Strongly correlated states of trapped ultracold fermions in a U(2) gauge potential

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Frontiers in quantum simulations with cold atoms
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M.Burrello, **MR**, M.Roncaglia, A.Trombettoni, PRB 91, 115117 (2015)
Outline

- Motivation: beyond standard
- U(2) potential & deformed LL
- non-monotonic Haldane pseudopotentials
- Novel incompressible states: Haffnian?
- Entanglement spectrum
- Conclusions
Quantum Engineering

• analog implementation of solid-state systems, with added values:
  • isolated neutral quantum systems (long coherence times)
  • high tunability of microscopic parameters (also interactions!)
  • access to many microscopic observables

• GOAL: answering questions untreatable by classical calculations (!?)

\[ H = -J \sum_{\langle i,j \rangle} b_i^\dagger b_j + \sum_i \epsilon_i \hat{n}_i + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1) \]


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Quantum Engineering

• BUT can we go beyond emulation / simulation of existing regimes?


e.g. Haldane model @ ETH

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Quantum Engineering

• BUT can we go beyond emulation / simulation of existing regimes?

  e.g. Haldane model @ ETH

• HERE, focus on Fractional Quantum Hall states:
  • a wealth of exotic states & topological properties predicted “mathematically” for “strange” interaction & gauge potential forms
  • but in semiconductors 2DEG, almost no tunability!

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Gauge potentials in cold atoms

- fast rotation
- lattice shaking
- adiabatic Berry phase
- Raman hopping

Dalibard, Gerbier, Juzeliunas, and Öhberg, RMP 83, 1523 (2011)

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Single particle Hamiltonian

\[ H = (p_x I + A_x)^2 + (p_y I + A_y)^2 \]

\[ m = 1/2 \]
\[ \hbar = e = c = 1 \]

- **U(1) magnetic field** + **SU(2) spin-orbit** = **U(2) gauge**

\[ \mathbf{A} = \left( -\frac{yB}{2} I + q\sigma_x; \frac{xB}{2} I + q\sigma_y, ; 0 \right) \]

\[ [A_x, A_y] \neq 0 \]

- spatial components of \( F^{\mu\nu} = [D^\mu, D^\nu] \) are not everything!

\[ \mathbf{F} = \mathbf{\nabla} \times \mathbf{A} + i\mathbf{A} \times \mathbf{A} = (B I - 2q^2\sigma_z) \hat{z} \]

\[ U(2) \neq U(1) \times U(1) \]
Single particle Hamiltonian

\[ H = (p_x \mathbb{I} + A_x)^2 + (p_y \mathbb{I} + A_y)^2 + \frac{\omega^2 r^2}{4} \mathbb{I} \]

- \( m = 1/2 \)
- \( \hbar = e = c = 1 \)

- **U(1) magnetic field** + **SU(2) spin-orbit** = U(2) gauge

\[ \vec{A} = \left( -\frac{y B}{2} \mathbb{I}, \frac{x B}{2} \mathbb{I} + q \sigma_x, \frac{y B}{2} \mathbb{I} + q \sigma_y, 0 \right) \]

\[ [A_x, A_y] \neq 0 \]

- spatial components of \( F^{\mu\nu} = [D^\mu, D^\nu] \) are not everything!

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\( U(2) \neq U(1) \times U(1) \)

- weak harmonic confinement

\[ B \equiv \sqrt{B^2 + \omega^2} \]

\[ \Delta \equiv B - B \sim \omega^2 / 2B \]

\[ -L_z \Delta \]
Single particle Hamiltonian

\[ H = (p_x \mathbb{I} + A_x)^2 + (p_y \mathbb{I} + A_y)^2 + \frac{\omega^2 r^2}{4} \mathbb{I} + V_s(x, y) \]

\[ m = \frac{1}{2} \]
\[ \hbar = e = c = 1 \]

• \text{U}(1) magnetic field + \text{SU}(2) spin-orbit = \text{U}(2) gauge

\[ \vec{A} = \left( -\frac{yB}{2} \mathbb{I} + q \sigma_x; \frac{xB}{2} \mathbb{I} + q \sigma_y, 0 \right) \]

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• weak harmonic confinement

\[ B \equiv \sqrt{B^2 + \omega^2} \]

\[ \Delta \equiv B - \mathcal{B} \sim \omega^2 / 2B \]

\[ -L_z \Delta \]

• compensating Zeeman field

\[ V_s(x, y) = -q \Delta (y \sigma_x - x \sigma_y) \]

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Deformed Landau Levels

\[ H = \left( p_x - \frac{yB}{2} + q\sigma_x \right)^2 + \left( p_y + \frac{xB}{2} + q\sigma_y \right)^2 - L_z \Delta \]

• q=0: orbital eigenstates \( \psi_{n,m} \)

• Lowest Landau Level (LLL) approx.

\[ N\Delta \ll 2B \quad k_B T \ll 2B \]

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- \( q=0 \): orbital eigenstates \( \psi_{n,m} \)
- Lowest Landau Level (LLL) approx.
  \( N\Delta \ll 2B \quad k_BT \ll 2B \)
- \( q\neq0 \): Jaynes-Cummings in the basis
  \( \{ \psi_{n-1,m} \uparrow, \psi_{n,m} \downarrow \} \)

\[ H_{n,m} = \tilde{\varepsilon}_{n,m} \mathbb{I} + D_n \begin{pmatrix} -\cos \varphi_n & \sin \varphi_n \\ \sin \varphi_n & \cos \varphi_n \end{pmatrix} \]

\[ \sin \varphi_n = \frac{2q\sqrt{2Bn}}{\sqrt{(B-\Delta/2)^2 + 8q^2Bn}} \]

\[ \varepsilon_{n,m} = \tilde{\varepsilon}_{n,m} - D_n \]

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Experimental considerations

- **U(1) magnetic field + SU(2) spin-orbit**

  M. Burrello, A. Trombettoni, PRA 84, 043625 (2011)

  \( k_d = k_1 - k_2 = k_d e_x \)


- **access to LLL regime: difficult by rotation!**

  A. L. Fetter, Rev. Mod. Phys. 81, 647 (2009)

  \( k_d = k_1 - k_2 = k_d e_x \)


  \( \varepsilon = \delta \omega / \omega \)


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• new hopes: synthetic optical gauge potentials & dimensions

see I. Spielman, I. Bloch, M. Lewenstein, etc.


• some rough estimates

\[ B \ell^2 \approx 1 \land \ell \approx 0.5 \mu m \rightarrow B \approx 4 \cdot 10^{-19} \text{g/s} \]

\[ \omega \approx 10 \div 100 \text{Hz} \rightarrow \Delta / B \approx 0.005 \div 0.05 \]

\[ \hbar / q \approx 1 \mu m \rightarrow q^2 / \hbar B \approx 0.1 \div 5 \]
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Haldane pseudopotentials

- partial wave decomposition of (central) interaction potentials

\[ \mathcal{H}_{\text{int}} = \sum_{M} \sum_{m_{\text{rel}}} W_{m_{\text{rel}}} \sum_{m_1, m_2} g [m_{\text{rel}}, M, m_1] g [m_{\text{rel}}, M, m_2] c_{M-m_1}^\dagger c_{m_1}^\dagger c_{m_2} c_{M-m_2} \]

- polarized electrons in Coloumb potential \( W_1 \gg W_3 \gg \ldots \) 

\[ \nu = 1/3 \quad \Psi_{1/3} = \prod_{i<j} (z_i - z_j)^3 \equiv \Theta^3 \] 

- \( s \)-wave scattering approx. for cold bosons! only \( W_0 \neq 0 \) 

\[ \mathcal{H}_2 = c_2 \sum_{i<j} \delta(z_i - z_j) \quad c_2 = \sqrt{8\pi a/\xi_z} \quad \nu = 1/2 \quad \Psi_{1/2} = \prod_{i<j} (z_i - z_j)^2 \equiv \Theta^2 \]

- LL filling factor \( \nu \approx \lim_{N \to \infty} \frac{N}{m_{\text{max}}} \)

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\[ H_{\text{int}} = \sum_{M} \sum_{m_{\text{rel}}} W_{m_{\text{rel}}} \sum_{m_1, m_2} g [m_{\text{rel}}, M, m_1] g [m_{\text{rel}}, M, m_2] c_{M-m_1}^{\dagger} c_{m_1}^\dagger c_{m_2} c_{M-m_2} \]

- spin1/2 fermions within U(2) DLL

\[ W_{m_{\text{rel}}}^{(n)} = V_{n-1,n-1}^{m_{\text{rel}}} \cos^4 \frac{\varphi_n}{2} + V_{n,n}^{m_{\text{rel}}} \sin^4 \frac{\varphi_n}{2} + V_{n,n-1}^{m_{\text{rel}}} \sin^2 \varphi_n \]

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• spin 1/2 fermions within U(2) DLL

\[ W_{m_{\text{rel}}}^{(n)} = V_{m_{\text{rel}}}^{n-1} \cos^4 \frac{\varphi_n}{2} + \sin^4 \frac{\varphi_n}{2} + V_{m_{\text{rel}}}^{n,n-1} \frac{\sin^2 \varphi_n}{2} \]

• only interspecies contact interactions

\[ \hat{V} = v \sum_{i<j} \delta (z_i - z_j) \langle \uparrow \downarrow | \uparrow \downarrow \rangle \]

! Non-Monotonic HP!  
? new FQH states?
Haldane pseudopotentials

$$\mathcal{H}_{\text{int}} = \sum_{M} \sum_{m_{\text{rel}}} W_{m_{\text{rel}}} \sum_{m_1, m_2} g [m_{\text{rel}}, M, m_1] g [m_{\text{rel}}, M, m_2] c^\dagger_{M-m_1} c^\dagger_{m_1} c_{m_2} c_{M-m_2}$$

- spin $\frac{1}{2}$ fermions within U(2) DLL

$$W_{m_{\text{rel}}}^{(n)} = V_{n-1, n-1} \cos^4 \frac{\varphi_n}{2} + V_{n, n} \sin^4 \frac{\varphi_n}{2} + V_{n, n-1} \sin^2 \frac{\varphi_n}{2}$$

- only interspecies contact interactions

$$\hat{V} = v \sum_{i<j} \delta (z_i - z_j) | \uparrow \downarrow \rangle \langle \uparrow \downarrow |$$

! Non-Monotonic HP!  
? new FQH states?

Dipoles needed for bosons


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Incompressible states

- $[\mathcal{H}, L_z] = 0$: yrast spectrum (disk)
  \[ E(L) = E(L) + L \Delta \quad L_z = Nn - \sum ma_m^\dagger a_m \]

- incompressibility gap
  \[ D(L) = \min[\delta E(L), E(L) - E(L - 1)] \]
  decides over stabilized states

- quasi-hole excitation $\Delta_{qh} \sim \delta$

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**Laughlin ansatz** $\nu = 1/3 \quad \Psi_{1/3} = \prod_{i<j} (z_i - z_j)^3 \equiv \Theta^3$

**incompressibility gap** $E_{qp} \approx D(L_{\text{Lau}}) \approx 0.013\nu \quad L_{\text{Lau}} \equiv 3N(N - 1)/2$
Laughlin ansatz: $\nu = 1/3$  
$\Psi_{1/3} = \prod_{i<j} (z_i - z_j)^3 \equiv \Theta^3$

Incompressibility gap: $E_{qp} \approx D(L_{Lau}) \approx 0.013\nu$  
$L_{Lau} \equiv 3N(N-1)/2$

Plateau lengths: $(N, N-2, N-4, \ldots) = CF$ theory

G. Dev, J. K. Jain, PRB 45, 1223 (1992)
**Laughlin ansatz** \( \nu = 1/3 \quad \Psi_{1/3} = \prod_{i<j} (z_i - z_j)^3 \equiv \Theta^3 \)

**incompressibility gap** \( E_{qp} \simeq D(L_{Lau}) \approx 0.013\nu \quad L_{Lau} \equiv 3N(N - 1)/2 \)

**plateau lengths** \((N, N-2, N-4, \ldots) = CF theory\)
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E(L)

D(L)

\[ E(L) \]

\[ D(L) \]

- numerics with small particle numbers ==> labelling complicated

e.g. \( N=10 \) \( L=111 \) Lau + 3qp or Jain 2/5 ?

Strongly correlated states of trapped ultracold fermions in a U(2) gauge potential

1st DLL: Jain states

\[ E(L) \]
\[ D(L) \]

• numerics with small particle numbers ==> labelling complicated
e.g. \( N=10 \) \( L=111 \) Lau + 3qp or \boxed{\text{Jain 2/5}}?


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1st DLL: other stable states

\[ L = 85 \]

\[ \rho(\vec{r}, \vec{r}_0) \]

- regular pattern of ground states: \( \sim \) pseudo-crystals (atoms + fluxes)

\[ \text{NO Pfaffian} \quad \Psi_{Pf} \propto \text{Pf} \left[ \frac{1}{z_i - z_j} \right] \prod_{i<j} (z_i - z_j)^2 \quad \text{at} \quad L = N(N - 1) - N/2 = 85 \]

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arXiv:1411.5962
• Laughlin ansatz \( \nu = 1/5 \) \( \Psi_{1/5} = \prod_{i<j} (z_i - z_j)^5 \equiv \Theta^5 \)

• incompressibility gap \( E_{\text{qp}}^{(1/5)} \approx D(L_{\text{Lau}}) \approx 0.005\nu \approx 0.3E_{\text{qp}}^{(1/3)} \)

• smoothened transitions due to \( W_3 \) ...
2nd DLL: three regimes

\[ N = 8 \]

Quasiparticles \[ \nu = 1/5 \]

Vortices \[ \nu = 1 \]

- Laughlin ansatz \[ \nu = 1/5 \quad \Psi_{1/5} = \prod_{i<j} (z_i - z_j)^5 \equiv \Theta^5 \]

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2nd DLL: three regimes

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$N = 8$

Quasiparticles
\[ \nu = \frac{1}{5} \]

Vortices
\[ \nu = 1 \]

• skyrmionic spin texture around vortex cores

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2nd DLL: three regimes

\[ N = 8 \]

- **Quasiparticles**
  - \( \nu = 1/5 \)
  - new regime !?

- **Vortices**
  - \( \nu = 1 \)

- **NO Laughlin**
  - \( \nu = 1/3 \)
  \[ \nu = 1/3 \quad \Psi_{1/3} = \prod_{i<j} (z_i - z_j)^3 = \Theta^3 \]

- **Haffnian !?**
  - \( \nu = 1/3 \)
  \[ \nu = 1/3 \quad \Psi_{\text{Hf}} \sim \mathcal{S} \left( \frac{1}{(z_1 - z_2)^2 \ldots (z_{N-1} - z_N)^2} \right) \prod_{i,j} (z_i - z_j)^3 \]


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\( L = 72 \)
\[ \rho(\vec{r}, \vec{r}_0) \]

\( L = 76 \)
\[ \rho(\vec{r}, \vec{r}_0) \]

\( L = 80 \)
\[ \rho(\vec{r}, \vec{r}_0) \]

- Haffnian !?
  \( L_{Hf} = 76 \)
  \[ \nu = 1/3 \quad \Psi_{Hf} \sim S \left( \frac{1}{(z_1 - z_2)^2 \ldots (z_{N-1} - z_N)^2} \right) \prod_{i,j} (z_i - z_j)^3 \]

- effective (d-wave) pairing \( \iff \frac{N}{2} = 4 \) peaks

- stabilized states (by \( \Delta \)) are rather \( L_{Hf} \pm \frac{N}{2} \)

- three-body interactions needed …


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Entanglement spectrum: intro

- Quantum information approach: (robust & intrinsic)

\[ S = A \cup \bar{A} \quad \rho_A = \text{Tr}_A |\psi\rangle\langle\psi| = \sum_l \lambda_l |l\rangle\langle l| \quad \text{ES}_l \equiv -\ln \lambda_l \]

H. Li and F.D.M. Haldane, PRL 101, 010504 (2008)

- Orbital partition ~ real space partition

\[ \rho_A^{(O)} = \left( \sum_{\{\bar{n}''\}} \Psi^e_{\bar{n}\otimes\bar{n}''} \Psi_{\bar{n}'\otimes\bar{n}''} \right) |\bar{n}\rangle_A \langle \bar{n}'| \]


- Particle partition irrespective of position

\[ \rho_A^{(P)} = \left( \langle \psi | \prod_{j \leq N_A} a^\dagger_{m_j} \prod_{k \leq N_A} a_{m_k} |\psi\rangle \right) |\bar{m}\rangle\langle \bar{m}'| \]

A. Sterdyniak, N. Regnault and B. A. Bernevig, PRL 106, 100405 (2011)
ES: Laughlin 1/3

- orbital partition $\sim$ real space partition
  \[ N_A = \sum_{m \leq M_A} n_m \quad L_A = \sum_{m \leq M_A} m n_m \]

\[ L_{1/3} = 3N(N - 1) = 135 \]

1st DLL

2nd DLL

- counting Laughlin edge modes 1, 1, 2, 3, 5, 7, 11, ...

- no clear ES gap ...

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ES: vortices

- **particle partition** irrespective of position
  \[
  \rho_A^{(P)} = \left( \langle \psi | \prod_{j \leq N_A} a_{m_j}^\dagger \prod_{k \leq N_A} a_{m_k} | \psi \rangle \right) | \bar{m} \rangle \langle \bar{m}' |
  \]

\[ L = 65 = N(N - 1)/2 + 2N \]

\[ L = 75 = N(N - 1)/2 + 3N \]

\[ N = 10 \]
\[ N_A = 5 \]
\[ N_A(N - N_A) = 25 \]

\[ L_{A,\text{min}} = 20 \]

- **consistent with central vortex ansatz**
  \[
  \Psi_{V_p} = \prod_i z_i^p \prod_{i < j} (z_i - z_j) \quad \rightarrow \quad L_{A,\text{min}} = N_A(N_A - 1)/2 + pN_A
  \]

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ES: Haffnian candidate

- **particle partition** irrespective of position

\[
\rho_A^{(P)} = \left( \langle \psi \big| \prod_{j \leq N_A} a^\dagger_{m_j} \prod_{k \leq N_A} a_{m_k} | \psi \rangle \right) | \vec{m} \rangle \langle \vec{m}' | 
\]

\[
L = 3N(N - 1) - N = 76
\]

- **conformal limit to cancel geom. factors**

\[
\psi_{\vec{m}}^{(CL)} \equiv \psi_{\vec{m}} \cdot \prod_{j \leq N} \sqrt{m_j}!
\]

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Conclusions & Outlook

- **U(2) potential:**
  - i) deformed LL (spin textures…)
  - ii) non-monotonic HP from s-wave only

- Novel incompressible states: Haffnian? d-wave pairing?

- Entanglement spectrum -- theoretical detector

- other LL deforming potentials? absence of Zeeman comp.?

- degeneracy points between LL’s?

- three-body terms? dissipation-induced?

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