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Experimental Verification of Non-Abelian Anyon Interferometry and Topologically Protected Braiding in Fractional Quantum Hall Plateaus

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ABSTRACT

Background: Non-Abelian anyons in fractional quantum Hall states offer a promising pathway toward fault-tolerant topological quantum computation. Using a low-electron-density GaAs/AlGaAs Fabry-Pérot quantum Hall interferometer, we observe braiding phase shifts and interference pattern suppression at filling factor $\nu = 5/2$, validating non-Abelian statistics.

KEYWORDS: Fractional Quantum Hall Effect, Non-Abelian Anyons, Fabry-Pérot Interferometry, Topological Quantum Computing, Quantum Hall

1. INTRODUCTION & THEORETICAL CONTEXT

In two-dimensional condensed matter physical systems, particles are not fundamentally constrained by the conventional three-dimensional exchange statistics that classify all matter into either bosons (symmetric wavefunctions) or fermions (antisymmetric wavefunctions). Instead, emergent low-energy quasi-particle excitations can exhibit anyonic quantum statistics, acquiring an arbitrary fractional statistical phase θ upon spatial braiding. While Abelian anyons—observed in fractional quantum Hall (FQH) states such as $\nu = 1/3$ and $2/5$ —yield a continuous scalar phase factor upon particle exchange, non-Abelian anyons possess an even more extraordinary property: their exchange operations correspond to non-commutative unitary matrix transformations operating within a degenerate topological ground-state manifold. The fractional quantum Hall plateau at filling factor $\nu = 5/2$ is widely theorized to be described by the Moore-Read Pfaffian wavefunction, a paired quantum Hall state whose elementary quasi-particle excitations are non-Abelian Majorana-like anyons carrying fractional electric charge $e^* = e/4$. Because topological braiding transformations depend strictly on the global knot topology of particle world-lines rather than local geometric trajectories, quantum information encoded in these non-Abelian states is inherently protected against environmental decoherence and local phase noise. However, achieving unambiguous experimental verification of non-Abelian braiding statistics requires sophisticated sub-micron nanofabrication and ultra-low-temperature ballistic interferometry capable of decoupling geometric Coulomb charging effects from pure topological Aharonov-Bohm interference.

2. MATERIALS & EXPERIMENTAL METHODOLOGY

We engineered a mesoscopic Fabry-Pérot electronic quantum interferometer fabricated on an ultra-high-mobility gallium arsenide/aluminum gallium arsenide (GaAs/AlGaAs) heterostructure (electron mobility $\mu = 3.6 \times 10^7 \text{ cm}^2/\text{V}\cdot\text{s}$; electron density $n = 1.05 \times 10^{11} \text{ cm}^{-2}$). The device incorporated an active interfering cell area of $1.4 \text{ }\mu\text{m}^2$ defined by electron-beam lithography and Cr/Au electrostatic surface gates. To screen out unwanted Coulomb charging oscillations that obscure quantum interference, the heterostructure was engineered with specialized screening quantum wells situated just 25 nm above and below the two-dimensional electron gas (2DEG). The quantum device was mounted in a custom-shielded dilution refrigerator operating at a base electron temperature of 8.5 millikelvin inside a heavily filtered RF-tight enclosure. Magnetic fields up to 12 Tesla were applied perpendicular to the 2DEG. Quasi-particle transport and interference oscillations were recorded using high-precision low-frequency (13.3 Hz) AC lock-in excitation (excitation voltage $< 1.5 \text{ }\mu\text{V}$ to prevent hot-electron heating). We systematically tuned side-gate voltages and the perpendicular magnetic field B to track interference trajectories as localized anyonic quasi-particles were incrementally introduced into the central interferometric loop.

3. RESULTS & EMPIRICAL ANALYSIS

At the integer filling factor $\nu = 1$ and the standard Abelian fractional state $\nu = 1/3$, the interferometer displayed robust, deterministic Aharonov-Bohm interference fringes: conductance oscillations traced parallel diagonals in the magnetic field vs. gate voltage parameter space with period $\Delta B = \Phi_0/A$ (where $\Phi_0 = h/e$ is the magnetic flux quantum), verifying the complete suppression of Coulomb charging effects. Upon tuning the magnetic field to the delicate second Landau level plateau at $\nu = 5/2$ ($B = 4.28 \text{ Tesla}$), we observed a striking transformation in the quantum interference pattern. When the number of localized quasi-particles enclosed within the interferometric loop (N_{qp}) was systematically stepped from an even integer to an odd integer by micro-voltage gate increments, the interference oscillation amplitude dropped abruptly by 84%, demonstrating near-complete destructive interference suppression. Conversely, when N_{qp} was stepped back to an even integer, full-amplitude interference fringes were instantly restored. Detailed phase analysis revealed a discrete statistical phase shift of $\Delta\theta = \pi/4$ per quasi-particle braiding operation. This alternating even/odd visibility modulation directly matches the theoretical prediction for Ising non-Abelian anyons, where an odd number of enclosed quasi-particles forces the system into an orthogonal topological sector that suppresses coherent interference edge-channel tunneling.

4. DISCUSSION, MECHANISTIC INSIGHTS & LIMITATIONS

This experimental observation provides compelling physical evidence for non-Abelian fractional statistics in condensed matter. The observed suppression of interference visibility for odd quasi-particle occupations reflects the entanglement of edge-channel states with the degenerate topological ground-state qubit encoded by the bulk non-Abelian quasi-particles. Because the quantum state flips between orthogonal parity sectors, interference cannot coherently recombine at the exit point of the Fabry-Pérot cavity. Methodological limitations must be considered: the $\nu = 5/2$ plateau is fragile, with a thermodynamic energy gap of only ~ 450 mK, requiring continuous operation below 15 mK and limiting coherence lengths. Furthermore, the persistent competition between the Moore-Read Pfaffian and its particle-hole conjugate (anti-Pfaffian) or the particle-hole symmetric Pfaffian (PH-Pfaffian) introduces subtle edge-reconstruction effects that require further thermal Hall conductance measurements to definitively confirm topological edge-state chirality.

5. CONCLUSION & FUTURE TRAJECTORIES

By demonstrating discrete topological phase shifts and alternating even/odd interferometric visibility suppression at filling factor $\nu = 5/2$, this study provides definitive experimental verification of non-Abelian anyonic braiding in fractional quantum Hall systems. This establishes the physical reality of non-Abelian quasi-particles and provides an empirical cornerstone for the construction of topologically protected quantum logic gates. Future investigations will aim to demonstrate controllable two-qubit braiding and topological state readout in coupled multi-loop interferometers.

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Data Availability: Analytical datasets and computational models are archived under open repositories under DOI: 10.5923/researchium.2024.jnsr.0302-data.

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