

Observation of Narrow-Band Noise Accompanying the Breakdown of Insulating States in High Landau Levels

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Recent magnetotransport experiments on high mobility two-dimensional electron systems have revealed many-body electron states unique to high Landau levels. Among these are reentrant integer quantum Hall states which undergo sharp transitions to conduction above some threshold field. Here we report that these transitions are often accompanied by narrow- and broad-band noise with frequencies which are strongly dependent on the magnitude of the applied dc current.

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Strong evidence now exists which suggests that in the presence of a modest perpendicular magnetic field B , a clean two-dimensional electron system (2DES) with density n_s supports many-body phases distinct from the fractional quantum Hall effect (FQHE) states which dominate at high fields [1]. These new phases form when the 2DES occupies three or more orbital Landau levels (LLs). Near half filling of the spin resolved LLs, e.g., at filling fraction $\nu = hn_s/eB = 9/2, 11/2, \text{etc.}$, states exhibiting highly anisotropic longitudinal resistance develop at temperatures below about 100 mK [2,3]. These are believed to be closely related to the striped charge density wave (CDW) states predicted by Hartree-Fock theory [4,5].

Near $1/4$ and $3/4$ filling of the same high LLs, additional phases exist whose main experimental signature is an *isotropic* vanishing of the longitudinal resistance and a reentrant integer quantization of the Hall resistance [2,3]. The reentrant aspect of these states suggests that they reflect collective, as opposed to single particle, insulating configurations of the electrons in the uppermost LL. Indeed, prevailing theory predicts that the ground state of the 2DES at these fillings is a pinned triangular CDW, analogous to a Wigner crystal but with two or more electrons per unit cell [4–7]. Estimates of the lattice constant of such “bubble” phases are on the order of 100 nm under typical circumstances. This picture is supported by nonlinear dc current-voltage (I - V) measurements in which sharp onsets to conduction are observed in the reentrant integer quantum Hall effect (RIQHE) states [8]. Such threshold behavior is a common feature of transport in conventional CDW systems, such as NbSe₃ [9]. It has also been observed in 2DESs at low filling of the $N = 0$ LL where Wigner crystallization is thought to occur [10]. Recently, Lewis *et al.* [11] observed sharp resonances in the microwave conductivity of the 2DES in the vicinity of the RIQHE states and suggested that they may reflect a pinning mode of the bubble crystal [12].

Here we report a remarkable new aspect of the RIQHE: the abrupt onset of conduction at high dc bias is often accompanied by narrow- and broad-band noise which is very sensitive to the dc current carried by the 2DES. While it is tempting to compare the narrow-band noise to the “washboard” noise encountered in the sliding transport of conventional CDW compounds [9], the low frequencies (~ 5 kHz) we observe may point to a different origin. Nevertheless, the dynamical features described here form an important part of the phenomenology of the RIQHE and include the first observation of narrow-band noise in the quantum Hall regime [13].

Noise accompanying RIQHE breakdown has been observed in four different GaAs/AlGaAs heterostructures. We focus here on a 30 nm GaAs quantum well containing a 2DES with density $n_s = 2.9 \times 10^{11} \text{ cm}^{-2}$ and mobility $\mu = 2.3 \times 10^7 \text{ cm}^2/\text{Vs}$. Eight diffused In Ohmic contacts were positioned at the corners and side midpoints of the 4×4 mm square sample. The linear response longitudinal resistance was obtained by driving low level purely ac current (typically 10 nA at 13 Hz) between midpoint contacts on opposite sides of the sample and recording the voltage drop between adjacent corner contacts. The non-linear response of the sample was observed using purely dc current excitation and monitoring both the dc and ac components of the resulting voltage.

Figure 1(a) shows the linear response longitudinal resistances measured with net current flow along the orthogonal $[110]$ and $[1\bar{1}0]$ crystal axes at $T = 50$ mK over the filling factor range $5 > \nu > 4$. As is usually the case when no external symmetry-breaking field is present [14], the resistance shows a deep minimum around $\nu = 9/2$ for current flow along $[110]$ and a strong maximum for current flowing along $[1\bar{1}0]$. Flanking the region of anisotropy are the RIQHE states around $\nu \approx 4 + 1/4$ and $4 + 3/4$ filling, where the longitudinal resistance vanishes isotropically. Although not shown, the Hall resistance is quantized in these regions at $h/4e^2$ and $h/5e^2$, respectively.

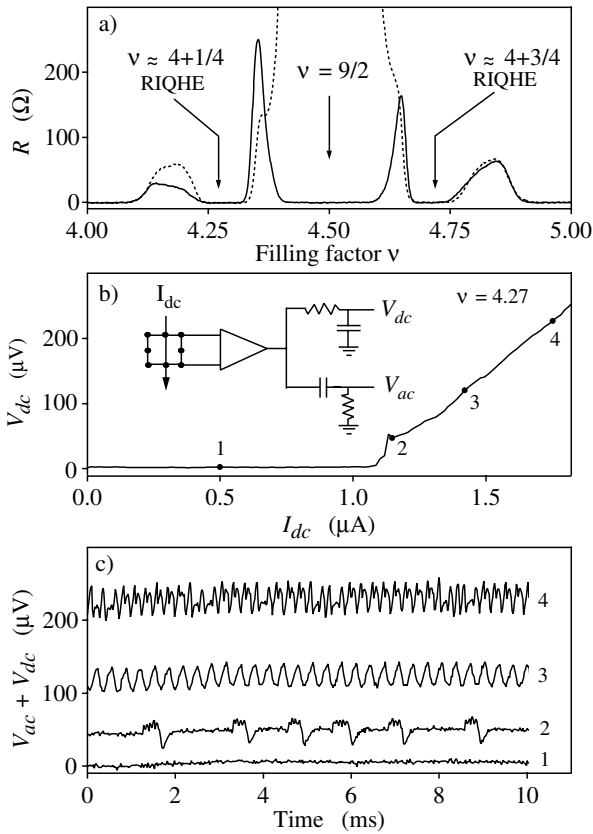


FIG. 1. Overview of the RIQHE and its breakdown phenomenon at $T = 50$ mK. (a) Linear response longitudinal resistance with the current directed along $[110]$ (solid line) and $[1\bar{1}0]$ (dashed line). The RIQHE states straddle the region of anisotropic transport around $\nu = 9/2$. (b) Nonlinear I - V data taken near the center of the $\nu \approx 4 + 1/4$ RIQHE. (c) Time dependences of the net longitudinal voltage $V_{ac} + V_{dc}$, taken at the values of I_{dc} labeled in (b).

I - V characteristics of the RIQHE states were obtained using a circuit, shown in Fig. 1(b). At $\nu = 4.27$, near the center of the high-field RIQHE, V_{dc} versus I_{dc} is shown in Fig. 1(b). For small I_{dc} the RIQHE remains intact, i.e., $V_{dc} = 0$. The current is flowing entirely within the filled $N = 0$ and $N = 1$ lower LLs while the quasiparticles in the partially filled $N = 2$ LL remain insulating. At $I_{dc} \approx 1.1 \mu A$, however, V_{dc} abruptly becomes nonzero as the RIQHE breaks down and current begins to flow in the $N = 2$ LL [8].

Figure 1(c) shows that along with the sharp dc response, a nonzero V_{ac} appears as the RIQHE breaks down. Four 10 ms traces of the net longitudinal voltage $V_{ac} + V_{dc}$, taken at different values of I_{dc} , are displayed. For $I_{dc} = 0.5 \mu A$, V_{ac} is very small and displays only background noise. Above the dc threshold current of $1.1 \mu A$, however, V_{ac} begins to fluctuate. Immediately above threshold, at $I_{dc} = 1.2 \mu A$, a reproducible burstlike pattern separated by irregular intervals is observed. At higher currents V_{ac} shows unambiguous narrow-band noise, oscillating around 3 kHz for $I_{dc} = 1.4 \mu A$. As I_{dc}

is increased further, the noise frequency rises: by $I_{dc} = 1.7 \mu A$, fluctuations on time scales of less than 0.1 ms are seen. We emphasize that this noise in V_{ac} develops spontaneously in the RIQHE regions of high LLs under purely dc current excitation. The noise arises from the 2DES itself and is not due to interactions with the external circuitry.

Figure 2 illustrates the spectral content of the noise associated with the breakdown of the RIQHE near $\nu \approx 4 + 1/4$. Figure 2(a) shows a typical dc I - V characteristic, the threshold to conduction occurring close to $1.0 \mu A$, while Fig. 2(b) displays a logarithmic plot of the simultaneously recorded Fourier power spectrum of V_{ac} . The full gray scale in Fig. 2(b) corresponds to a noise power variation of 37 dB. The faint horizontal lines running across the entire image are artifacts arising from background electronic pickup. It is apparent from the figure that as the dc breakdown current is exceeded, the power spectrum erupts from quiescence into a rich pattern of sharp spectral lines and their harmonics along with weaker broad-band features. The narrow-band features can be very sharply defined: Q factors of 25 are typical but values in excess of 1000 have been seen.

It is evident from Fig. 2(b) that the noise “fingerprint” is strongly dependent upon the dc current flowing through the sample. Indeed, in some respects the noise power spectrum mirrors the dc I - V characteristic: Immediately above threshold V_{dc} rises linearly with I_{dc} ; at the same time, the frequencies of the dominant noise modes also rise roughly linearly. At higher dc currents, V_{dc} exhibits sharp steplike features and ultimately begins to fall. Likewise, the power spectrum undergoes abrupt structural changes and eventually the dominant mode frequencies also begin to subside.

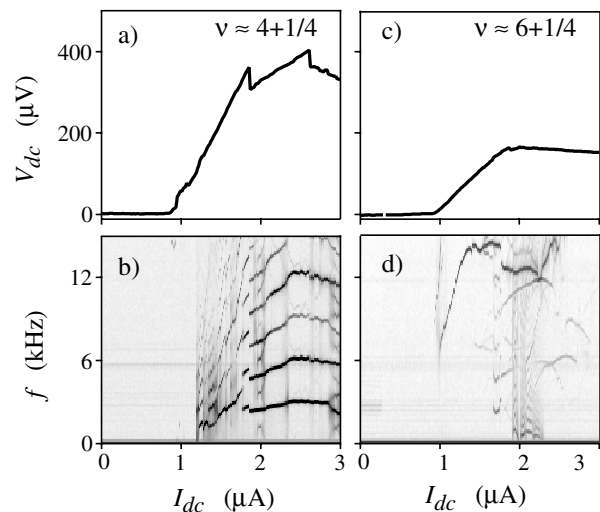


FIG. 2. Spectral characteristics of noise associated with RIQHE breakdown. (a),(b) I - V characteristic and noise power spectra at $\nu = 4.29$ and $T = 50$ mK. (c),(d) I - V characteristic and noise power spectra at $\nu = 6.24$ and $T = 50$ mK.

The slight differences between the dc I - V data in Figs. 1(b) and 2(a), which were taken at the same temperature and magnetic field, are typical of the day-to-day variations encountered during the course of the experiment. Similarly, the noise spectrum exhibited variations from measurement to measurement under identical conditions as well as between measurements taken at slightly different filling factors within a given RIQHE or with different voltage contact configurations. In spite of these quantitative differences, the qualitative features of the noise, i.e., its onset near dc breakdown, its strong current dependence, and its complex spectral makeup, are robust.

Noise features similar to those seen in the RIQHE near $\nu \approx 4 + 1/4$ have also been found in several other RIQHE states. In addition to the RIQHE near $\nu \approx 4 + 3/4$ in the same spin branch of the $N = 2$ LL, narrow-band noise has been observed in RIQHE states near $\nu \approx 5 + 1/4$ and $6 + 1/4$, the last being in the $N = 3$ LL. Although the strength and detailed spectral makeup of the noise vary widely, the qualitative effect is the same. Figures 2(c) and 2(d) show representative I - V data and noise spectra from the RIQHE near $\nu \approx 6 + 1/4$.

The noise accompanying RIQHE breakdown is restricted to the same narrow ranges of filling factor and low temperatures as the sharp features in the dc I - V curves [8]. In Fig. 3 the average noise level, $\langle V_{\text{rms}} \rangle$, in the filling factor range $5 > \nu > 4$ is overlaid on the longitudinal resistance data shown in Fig. 1(a). The quantity $\langle V_{\text{rms}} \rangle$ represents the rms noise voltage in a bandwidth of 1 to 25 kHz, calculated from the noise spectra at fixed dc current and averaged over all I_{dc} from 0 to $3 \mu\text{A}$. Qualitatively, $\langle V_{\text{rms}} \rangle$ is just the averaged intensity of a noise fingerprint such as the one in Fig. 2(b). The baseline of $\langle V_{\text{rms}} \rangle$ in Fig. 3, about $1.4 \mu\text{V}$, is equal to the background noise signal in the 1–25 kHz bandwidth at $I_{\text{dc}} = 0$. Clearly, excess noise above this baseline is absent over most of the range $4 < \nu < 5$. In particular, no excess

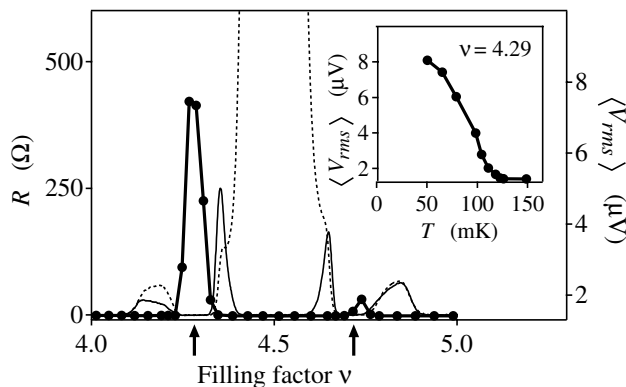


FIG. 3. Comparison of linear response longitudinal resistances R and average noise voltage $\langle V_{\text{rms}} \rangle$ for $4 < \nu < 5$ at $T = 50$ mK. Light solid trace: R with current directed along $[1\bar{1}0]$. Dashed trace: R with current directed along $[110]$. Dark trace with dots: $\langle V_{\text{rms}} \rangle$. Arrows indicate RIQHE states. Inset: Temperature dependence of $\langle V_{\text{rms}} \rangle$ at $\nu = 4.29$.

noise is observed in the integer QHE regions at $\nu = 4$ and $\nu = 5$, nor in the region of anisotropic transport around $\nu = 9/2$. (The latter is true regardless of the direction of the current flow.) In contrast, a strong peak in $\langle V_{\text{rms}} \rangle$ is observed in the RIQHE region around $\nu \approx 4 + 1/4$, and a lesser but still noticeable peak is present in the RIQHE near $\nu \approx 4 + 3/4$. The substantial difference in the noise power exhibited by these two RIQHE states is not understood. We emphasize, however, that such apparent breakdowns of particle-hole symmetry in 2D electron systems are commonplace. For example, recent studies of the subtle FQHE [15] and insulating phases [16] in the $N = 1$ LL have revealed a similar lack of symmetry about half filling. As in the present situation, the collective states on the high magnetic field side of half filling are stronger than their counterparts on the low field side. Spin effects and/or LL mixing may be involved, but there is as yet no real understanding of such phenomena.

The inset to Fig. 3 shows that the excess noise observed in the RIQHE is strongly temperature dependent, disappearing above about 100 mK just as all other signatures of the recently discovered collective phenomena in high LLs [1].

Because the breakdown of the RIQHE may reflect the depinning of an electron bubble lattice, it is logical to compare the observed narrow-band noise with the washboard noise encountered in conventional CDW compounds [17]. Washboard noise is believed to reflect the spatial periodicity of the depinned CDW as it slides across the impurity potential in the sample. Consistent with this, the noise frequency is found to be proportional to the current carried by the CDW [9]. In the present case of a 2DES, the generally increasing frequency of the narrow-band noise immediately above the RIQHE breakdown is suggestive of a similar mechanism. In addition to washboard noise, conventional CDW systems exhibit a variety of interference phenomena between narrow-band noise modes and externally applied ac signals [9]. Indeed, we have recently observed similar effects in RIQHE breakdown, including examples of mode locking and mode mixing [18].

Despite these similarities, it is difficult to understand the very low frequencies of the noise observed in our experiment. Assuming, for example, that 100 nA flows via the sliding of a bubble CDW with a 100 nm lattice constant, the expected washboard frequency in our sample (assuming the current density is uniform) would be on the order of 10 MHz, not the few kHz that we observe. There are, of course, uncertainties in such an estimate. For example, the fraction of the total current I_{dc} which flows in the partially filled $N = 2$ Landau level is not accurately known. Below breakdown I_{dc} flows entirely within the $N = 0$ and $N = 1$ LLs beneath the Fermi level. Far above breakdown, or, equivalently, at very high temperatures, at most $\sim 6\%$ ($= 0.25/4.25$) of I_{dc} at $\nu = 4 + 1/4$ flows in the valence LL. Immediately above breakdown the situation is less clear. Hall voltage

measurements suggest that the fraction of I_{dc} flowing in the valence LL increases smoothly from zero at breakdown to a few percent well above it, but it is difficult to analyze such data in a model-independent way. Although this current shunting effect could reduce the expected noise frequencies substantially, it seems unlikely that it can account for the kHz noise frequencies which are still observed when the I_{dc} exceeds breakdown by hundreds of nA.

The observation of anomalously low-frequency narrow-band noise does not rule out a sliding charge density wave picture of RIQHE breakdown. In fact, the low bandwidth (~ 100 kHz) of our current experimental setup leaves higher frequency “conventional” narrow-band noise undetectable in any case. Nonetheless, the existence of low-frequency noise demands a more complex model than an ideal bubble lattice uniformly sliding across the macroscopic dimensions of our samples. Such a more realistic scenario will have to incorporate the well-known inhomogeneity of current flow in the quantum Hall regime and the possibility of nonuniform plastic or filamentary flow within the driven CDW lattice. The latter phenomena are thought to occur in other 2D systems, such as driven vortex lattices [19], and have been discussed in the context of the depinning of the hypothesized Wigner crystal in the lowest LL at very low filling factors [20,21].

The noise reported here might instead be related to the processes responsible for the breakdown of the conventional integer QHE [22]. The phenomenology of QHE breakdown is quite rich, with substantial differences between samples of different density, mobility, and geometry. Numerous mechanisms [22] for the breakdown have been proposed, including runaway heating, Zener tunneling, inter-LL transitions, backscattering filament formation, and magnetoexciton generation [23]. Not surprisingly, no single theory satisfactorily explains all the experimental results. While the breakdown of the RIQHE resembles that of the conventional integer QHE, there are important differences. For example, the observed threshold fields for conventional integer QHE breakdown in comparable bulk 2D samples exceed those we find in the RIQHE by large factors, typically 10^3 – 10^4 . In addition, narrow-band noise has not been observed in conventional integer QHE breakdown.

In conclusion, we have observed complex noise spectra accompanying the breakdown of the reentrant integer quantized Hall states of 2DESs in high LLs. These states, which represent insulating configurations of the electrons in the uppermost LL, may well be pinned bubble charge density waves. After breakdown under the stress of a large Hall electric field, both narrow- and broad-band noise appears in the current-voltage characteristics of these states. Although the frequencies of the narrow-band modes generally increase with the current driven

through the system, they are too low to be readily accounted for by a simple sliding charge density wave model.

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