Hall conductors *Phys. Rev. B* **61**, 2014 (2000).
- [28] C. Kallin and B. I. Halperin, Excitations from a filled Landau level in the two-dimensional electron gas, *Phys. Rev. B* **30**, 5655 (1984); Many-body effects on the cyclotron resonance in a two-dimensional electron gas, *Phys. Rev. B* **31**, 3635 (1985).
- [29] S. M. Girvin, A. H. MacDonald, and P. M. Platzman, Magneto-roton theory of collective excitations in the fractional quantum Hall effect, *Phys. Rev. B* **33**, 2481 (1986).
- [30] L. Landau, Theory of the Superfluidity of Helium II, *Phys. Rev.* **60**, 356 (1941).
- [31] D. I. Bradley, S. N. Fisher, A. M. Guénault, R. P. Haley, C. R. Lawson, G. R. Pickett, R. Schanen, M. Skyba, V. Tsepelin, and D. E. Zmeev, Breaking the superfluid speed limit in a fermionic condensate, *Nat. Phys.* **12**, 1017 (2016).
- [32] L. Chomaz, R. M. W. van Bijnen, D. Petter, G. Faraoni, S. Baier, J. H. Becher, M. J. Mark, F. Wächtler, L. Santos, and F. Ferlaino, Observation of roton mode population in a dipolar quantum gas, *Nat. Phys.* **14**, 442 (2018).
- [33] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevLett.121.136804> for a derivation of the magnetoexciton dispersion. It contains Refs. [28,34–39].
- [34] M. O. Goerbig, Quantum Hall Effects, in *Ultracold Gases and Quantum Information, Proceedings of the Les Houches Summer School 2009*, edited by C. Miniatura *et al.* (Oxford University Press, Oxford, 2009), [arXiv:0909.1998](https://arxiv.org/abs/0909.1998).
- [35] G. F. Giuliani and G. Vignale, *Quantum Theory of the Electron Liquid* (Cambridge University Press, Cambridge, England, 2005).
- [36] J. Koch and F. von Oppen, Franck-Condon Blockade and Giant Fano Factors in Transport through Single Molecules, *Phys. Rev. Lett.* **94**, 206804 (2005).
- [37] W. Yang, S. Berthou, X. Lu, Q. Wilmart, A. Denis, M. Rosticher, T. Taniguchi, K. Watanabe, G. Fève, J.-M. Berroir, G. Zhang, C. Voisin, E. Baudin, and B. Plaçais, A graphene Zener-Klein transistor cooled by a hyperbolic substrate, *Nat. Nanotechnol.* **13**, 47 (2018).
- [38] R. Roldán, M. O. Goerbig, and J.-N. Fuchs, The magnetic field particle-hole excitation spectrum in doped graphene and in a standard two-dimensional electron gas, *Semicond. Sci. Technol.* **25**, 034005 (2010).
- [39] M. O. Goerbig, Electronic properties of graphene in a strong magnetic field, *Rev. Mod. Phys.* **83**, 1193 (2011).
- [40] A. M. Martin, K. A. Benedict, F. W. Sheard, and L. Eaves, Model for the Voltage Steps in the Breakdown of the Integer Quantum Hall Effect, *Phys. Rev. Lett.* **91**, 126803 (2003).
- [41] L. Eaves, S. T. Stoddart, R. Wirtz, A. C. Neumann, B. L. Gallagher, P. C. Main, and M. Henini, Quantum Hall effect breakdown in two-dimensional hole gases, *Physica (Amsterdam)* **6E**, 136 (2000).
- [42] Actually a residual current noise is observed in the ballistic QH regime, which is hardly visible in Figs. 1(a)–1(h) and 2(c). It corresponds to a noise temperature $k_B T_N = S_I/4G_{ds} \lesssim 0.02 eV_{ds}$ that is one order of magnitude smaller than the hot electron limit $k_B T_N = \sqrt{3}/8 eV_{ds}$ for homogeneous Joule heating [37]. We attribute it to the local contact heating associated with the Joule power release in the source and drain.
- [43] Note that in a two-terminal device the electric field rotates from transverse to longitudinal as transport turns from the dissipationless Hall regime to the dissipative Ohmic regime.
- [44] A. C. Betz, F. Violla, D. Brunel, C. Voisin, M. Picher, A. Cavanna, A. Madouri, G. Fève, J.-M. Berroir, B. Plaçais, and E. Pallecchi, Hot Electron Cooling by Acoustic Phonons in Graphene, *Phys. Rev. Lett.* **109**, 056805 (2012).
- [45] A. C. Betz, S. H. Jhang, E. Pallecchi, R. Ferreira, G. Fève, J.-M. Berroir, and B. Plaçais, Supercollision cooling in undoped graphene, *Nat. Phys.* **9**, 109 (2013).
- [46] A. Laitinen, M. Kumar, M. Oksanen, B. Plaçais, P. Virtanen, and P. J. Hakonen, Coupling between electrons and optical phonons in suspended bilayer graphene, *Phys. Rev. B* **91**, 121414(R) (2015).
- [47] Note that bunching quality depends crucially on the accuracy of the drain gating compensation as explained in Ref. [37].
- [48] R. Roldán, J.-N. Fuchs, and M. O. Goerbig, Spin-flip excitations, spin waves, and magnetoexcitons in graphene Landau levels at integer filling factors, *Phys. Rev. B* **82**, 205418 (2010).
- [49] F. Wendler, M. Mittendorff, J. C. König-Otto, S. Brem, C. Berger, W. A. de Heer, R. Böttger, H. Schneider, M. Helm, S. Winnerl, and E. Malic, Symmetry-Breaking Supercollisions in Landau-Quantized Graphene, *Phys. Rev. Lett.* **119**, 067405 (2017).