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Formation of helical domain walls in the fractional quantum Hall regime, a step toward realization of high order non-Abelions

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We propose an experimentally-feasible platform to realize parafermions (high order non-Abelian excitations) based on spin transitions in the fractional quantum Hall effect regime. As a proof-of-concept we demonstrate a local control of the spin transition at a filling factor $2/3$ and formation of a conducting fractional helical domain wall (fhDW) along a gate boundary. Coupled to an s-wave superconductor these fhDWs are expected to support parafermionic excitations. We present exact diagonalization numerical studies of fhDWs and show that they indeed possess electronic and magnetic structures needed for the formation of parafermions. Reconfigurable network of fhDWs will allow manipulation and braiding of parafermionic excitations in multi-gate devices.

Topological quantum computation can be performed with Majorana fermions (MF)¹, but MF-based qubits are not computationally universal². Parafermions (PFs), higher order non-Abelian excitations, are predicted to have denser rotation group and their braiding enables two-qubit entangling gates^{3,4}. A two-dimensional array of parafermions can serve as a building block for a system which supports Fibonacci anyons with universal braiding statistics⁵, a holy grail of topological quantum computing. In an important conceptual paper Clark *et al.* proposed that PF excitations can emerge in the fractional quantum Hall effect (FQHE) regime if two counter-propagating fractional chiral edge states with opposite polarization are brought into close proximity in the presence of superconducting coupling⁶. Here we propose that domain walls formed at spin phase transitions in the FQHE regime have the prerequisite helical structure to support PF excitations when coupled to an s-wave superconductor. We demonstrate experimentally that in a triangular quantum well a 2D system can be tuned across a spin transition at a filling factor $\nu = 2/3$ using electrostatic gating. We also demonstrate formation of conducting channels at boundaries between incompressible polarized and unpolarized $\nu = 2/3$ states. These channels are formed from two counter-propagating $\nu = 1/3$ states with opposite spin orientation, we will refer to them below as fractional helical domain walls (fhDW) in analogy to helical channels formed along the edges in the quantum spin Hall effect. Local control of polarization allows formation of a reconfigurable network of fhDWs with fractionalized charge excitations and, potentially, parafermion manipulation and braiding. We present exact diagonalization numerical studies of fhDWs.

Helical channels are commonly associated with the quantum spin Hall effect⁷, topological insulators⁸ or nanowires with spin-orbit interactions^{9,10}, where Coulomb interactions are not strong enough to fraction-

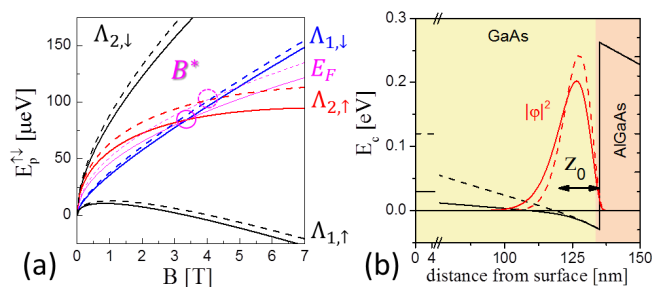


FIG. 1. (a) Energy spectrum of Λ -levels for CFs, Eq. 1. For $\nu = 2/3$ (two filled Λ -levels) the spin polarization of the top level changes at B^* , when $\Lambda_{1,\downarrow}$ and $\Lambda_{2,\uparrow}$ cross. Solid and dotted lines are calculated for two different values of the wavefunction extent z_0 . (b) The calculated wavefunction in a triangular quantum well formed at a GaAs/AlGaAs heterojunction interface. Solid and dotted lines correspond to the two different gate voltages and show the change of z_0 . Note the break in the horizontal axis.

alize charges. A natural system to look for PFs is a 2D electron gas (2DEG) in the FQHE regime, where edge states support fractionally charged excitations. In the conventional QHE setting, though, edge modes are *chiral*. *Helical* channels can potentially emerge as domain walls during a quantum Hall ferromagnetic transition. It has been predicted that domain walls formed in the integer QHE regime at a filling factor $\nu = 1$ have helical magnetic order¹¹. Experimentally, local electrostatic control of domain walls in the integer QHE regime at $\nu = 2$ was recently demonstrated in magnetic semiconductors¹², and their electronic and magnetic structure has been calculated¹³.

In the FQHE regime spin transitions have been observed at a filling factor $\nu = 2/3$ and other fractions^{14,15}. At the transition, the 2DEG spontaneously phase sep-

arates into regions of different spin polarizations, and conducting domain walls are formed along the domain boundaries^{16,17}. An experimental challenge is to devise a system where spin transitions in the FQHE regime can be controlled locally, allowing formation and manipulation of DWs. Theoretically, neither magnetic nor electronic structure of these domain walls is known.

It has been realized that hard $\nu = 2/3$ edge states at the 2D gas boundaries are complex objects with chiral downstream propagation of charge excitations and neutral energy-carrying modes propagating both up- and downstream¹⁸⁻²⁰. Recent experiments show that two co-propagating $\nu = 1/3$ charge modes at the edge of a sample are weakly interacting and can be spatially separated²¹. Thus, a domain wall formed between two spin polarized domains at $\nu = 2/3$ ferromagnetic transition can be formally constructed from two counter-propagating $\nu = 1/3$ chiral charge modes with opposite spin polarization, similar to the domain walls formation in the integer quantum Hall ferromagnetic transition¹³.

Spin transitions in the FQHE regime can be readily understood within the framework of the theory of composite fermions (CF)²², where FQHE states at filling factors $\nu = \nu^*/(2\nu^* - 1)$ for $1/2 < \nu < 1$ are mapped onto integer QHE states with a filling factor ν^* for CFs. The energy spectrum of CF Λ -levels with an index $p = 1, 2, 3 \dots$ can be written as

$$E_p^{\uparrow\downarrow} = \hbar\omega_c^{cf} \left(p - \frac{1}{2} \right) \pm g\mu_B B. \quad (1)$$

The CF cyclotron energy $\hbar\omega_c^{cf}$ is proportional to the charging energy $E_c = e^2/\sqrt{l_m^2 + z_0^2}$, where $l_m \propto \sqrt{B_\perp}$ is the magnetic length, $B_\perp = B \cos\theta$ is the out-of-plane component of the magnetic field B , and z_0 is the extent of the wavefunction in the out-of-plane direction. The second term is the Zeeman energy. Due to the difference in B -dependences of the two terms, levels $\Lambda_{p,\downarrow}$ and $\Lambda_{p+1,\uparrow}$ cross at some $B^* > 0$, see Fig. 1. Thus, for $\nu^* = 2$ (two Λ -levels are filled) the top energy level undergoes a spin transition at B^* . The $\nu = 2/3$ state is unpolarized for $B < B^*$ and fully polarized for $B > B^*$.

Conventionally, FQHE spin transitions are studied in tilted magnetic fields, where *global* control of the field angle θ changes the ratio of Zeeman and cyclotron energies. For a triangular confinement, though, z_0 is gate dependent, $z_0 = z_0(V_g)$ (see Fig. 1b), and *local* control of E_c and B^* at a fixed B becomes possible. Within the Fang-Howard approximation of the wavefunction in a triangular well, $z_0 = 3/b$, where $b \propto n^{1/3}$ is a function of electron density. For GaAs parameters and $B^* \approx B_{\nu=2/3} \approx 4 - 6$ T, the field B^* becomes density and gate dependent: $\delta B^*/B^* \approx 0.3\delta n/n$, $\delta n/n = \delta V_g/V_g$. The field position of the $\nu = 2/3$ state is also density and gate dependent, $\delta B_{\nu=2/3}/B_{\nu=2/3} = \delta n/n$. Thus, for a well-developed wide $\nu = 2/3$ state and a sharp spin transition there should be a range of magnetic fields where spin polarization of the top level can be tuned locally by electrostatic gating.

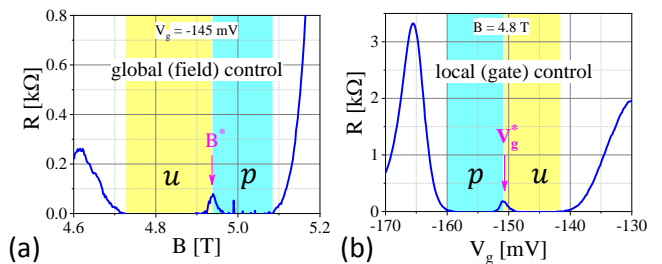


FIG. 2. Resistance in the vicinity of $\nu = 2/3$ state is measured as a function of (a) magnetic field B at a constant gate voltage V_g or (b) as a function of V_g at a constant B . Yellow and cyan colors mark unpolarized (u) and fully polarized (p) $\nu = 2/3$ states. B^* and V_g^* mark the spin transition.

In order to demonstrate electrostatic control of polarization we have grown a number of wafers where high mobility 2D electron gas is confined at a single GaAs/AlGaAs interface. Inverted GaAs/AlGaAs heterojunctions are grown by molecular beam epitaxy, the top layer is 130-230 nm thick GaAs, Si δ -doping placed 70-300 nm beneath the heterojunction interface. The top 25 nm of GaAs are lightly doped to reduce the surface pinning potential. In the main text we present data on devices fabricated from wafers A (Fig. 2) and D (Fig. 3), wafers parameters can be found in²³. Inverted heterostructures allow electrostatic gating of a shallow 2D gas with no hysteresis, also in similar wafers proximity-induced superconductivity has been reported²⁴. Ohmic contacts are formed by annealing Ni/AuGe/Ni/Au 6nm/120nm/20nm/20nm in a H_2/N_2 atmosphere. 10 nm - thick Ti gates are separated from GaAs and from each other by 50 nm Al_2O_3 grown by an atomic layer deposition (ALD). The gates are semi-transparent and a 2D electron gas is created by shining red LED at ~ 4 K. Measurements were performed in a dilution refrigerator with the base temperature $T \approx 30$ mK using a standard lock-in technique with excitation current $I_{ac} = 0.1 - 10$ nA.

Magnetoresistance in the vicinity of a $\nu = 2/3$ plateau is shown in Fig. 2a. At the base temperature a 0.35 T - wide incompressible state is interrupted by a small peak at $B^* = 4.94$ T. This peak has all the characteristics of a spin phase transition studied in the past, including strong current dependence and hysteresis with respect to the field sweep direction, which appears at high bias currents¹⁵. We identify this peak with the spin transition, unpolarized (u) and polarized (p) $\nu = 2/3$ states are highlighted with yellow and cyan on the plot. The most important data is shown in Fig. 2b, where resistance is plotted as a function of a gate voltage V_g measured at a fixed magnetic field. Similarly to the field scan, a 18 mV - wide $\nu = 2/3$ plateau is interrupted by a small peak at $V_g^* = -151$ mV, which we identify with the spin transition. The transition peak is narrow, ≈ 6 mV with well-defined $\nu = 2/3$ states with different polarization on the two sides of the peak. Thus, it is possible to control spin polarization locally by electrostatic gating.

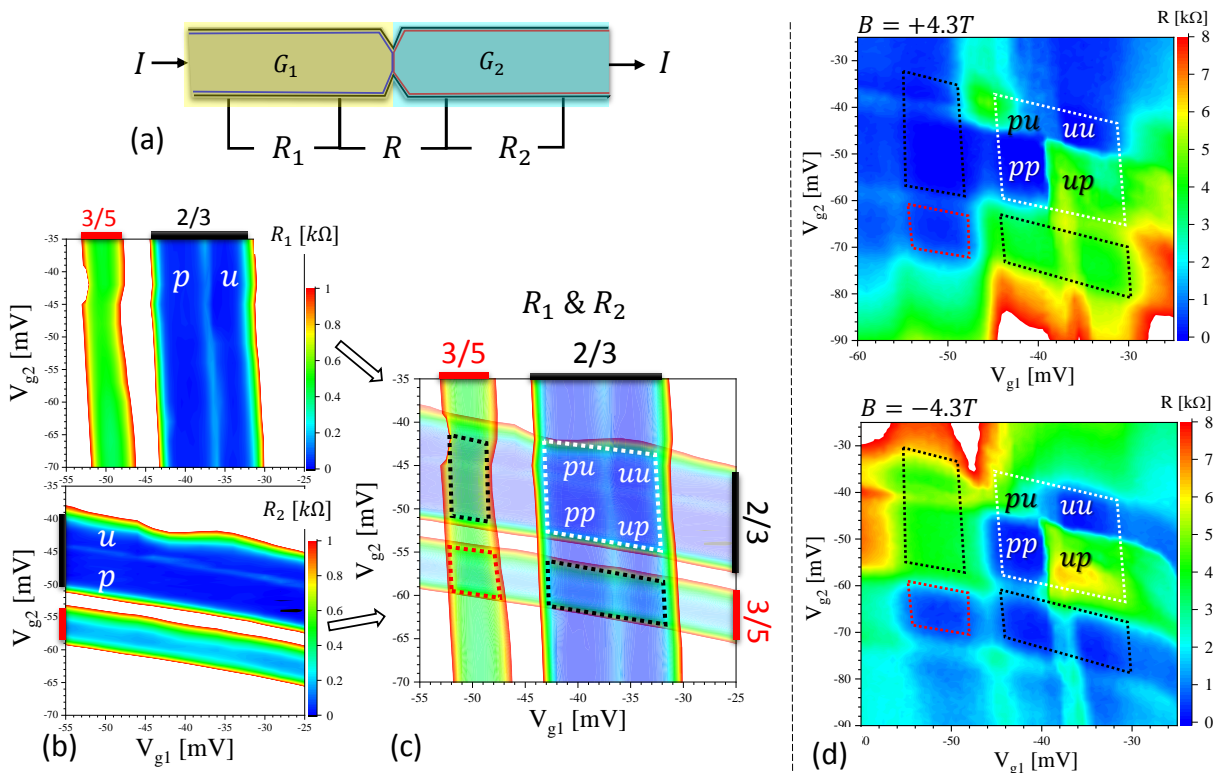


FIG. 3. (a) Sample layout. (b) Resistance R_1 and R_2 under gates G_1 and G_2 is measured as a function of gate voltages V_{g1} and V_{g2} . Letters u and p mark unpolarized and polarized states. In (c) R_1 and R_2 are plotted on top of each other. The region where $\nu = 2/3$ under both gates is outlined with a white dotted line, $s_1 s_2$ indicates polarization under G_1 and G_2 . In (d) resistance R across the gate boundary is plotted for two fields directions. Nonzero R in (up) and (pu) quadrants indicates formation of a conducting domain wall between polarized and unpolarized $\nu = 2/3$ states. Lithographical length of the gate boundary is $7 \mu\text{m}$. Resistance in (b,c) is measured with $I_{ac} = 1.3 \text{ nA}$, in (d) with $I_{ac} = 0.13 \text{ nA}$.

Formation of a conducting domain wall at a boundary between unpolarized and polarized $\nu = 2/3$ regions is shown in Fig. 3. A 2D gas is separated into two regions where density is independently controlled by gates G_1 and G_2 . The length of the gate boundary is $7 \mu\text{m}$ for the shown device. Resistances R_1 and R_2 for the 2D gases under the two gates are combined into a single plot in (c) in order to visualize regions in the $(V_{g1} - V_{g2})$ plane where FQHE states on both sites of the boundary overlap (a small coupling between the gates results in slightly non-orthogonal evolution of the features). A small bump in the middle of the $\nu = 2/3$ state is the spin transition (the data is taken with high $I_{ac} = 1.3 \text{ nA}$ in order for the transition to be visible above the noise level), and separates the $2/3$ region into four quadrants with different polarizations across the gate boundary. In (d) resistance measured across the gate boundary is plotted as a function of both gate voltages. In the region outlined red incompressible $3/5$ states are formed on both sites of the gate boundary and $R = 0$. A chiral channel is formed between $2/3$ and $3/5$ states (two regions outlined black). In this case resistance is gradient- and field direction-dependent: $R = 0$ or $R = 1/6 R_q$, where $R_q = h/e^2$. Within the $2/3$ state $R = 0$ in the

(pp) and (uu) quadrants, indicating formation of a well defined incompressible state under the gate boundary. When polarization of the $2/3$ state changes across the gate boundary R becomes non-zero indicating formation of a conducting channel. Resistance $R \sim 3 - 5 \text{ k}\Omega$ does not depend significantly on the direction of the density and polarization gradient (up or pu) nor on the magnetic field direction, consistent with the formation of a helical domain wall. In the current geometry resistance of the fhDW is not measured directly, within Landauer-Büttiker formalism we extract $(10 - 20)R_q$ channel resistance for $2-7 \mu\text{m}$ - long fhDWs with no clear scaling with the length. The lack of scaling may indicate that scattering predominantly occurs in hot spots formed at tri-junctions where fhDW merges with edge states.

In order to investigate the structure of domain walls formed between spin-unpolarized and spin-polarized regions we performed exact diagonalization studies of a system with small number of particles. To simulate edge states we use the disk geometry^{25,26} shown schematically in Fig. 4. Long-range Coulomb interactions between electrons are introduced using Haldane pseudopotentials. A neutralizing background and a confinement potential are used to hold electrons inside the disk. As is evi-

dent from experiments, spin transition can be controlled by modulation of either Coulomb or Zeeman energies interchangeably, see e.g. Fig. 2. In our modeling we use spatially-dependent Zeeman effect to control spin polarization of the 2DEG. The central region of the disk of radius $R_1 = 2.9l_m$ is characterized by a high Zeeman energy term E_Z^{max} , while the outer region with the outer diameter $R_2 = 4.8l_m$ is set to $E_Z^{min} = 0$. The Zeeman term varies smoothly within $R_1 < r < R_1 + \Delta R$, where $\Delta R = 0.4l_m$, resulting in a smooth variation of wavefunctions across the disk and avoiding spurious effects originating from abrupt changes. Note that due to a strong penetration of electron wavefunctions from the $R_1 < r < R_2$ region into the $r < R_1$ region, the variation of the average spin splitting $\int \psi(r)^* E_Z(r) \psi(r) d^2r$ for the two close modes on two sides of the domain wall is $< 6\%$, similar to the experimental conditions. Therefore our model studies soft edges characterizing the experiment.

We include up to 12 electrons in the exact diagonalization calculation for a fully spin-polarized states and 8 electrons for unpolarized states or coexisting polarized and unpolarized states at $\nu = 2/3$. Energies and wavefunctions for the ground state and edge states, their density and spin density distributions for the disk geometry have been calculated, see²³ for details. The ground state for 8 particles has the total angular momentum projection $L_z = 46$, in agreement with the composite fermion theory²². The ground state is spin polarized in the interior part of the disk and spin-unpolarized in the exterior area, as expected. The total spin projection of the ground state is $S_z = +2$. The lowest excited states with the same spin projection, which correspond to the addition or subtraction of a single flux, have angular momenta $L_z = 45$ and 47 . These states are the current carrying states defining the domain wall. The difference in spin polarizations between these two states in shown in Fig. 4b, it smoothly changes sign across the domain wall. There is $\approx 0.5l_m$ outward shift of the position of the midpoint of the domain wall in the actual spin density profile relative to the profile of the defining Zeeman term. This shift is due to smaller wavefunction weights in the outward region.

The two edge states with different L_z on the disk have different angular velocities. When mapped onto a plane, these two states will have different linear velocities, i.e. their velocities will have counter-propagating components. Combined with the different spin polarization these states will have a finite overlap with Cooper pair wavefunctions in a proximity s-wave superconductor, as has been shown for domain walls in integer quantum Hall ferromagnets¹³. A proximity-induced topologically non-trivial superconductor, defined by the

counter-propagating CFs modes with different polarization, is expected to emerge in the domain wall region. Due to higher degeneracy of the composite fermion Λ -levels compared to the degeneracy of the Landau levels, parafermion states will emerge at the boundary of topo-

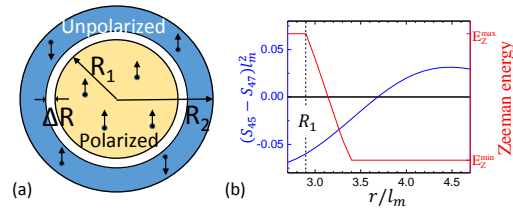


FIG. 4. (a) Disk geometry for the simulation domain. (b) The blue curve is the difference between spin densities $S_z(r)$ for the modes with angular momentum $L_z = 45$ and 47 , the current-carrying exciting states on the two sides of the domain wall formed around R_1 . Profile of the spatially-dependent Zeeman interaction used to form the domain wall is shown in red.

logical and trivial s-wave superconductors, as predicted in the Ref. [6].

In summary, we propose that domain walls formed during ferromagnetic spin transitions in the fractional quantum Hall effect regime can be used as building blocks to form topological superconductors that support parafermion excitations. Exact diagonalization study of spin transitions in a disk geometry confirm that domain walls, formed between spin-up and spin-down domains at $\nu = 2/3$, indeed possess electronic (two counter-propagating modes) and magnetic (opposite spin orientation for the two modes) structure needed to couple to an s-wave superconductor. We demonstrate that in triangular quantum wells spin transitions can be controlled locally by electrostatic gating and conducting helical domain walls can be formed in multi-gate devices. Such local control allows formation of reconfigurable networks of domain walls. In the presence of proximity-induced superconducting coupling the system becomes a reconfigurable network of one-dimensional topological superconductors with parafermion excitations.

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