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 \( V_D = E \times B / B^2 \) approaches the cyclotron velocity \( R_c \omega_c / \omega_c \), where \( R_c \) and \( \omega_c \) 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, \( E_c \sim h \omega_c / e R_c \), with \( \omega_c = eB / m^* \) and \( R_c = \sqrt{N / I_B} \), where \( m^* \) is the effective mass, \( N \) the number of occupied Landau levels (LLs), and \( I_B = \sqrt{\hbar / eB} \) 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 \( J > 50 \text{ A/m} \) [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 (\( v_{bd} = J_{bd} / n e \)) 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...
magnetoe exciton (ME) minimum [28]. Similar excitations exist in fractional QHE [29] that are longitudinal and called magnetotorons 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 $v_c = E_c/B \sim \omega_c t_B/\sqrt{N}$. 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) microsample, a two-terminal rectangular sample of dimensions $L \times W = 4 \times 3 \mu m$ [33], chosen here as a prototypical masssive 2DES ($m^*/m_0 \approx 0.03$). 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 $v_{\text{bd}} \approx v_c$. We reveal the collective nature of breakdown using shot noise. We report on large Fano factors $F \lesssim 20$ 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 $S_f \approx 2eI_{\text{bd}}$. 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 $I_{\text{bd}} = G_H V_{\text{bd}}$ with $G_H = |n|e/B$ [43]. In this sample the breakdown currents, $J_{\text{bd}} \approx 1200 \text{ A/m}$ ($B = 7 \text{ T}, V_g = -6\text{V}$), 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 $k_B T_e \approx S_f/4G_{\text{bd}}$ below a hot-electron limit $k_B T_e \sim eV_{\text{bd}}/2$, 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 $v_D = J_{ds}/ne$ 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(b)]. They can be fitted to the Zener tunneling limit $v_c = (E_c, \hbar e/Nm^2)^{1/3}$ (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 $|n| = 2.15 \times 10^{12}$ 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 $V_c \approx 0.6$ (at $B = 2$) to $V_c \approx 4$ V (at $B = 7$ T). Current noise is scaled by the constant saturation conductance $G_{sat} = 0.6$ 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 $E_c = \hbar \omega_c/4G_{sat}$ and cyclotron energy $\hbar \omega_c$, respectively.

Note: The text continues with a discussion of the experimental results and theoretical predictions, including the scaling behavior and the breakdown mechanism. The figures illustrate these concepts with graphs and diagrams, showing the drift velocity, noise, and current as functions of bias voltage. The text mentions the importance of the Zener tunneling limit and the quantum Hall scaling, which are key phenomena in the study of quantum Hall effects and their breakdown in magnetic fields.
The spectral weight of the MEs is restricted to a wave-vector instability, the excitation must have a nonzero spectral weight at large wave vectors. However, in order to have a true critical fields. 

\[ \omega_{\text{ME}}(q) \approx \omega_c \left(1 + \frac{r}{2\pi q} J_1(2Nq/kF)\right) - v_D \cdot \mathbf{q}, \]  

(1)

in terms of the Bessel function \( J_1(x) \) [33]. Here, the doping-dependent Seitz radius, \( r = 1/\alpha_a k_F \approx 0.5 \ldots 1 \), is given by the effective Bohr radius \( a_b \approx 0.5 \, \text{Å} \times (m_e/m^*)^{1/2} \), with \( e^2/2\approx 3.2 \) for BN. While magnetoexcitons are always gapped \( \omega_{\text{ME}}(q) \gtrsim \omega_c \), the latter tilts the dispersion by \( -v_D \cdot \mathbf{q} \). 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 \( 1/\sqrt{2Nl_b} \leq q \leq 2/\sqrt{2Nl_b} = 2k_F \) [38,39,48], and the instability thus occurs when \( \omega_{\text{ME}}(q) \approx 2\sqrt{2Nl_b} \approx \omega_c \approx 2v_D \sqrt{2Nl_b} \). This yields the above-mentioned scaling law \( v_c = E_c/B \approx \omega_c l_b / \sqrt{N} \) 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 \( \omega_{\text{ME}}(q) - v_D q \) in increasing drift velocities \( v_D = 0, 0.5, \) and \( 1 \times 10^5 \) m/s for our typical experimental parameters \( |n| = 2 \times 10^{12} \, \text{cm}^{-2} (V_g = -3 \, \text{V}), B = 4 \, \text{T} (N = 5) \). 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 \( v_L = v_c/k_F \approx 1 \times 10^5 \) m/s in agreement with the experimental (4 T) value in Fig. 2(a), where \( v_{\text{bd}} = 1.1 \times 10^5 \) 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 second evidence is the large Fano factor observed at \( E \gtrsim E_{\text{bd}} \). 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 \( \epsilon_c \sim \epsilon^2/(eW) \approx 2 \) meV. A second evidence of the collective nature of breakdown comes from the current noise peak itself at \( \mathcal{E} \gtrsim 2E_{\text{bd}} \). Its large amplitude, \( S_I/2e = I_{\text{ds}} \) in Figs. 1(a)–1(h) or \( k_B T_N = S_I/4G_{\text{sat}} \approx 100 \hbar \omega_c = eV_{\text{ds}}/2 \) 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 \( S_I/2e < I_{\text{ds}} \).

It is further supported by the hint of a QHE-metal transition at very high electric fields \( (E \gg E_{\text{bd}}) \), characterized by a constant differential conductance \( G_{\text{bd}} \rightarrow G_{\text{sat}} \approx 0.6 \) 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

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