



Anisotropy in two-dimensional electronic quantum Hall systems at half-filled valence Landau levels

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Abstract

Strongly correlated electronic systems in two dimensions have constantly been a source of new discoveries. For example, the integer and fractional quantum Hall (QH) effects have emerged when such systems have been subjected to strong perpendicular magnetic fields. Recently, in the transitional regions between QH plateaus, strong magneto-transport anisotropies have been observed below ca. 100 mK. In this paper, we explain the emergence of broken rotational symmetry at half-filled valence Landau levels in terms of quantum liquid crystalline states with nematic order. Quantum Monte Carlo simulations indicate that while isotropic states are stable in the lowest and first excited Landau level, there are regions of instability towards liquid crystalline states in higher Landau levels. A possible connection of the recently discovered magneto-transport anisotropy in low magnetic fields and these liquid crystalline states is discussed.

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1. Introduction

Recent transport experiments in very-high-mobility GaAs/AlGaAs heterostructures have revealed the existence of regimes of magnetic field in which a two-dimensional electronic system (2DES) exhibits characteristics of a compressible liquid state with an unexpectedly large temperature-dependent magneto-transport anisotropy [1,2]. Such experiments have established a qualitative difference between half-filled states at higher valence Landau levels with index $N = 2, 3, \dots$ and those in the lowest Landau level (LLL) and first excited Landau level ($N = 1$). As temperature is lowered below ca. 100 mK, longitudinal resistance grows very rapidly and highly anisotropic states are observed around filling factors, $\nu = \frac{9}{2}, \frac{11}{2}, \dots$. In virtually all samples the high (hard) resistance direction is found to be parallel to the $[1\bar{1}0]$ GaAs crystalline axis. The consistent orientation of

anisotropic phases with respect to the GaAs crystalline axes is a key aspect which currently lacks understanding.

Many authors interpret the appearance of such huge longitudinal resistance magneto-transport anisotropy as strong evidence for the creation of a unidirectional (or striped) charge density wave (CDW) state as predicted via Hartree–Fock (HF) theory [3]. The HF-CDW theory predicts that electrons in partially occupied high Landau levels form domains (stripes) with filling factors equal to 1 and 0. Related phenomena such as novel crystal phases [4] and reorientation of stripe directions [5,6] have been explored both theoretically and experimentally in this context. Within the HF-CDW theory framework, stripes form at a temperature in the order of a few Kelvin in contrast with the experimental observation that anisotropy only sets in at much lower temperatures of the order of 100 mK [7]. Disorder could also lower the transition temperature within the HF-CDW theory. While disorder and other minor effects may account for some of the discrepancies with the experiment, other scenarios cannot be ruled out. One possibility is that the appearance of

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anisotropy reflects the orientational ordering of local regions having pre-existing order [8,9], analogous to what happens in an isotropic liquid to an anisotropic nematic liquid crystal transition. In this context, the onset of anisotropy is viewed as a transition to a quantum Hall nematic (QHN) state, rather than the first signal of the creation of a CDW modulation [9,10].

2. Results and summary

In this work, we use quantum Monte Carlo (QMC) simulations to study the stability of QHN electronic phases at half-filled valence Landau levels. Such phases have no translational order, but possess a degree of quasi-long-range orientational order. Anisotropic phases at filling factor, $\nu = 2N + 1/2$, are described by a special class of broken-rotational-symmetry (BRS) wavefunctions [11,12] which are constructed by properly splitting the zeroes of isotropic Laughlin polynomials in the trial wavefunction

for a half-filled LL [13,14]:

$$\Psi_\alpha = \hat{P}_N \prod_{j < k}^{N_e} (z_j - z_k + \alpha)(z_j - z_k - \alpha) \times e^{-\sum_{j=1}^{N_e} |z_j|^2 / 4l_0^2} \times \det[\varphi_{\mathbf{k}}(\mathbf{r}_i)], \quad (1)$$

where α is a nematic director whose phase is associated with the angle relative to GaAs hard resistance crystalline axis, \hat{P}_N represents a projection operator onto the N th Landau level, $z_j = x_j + iy_j$ is the complex two-dimensional position of j th electron, $\det[\varphi_{\mathbf{k}}(\mathbf{r}_i)]$ is a Slater determinant of two-dimensional plane waves for spin-polarized electrons that fill a Fermi disk up to momentum k_F , N_e is total number of electrons and l_0 is the magnetic length. For simplicity we consider α real so that the system has a stronger modulation in the x -direction (R_{xx} is hard resistance direction parallel to the $[1\bar{1}0]$ GaAs crystalline axis).

The above BRS wavefunction (which is antisymmetric and translationally invariant) is an obvious starting

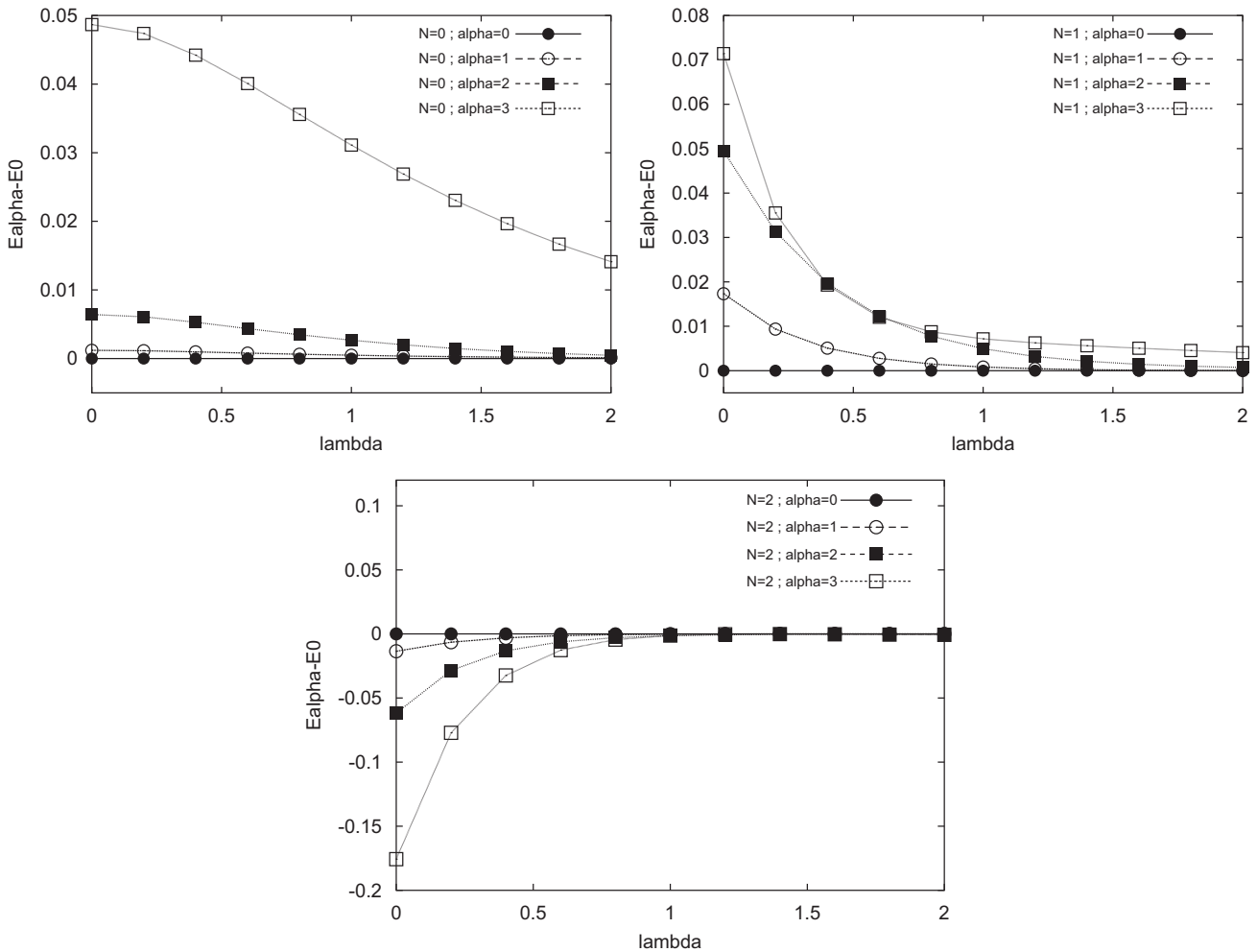


Fig. 1. Correlation energy per electron for BRS liquid crystalline states at $\nu = 2N + 1/2$ with $\alpha = 1, 2$ and 3 relative to the isotropic ($\alpha = 0$) liquid state: $\Delta E_x^{(N)} = E_x^{(N)} - E_0^{(N)}$ for $N = 0, 1$ and 2 as function of parameter λ . Energies are in units of $e^2/(\epsilon l_0)$.

point to study *nematic* quantum Hall (QH) liquid crystals at half-filled valence Landau levels [15]. For $\alpha = 0$ the wavefunction regains its rotational symmetry by transforming into the composite fermion, isotropic Rezayi–Read Fermi-liquid wavefunction [13,14].

The microscopic approach that we adopt allows us to perform a systematic study of the stability of various BRS liquid crystalline states relative to their isotropic liquid counterparts. In all QMC simulations, we considered a standard 2DES model in disk geometry where the interaction potential between electrons has the form:

$V_\lambda(r_{12}) = e^2/(\epsilon\sqrt{r_{12}^2 + \lambda^2})$ where λ is a finite thickness correction [16]. For an ideal two-dimensional sample, $V_{\lambda=0}(r_{12})$ is a pure Coulomb potential. We performed extensive QMC simulations to calculate various important quantities, among them the angle-averaged static structure factor, $\bar{S}(q) = \int_0^{2\pi} (d\theta_q/2\pi) S(\mathbf{q})$. The correlation energy per electron at arbitrary N and given α 's was calculated within the single-LL approximation using the formula

$$E_\alpha^{(N)} = \frac{1}{4\pi} \int_0^\infty dq q \tilde{V}_\lambda(q) \left[L_N \left(\frac{q^2 t_0^2}{2} \right) \right]^2 [\bar{S}(q) - 1], \quad (2)$$

where $\tilde{V}_\lambda(q) = (2\pi e^2/\epsilon q) \exp(-\lambda q)$ is the two-dimensional Fourier transform of $V_\lambda(r_{12})$, $L_N(x)$ are Laguerre polynomials and $\bar{S}(q)$ is calculated in the LLL from QMC simulations with up to $N_e = 109$ electrons. For simplicity, we omitted the projection operator. The calculated energy differences between anisotropic BRS liquid crystalline states ($\alpha \neq 0$) and their isotropic liquid counterparts ($\alpha = 0$) are shown in Fig. 1 for various values of valence Landau level, N .

The current QMC results are in good qualitative agreement with our earlier findings obtained using the

Fermi hypernetted chain method [15]. These results indicate that, while isotropic liquid states are stable in the LLL and first excited Landau level, there are regions of instability towards anisotropic BRS liquid crystalline states in higher Landau levels.

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