Anomalous 5/2 Quantum Hall Phase Due to Landau-Level Mixing

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INTRODUCTION

✤ Current carrying 2D electron gas subjected to high magnetic field at vey low temperature

⇒ Discretize Fermi sea ⇒ Landau levels

⇒ Quantum Hall effect

✤ Filling factor, $\nu = N/N_\phi \Rightarrow$ Integer, Fraction

✤ $\nu = 5/2 \Rightarrow 1/2$-filled second Landau level

⇒ Enigmatic state

✤ $\nu = 5/2 \Rightarrow$ Hosts non-Abelian quasi-particle ⇒ qubit of fault tollerent *Topological* quantum computer[1]

✤ Topologically distinct possible candidates for 5/2,

Phases	Flux, N_ϕ	Model wave function	K
Pfaffian (Pf)	$2N-3$	Moore-Read Pfaffian[2]	7/2
Anti-Pfaffian (A-Pf)	$2N+1$	Moore-Read Conjugate	5/2
Particle-hole symmetric Pfaffian (PH-Pf)	$2N-1$	?	3/2

The Debate

Theoretical studies favour ⟹ A-Pf	⚡	Experimental observations favour[3,4] ⟹ PH-Pf

LANDAU LEVEL MIXING THEORY

✤ 5/2 state observed at $\Rightarrow B \sim 12-1$ T

✤ **For GaAs sample LLM strength, $\kappa \sim$ 0.7-2.5** $\quad (\kappa = 2.52/\sqrt{B})$

✤ Theoretical predictions were limited to $\kappa \lesssim 1$

✤ **The "realistic regime", $\kappa \gtrsim 1$ remained UNEXPLORED !!**

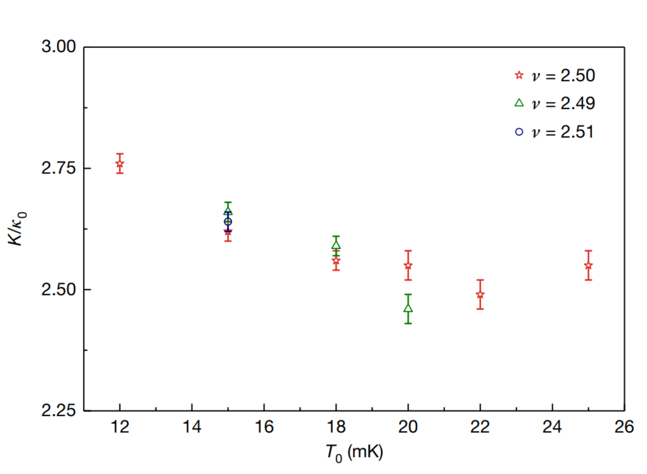
✤ Effective Hamiltonian[5],

$$\hat{H}_{\rm eff}(\kappa) = \sum_m \left[V_m^{(2)}\Big|_{Coulomb} + \kappa\, \delta V_m^{(2)} \right] + \sum_m \kappa\, V_m^{(3)}$$

where $V_m^{(2)}$ and $V_m^{(3)}$ are two and three body m-th pseudpotentials respectively

EXPERIMENTAL EVIDENCE

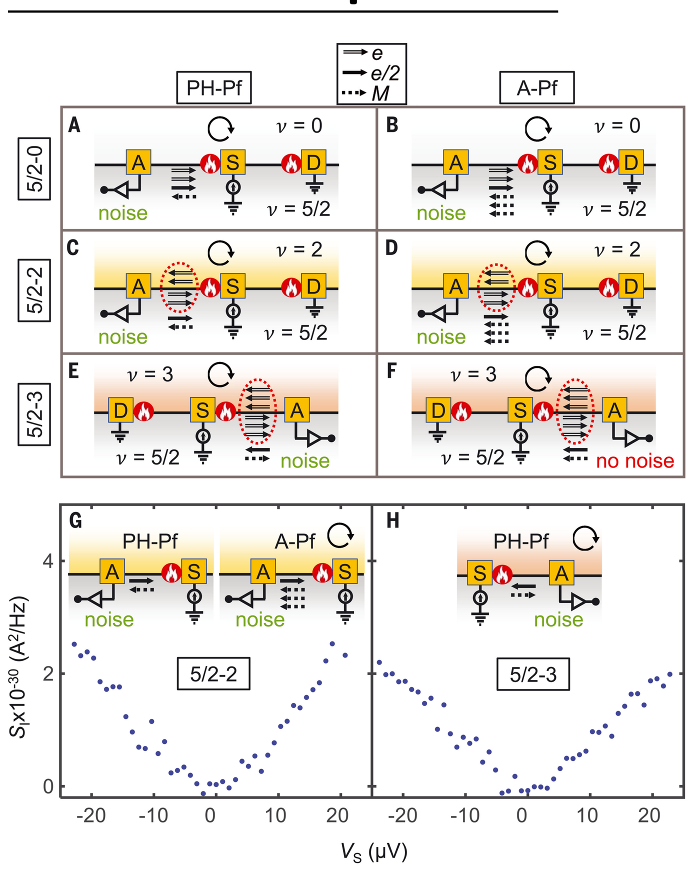
Thermal Hall Conductivity Measurement[3]



✽ Normalized thermal conductance coefficient $K = (2.53 \pm 0.04)\kappa_0$ for $T_o = 18-25$mK

✽ $T_0 \leqslant 15$mk ⇒ increase of equilibration length of counter propagating modes ⇒ K rises

Shot Noise Experiment[4]

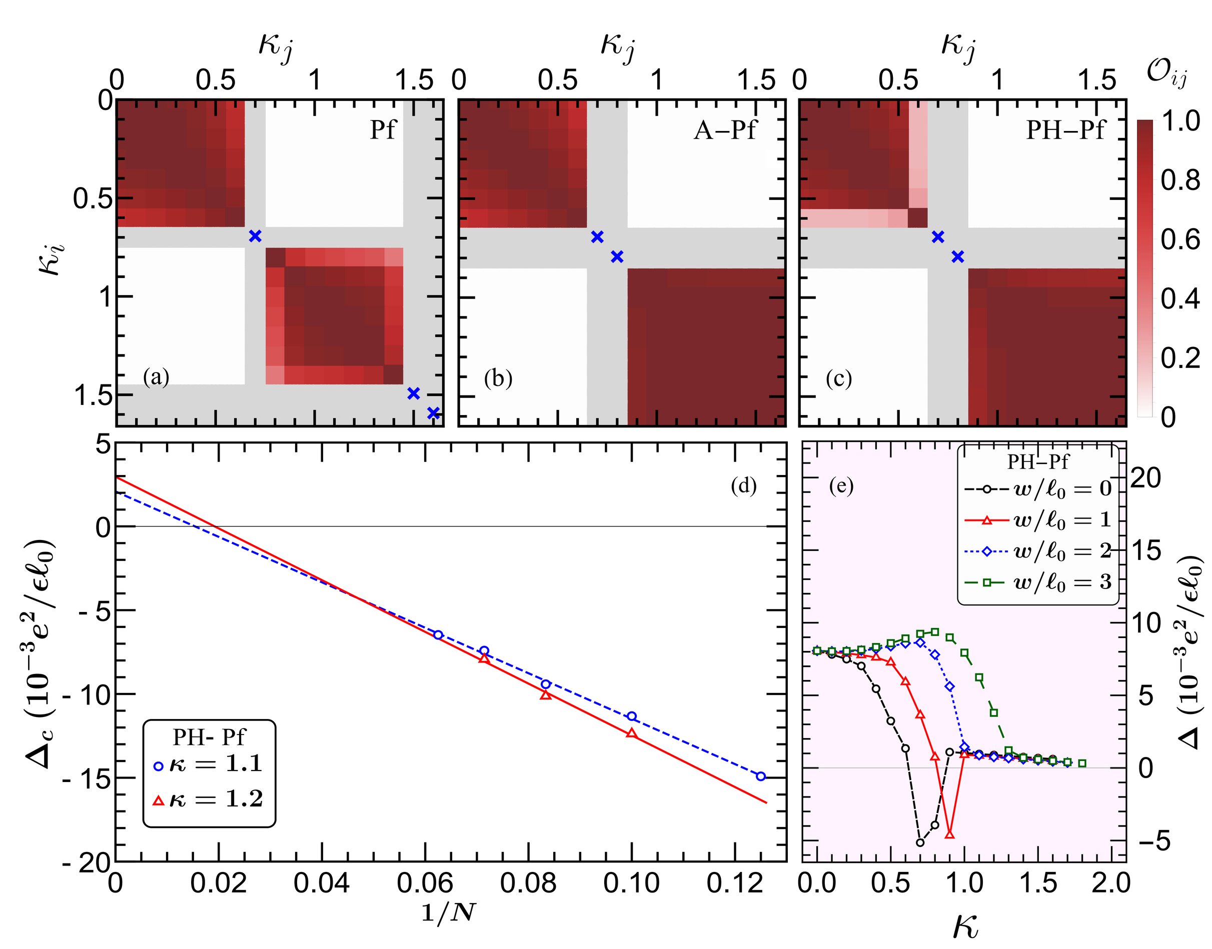


Measurement of Down stream noise at the interface of $\nu = 5/2$ and $\nu = 3$,

✽ PH-Pf: DOWN stream Majorana mode ⇒ Noise

✽ A-Pf: UP stream Majorana mode ⇒ NO Noise

LANDAU LEVEL MIXING - EMERGENCE OF ANOMALOUS PHASE ($\mathscr{A}$-PHASE)



➢ Fig (a)-(c), exact overlap matrix, $\mathscr{O}_{ij} = \langle \Psi_{ex}(\kappa_i) | \Psi_{ex}(\kappa_j) \rangle$ for Pf, A-Pf, PH-Pf at $N = 14, 12, 14$ respectively

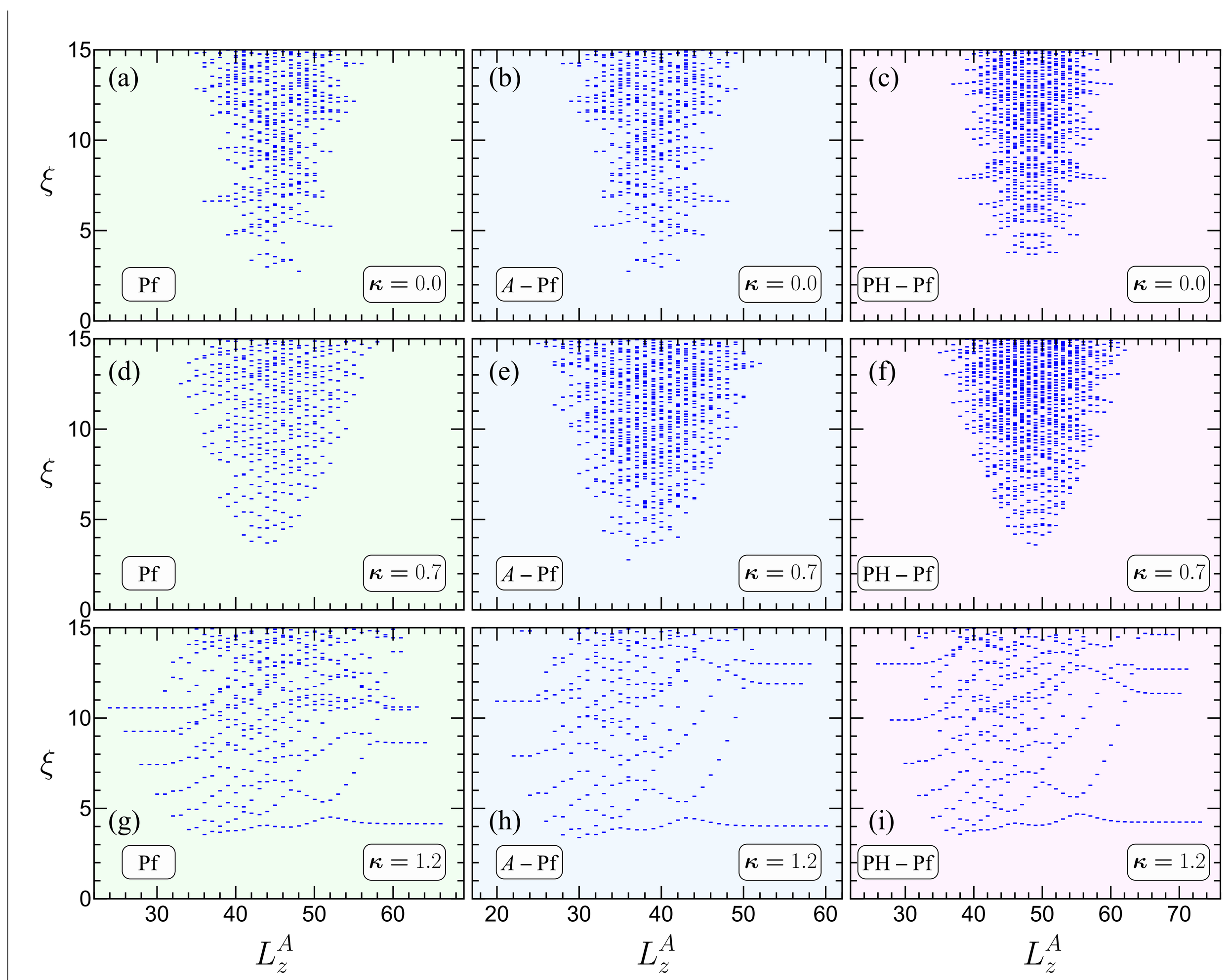
➢ Blue crosses ⇒ unquantized points;
Gray zones ⇒ unquantized regime

➢ Finte charge gap, Δ_c for PH-Pf at thermodynamic limit

➢ Finte neutral excitation gap, Δ for PH-Pf at high-κ

✪ **$\kappa \sim$ 0.7-1.5 ⟹ Reentrant Anomalous Phase**

☛ **Experimental Regime**



➢ Fig (a)-(i) Entanglement spectra of exact states of Pf, A-Pf, PH-Pf fluxes for different κ sectors

➢ Well gapped ES in the $\mathscr{A}$-phase

➢ Close similarities of ES in the $\mathscr{A}$-phase ⇒ Unique topological order irrespective of different flux

PROPOSED WAVE FUNCTION FOR 5/2 STATE IN THE $\mathscr{A}$-PHASE

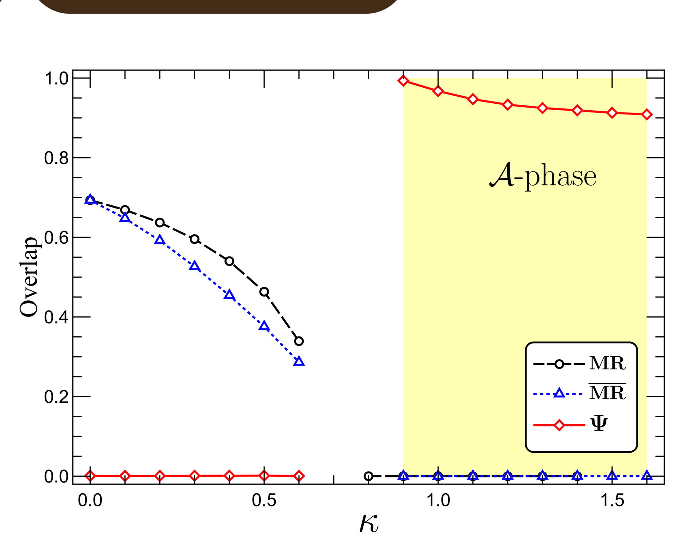
$$\Psi = J_N\, \mathscr{S} \left[\prod_{1 \leqslant i,j \leqslant N/2} \left(z_i - z_{N/2+j} \right)^2 \right]$$

✣ $J_N = \prod_{i<j}^N (z_i - z_j)$ is the N-particle Jastrow factor; z_i electronic coordinates.

✣ Two **Bose-Einstein condensates** of non-interacting composite bosons consisting $N/2$-particles with strong repulsion.

✣ Total flux $= 2N-1$ (PH-Pf)

OVERLAP



✦ In the lower κ-phase,

✧ The overlaps of MR and $\overline{\rm MR}$ decays with κ

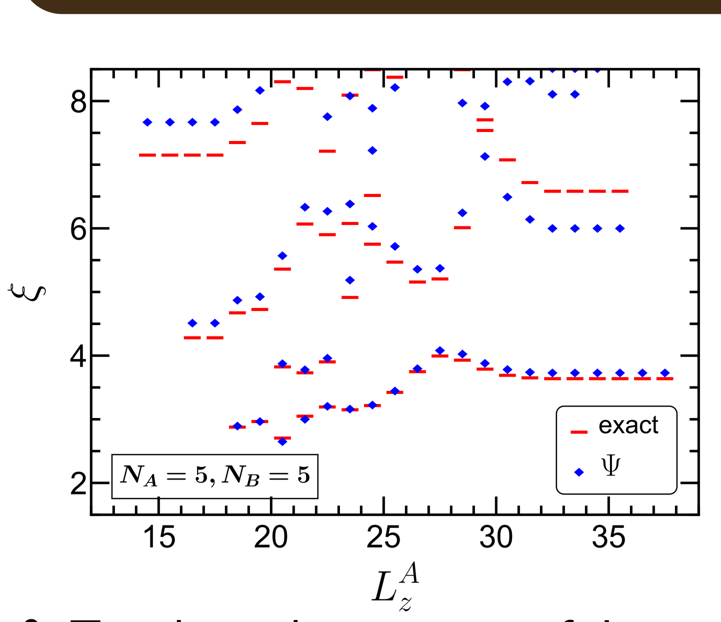
✧ Overlap of Ψ is zero

✦ In the $\mathscr{A}$-phase,

✧ The overlaps of MR and $\overline{\rm MR}$ is zero

✧ Overlap of Ψ is consistently very high

TOPOLOGICAL PROPERTIES



✤ **Entanglement Spectra** (ES) of exact state at PH-Pf flux and Ψ

➥ Excellent matching of low lying sector

✿ Topological properties of Ψ is encoded in **K-matrix**,

$$\mathbf{K} = \begin{pmatrix} 1 & 3 \\ 3 & 1 \end{pmatrix}, \quad \vec{t} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}, \quad \vec{s} = \begin{pmatrix} 1/2 \\ 1/2 \end{pmatrix}$$

✿ Filling factor, $\nu = \vec{t}^T.\mathbf{K}^{-1}.\vec{t} = 1/2$

✿ Shift $= (2/\nu)\ \vec{t}^T.\mathbf{K}^{-1}.\vec{s} = 1$

✿ Ground state degeneracy, $\mathfrak{D} = |{\rm Det}(\mathbf{K})^g| = 8^g$

✿ Eigen-values of $\mathbf{K}$: one +ve, one -ve ⇒ Central charge = 0

✿ Macroscopic $N/2$ bosons can sit together ⇒ coset group $\mathbb{Z}_2$ ⇒ possibly supports Majorana edge Mode

✿ Total central charge $= 2+0+1/2 = 5/2$

SUMMARY

✯ Our work finds a possible resolution to the earlier theoretical debate and experimental observation.

✯ We have identified a reentrant anomalous phase, distinct from conventional Pf or A-Pf phase at an intermediate range of LLM.

✯ We propose a wave function for this phase having similar flux of PH-Pf which possesses very high overlap and good matching of low-lying ES.

✯ The unique topological order observed for this A-phase should possibly correspond to the experimentally observed phase.

References

1. S. D. Sarma, M. Freedman, C. Nayak, Phys. Rev. Lett. 94, 166802, (2005)
2. G. Moore and N. Read, Nuclear Physics B 360, 362 (1991)
3. M. Banerjee *et. al.*, Nature 559, 205 (2018)
4. 5. B. Dutta *et. al.*, Science 375, 193–197 (2022)
5. M. R. Peterson and C. Nayak, Phys. Rev. B 87, 245129 (2013)
6. S. Das, S. Das, S. S. Mandal, arXiv:2206.04419

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