Non-Abelian states of matter

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Quantum mechanics classifies all elementary particles as either fermions or bosons, and this classification is crucial to the understanding of a variety of physical systems, such as lasers, metals and superconductors. In certain two-dimensional systems, interactions between electrons or atoms lead to the formation of quasiparticles that break the fermion–boson dichotomy. A particularly interesting alternative is offered by 'non-Abelian' states of matter, in which the presence of quasiparticles makes the ground state degenerate, and interchanges of identical quasiparticles shift the system between different ground states. Present experimental studies attempt to identify non-Abelian states in systems that manifest the fractional quantum Hall effect. If such states can be identified, they may become useful for quantum computation.

Electrons are fermions; photons are bosons. Although seemingly a mundane statement about the symmetries of a quantum mechanical wavefunction when two identical particles are interchanged (for instance with respect to degrees of freedom such as position or momentum), this statement is in fact a pillar of the understanding of nature, and a basis of the understanding of the periodic table and the existence of metals, to list just two examples. Such quantum statistical considerations also affect the behaviour of composites of quantum particles: helium-4 atoms are bosons and form superfluids at low temperatures; and pairs of electrons are effectively bosons, which is how Cooper pairs of electrons make the phenomenon of superconductivity possible.

Non-Abelian systems[1,2] contain composite particles that are neither fermions nor bosons and have a quantum statistics that is far richer than that offered by the fermion–boson dichotomy. The presence of such quasiparticles manifests itself in two remarkable ways. First, it leads to a degeneracy of the ground state that is not based on simple symmetry considerations and is robust against perturbations and interactions with the environment. Second, an interchange of two quasiparticles does not merely multiply the wavefunction by a sign, as is the case for fermions and bosons. Rather, it takes the system from one ground state to another. If a series of interchanges is made, the final state of the system will depend on the order in which these interchanges are being carried out, in sharp contrast to what happens when similar operations are performed on identical fermions or bosons. It is this 'ordering' dependence that justifies the name 'non-Abelian' ('non-commutative' in mathematical terms). Just as the minus sign that accompanies the interchange of two fermions is independent of details such as their interaction or environment, the effect of the interchange of two non-Abelian quasiparticles is insensitive to noise from the environment around them.

Non-Abelian states have generated great interest recently[1–5], for three main reasons. The first is the theory behind them. Understanding of their origin and properties is in its infancy. The second is the challenge to observe them in an experiment. There are some systems in which strong theoretical arguments suggest the existence of non-Abelian quasiparticles, and that motivates a search for their experimental discovery. Third, if non-Abelian states were shown to exist in realizable systems, they would be ideal candidates for constructing topological quantum computers[6–8]. A quantum computer needs a set of quantum states that is well separated from the rest of the world. The degenerate ground states of a non-Abelian system, separated by an energy gap from the rest of the spectrum, deliver that. Furthermore, a quantum computer needs a minimum sensitivity to noise and decoherence, and this requirement is amply satisfied by the insensitivity of the effect of interchange of non-Abelian quasiparticles to noise and perturbations. The topological aspects of these interchanges motivate the name 'topological quantum computation'.

There are real-life settings in which existing theory predicts non-Abelian states of matter to exist, but they are not numerous[2]. Systems that manifest the fractional quantum Hall effect are believed to have a series of states that are non-Abelian[9–27]. Closely related states may be realized in cold atoms[28,29], superconductors of p-wave pairing symmetry[2] and hybrid systems of superconductors with so-called topological insulators[30–32] (see page 194) and/or semiconductors[33]. Non-Abelian lattice spin models have been proposed[19] but are far from experimental realization. Among all of these, the most prominently studied candidate for an experimentally accessible non-Abelian state is the $\nu = 5/2$ quantum Hall state[9–27].

In this Review, I discuss the properties of non-Abelian states, the systems in which they are expected to emerge, the possible ways of identifying them and the status of the experimental attempts to find them. I focus mainly on the $\nu = 5/2$ quantum Hall state but also touch on hybrid systems that combine the effects of spin–orbit interaction with superconductivity.

Non-Abelian quasiparticles

Non-Abelian quasiparticles appeared on the quantum mechanical stage after several decades of engagement with the quantum mechanics of identical particles. The originators of quantum mechanics distinguished fermions from bosons through the symmetry restrictions imposed on their many-body wavefunctions. A wavefunction, $\Psi(r_1, \ldots, r_N)$, of N identical spin-polarized particles whose coordinates are $r_1, \ldots, r_N$ must be odd under the interchange of the positions of two of the particles if they are fermions, and even if they are bosons.

In the past three decades, it has been realized that in two spatial dimensions the statistics of quasiparticles formed as composites of the elementary particles of a system is not limited to the fermion–boson dichotomy. As a first break from that dichotomy, the interchange of two quasiparticles may multiply the wavefunction by a phase. That phase may take any value and, as a consequence, the quasiparticles are known as 'anyons'.

The second break from the fermion–boson dichotomy, embodied by so-called non-Abelian quasiparticles, is much more surprising: an interchange of two quasiparticles does not merely multiply the ground-state wavefunction by a phase factor; rather, it shifts the system to a different ground state.

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Defining characteristics of non-Abelian states

To introduce the four defining characteristics of non-Abelian states of matter, it is useful to think of a two-dimensional (2D) fluid in which several vortices are localized at large distances from one another. Four conditions need to be satisfied for these vortices to become non-Abelian quasiparticles. First, there must be an energy gap separating the fluid's ground state from its excitations (Fig. 1a). Second, the ground state of the system must be degenerate, with the degeneracy being exponentially large in the number of vortices. Third, the degeneracy should be robust, and insensitive to weak noise and perturbations. Fourth, when vortices are made to 'braid', that is, to encircle one another or interchange their positions (Fig. 1b), the system should transform from one ground state to another, with the transformation being determined only by the topology of the quasiparticles' trajectory: two braiding trajectories that may be deformed into one another without the quasiparticles ever getting close should apply the same transformation to the system, up to a phase factor. It is the combination of an energy gap, ground-state degeneracy, robustness and topology — all of which are elaborated on below — that defines non-Abelian states of matter.

Although energy gaps are common in many-body systems, the combination of an energy gap with the three other characteristics is unique to non-Abelian states. To elaborate on these characteristics, it is necessary to be slightly more formal. The fluid in the picture above is made up of a large number of microscopically identical particles (usually electrons, but they could also be atoms, for instance) whose set of degrees of freedom is $\{r_i\}$. The vortices in turn are collective degrees of freedom, created by the collective behaviour of the microscopic particles. Their number is much smaller (Fig. 1b) than the total number of particles forming the background fluid. Assume that they are localized at the coordinates $\{R_j\}$. The wavefunctions of the set of degenerate ground states, $|\Psi_\alpha(R_j)\rangle$, enumerated by the index α, are thus functions of the particles' coordinates, $\{r_i\}$, and depend on the vortices' coordinates, $\{R_j\}$, as parameters.

A braiding — a quasiparticle interchange operation — is carried out when the vortices slowly move along a trajectory, $\{R_j(t)\}$, that starts and ends in the same configuration, $\{R_j\}$ (Fig. 1b). If there is just a single, non-degenerate, ground state, the slowness ('adiabaticity') of the motion and the existence of an energy gap guarantee that the final state of the system is identical to the initial state, up to a possible phase factor. A series of such braidings results in a product of phase factors. Such a product is commutative and, hence, the quasiparticles are Abelian anyons.

By contrast, if the ground state is degenerate, a braiding may transform one ground state, $|\Psi_\alpha(R_j)\rangle$, into a different one, $|\Psi_\beta(R_j)\rangle$. The transformation, $U_{\alpha\beta}$, which is a unitary matrix, depends only on the topology of the quasiparticles' trajectory, that is, on their windings around one another and their mutual interchanges of position. It does not depend on the detailed geometry of the trajectory. The transformation that corresponds to a set of consecutive braidings is a product of such unitary matrices. Matrix product is non-commutative, hence the term 'non-Abelian' and the naming of the quasiparticles as non-Abelian anyons. The degeneracy of the ground state and the non-Abelian statistics of the quasiparticles therefore go together.

Degeneracies in quantum spectra usually originate from a symmetry of the underlying Hamiltonian, and are removed when the symmetry is violated, for instance by the application of perturbations such as impurities or applied electric or magnetic fields. The degeneracy of the ground state in a non-Abelian state is different. It does not originate from a simple symmetry of the system, and as such it is robust. Small changes in the details of the system — varied interactions or varied disorder — do not lift the degeneracy. The degeneracy is only removed if a change to the system is large enough to close the energy gap between the ground state and the excitations (Fig. 1a), which would take the system to another state of matter, or if the quasiparticles are brought close to one another. In the second case, the degeneracy is lifted by terms that are exponentially small in the ratio of the spatial separation between the quasiparticles and a microscopic length, the coherence length of the underlying fluid.

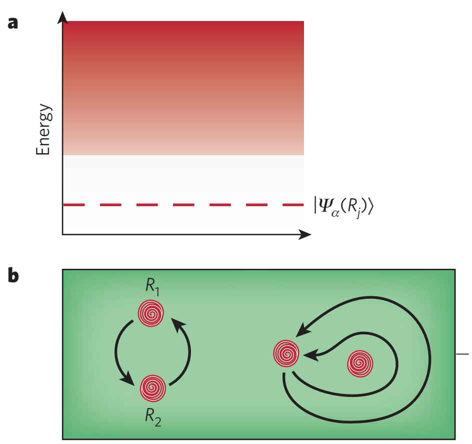

Figure 1 | Characteristics of non-Abelian systems. In the presence of vortices — non-Abelian quasiparticles — the spectrum includes a set of degenerate ground states, $|\Psi_\alpha(R_j)\rangle$, separated by an energy gap from a continuous spectrum of excitations. **a**, Spectrum. **b**, Vortices and possible braidings of their positions. The two winding trajectories on the right are topologically equivalent.

The inner makings of a non-Abelian state

The question of what it is in the microscopic interactions between the constituents of a system that gives rise to a non-Abelian state of matter is a question of great interest and scarce understanding. Consider, for example, the fractional quantum Hall state (Box 1), which so far is the main arena for the study of non-Abelian states. A partially filled Landau level is characterized by its 'filling fraction', ν, and by the type of interaction between its electrons. For a wide range of interaction parameters, the degeneracy of the ground state is insensitive to the details of the interaction but is exponentially sensitive to ν. For example, the ground-state degeneracy is exponential in (small) $|\varepsilon|$ for $\nu = 5/2 + \varepsilon$, thus making the $\nu = 5/2$ case non-Abelian (at least for a certain range of interactions), whereas no such degeneracy appears for $\nu = 7/3 + \varepsilon$.

A hint to a possible origin of non-Abelian systems may lie in the observation that most theoretical constructs of these systems are fluids in which microscopic particles of arbitrary quantum statistics group to form clusters whose statistics is effectively bosonic[1,18]. These clusters then form a Bose–Einstein condensate. Generally, breaking of a cluster in that condensate costs energy, at least as much as the energy gap. Crudely speaking, vortices formed in these Bose–Einstein condensates become non-Abelian quasiparticles when their presence allows clusters to be broken at no energy cost, leading to ground-state degeneracy.

In the simplest example, the cluster is a Cooper pair of fermions and the condensate is a Bardeen–Cooper–Schrieffer superconductor (see page 176 for a discussion on the connections between superfluidity, superconductivity and Bose–Einstein condensation in systems of quantum particles). Generally, the spectrum of a superconductor has excited states in which some Cooper pairs are broken, and these states are separated by an energy gap from the ground state. In the language of 'second quantization', these excitations are created and annihilated by a set of creation and annihilation operators. For some superconductors, in which the two fermions that constitute the Cooper pair have a relative angular momentum equal to an odd multiple of $\hbar$ (Planck's constant divided by 2π), the presence of vortices makes the energy cost for some of the excitations vanish, thus leading to a degeneracy of the ground state. The simplest of these superconductors, which has an angular momentum of $\hbar$ per pair, is known as a p-wave superconductor. The operators that create and annihilate the cost-free excitations in this type of superconductor are known as Majorana operators. They are Hermitian operators formed by equal-weight superposition of fermionic creation and annihilation operators, and as such are electrically neutral (see Box 2 and a recent review of Majorana fermions[34]).

Candidate systems

Given the well-developed understanding of Cooper pairs in superconductors, it is not surprising that the best-understood candidate systems

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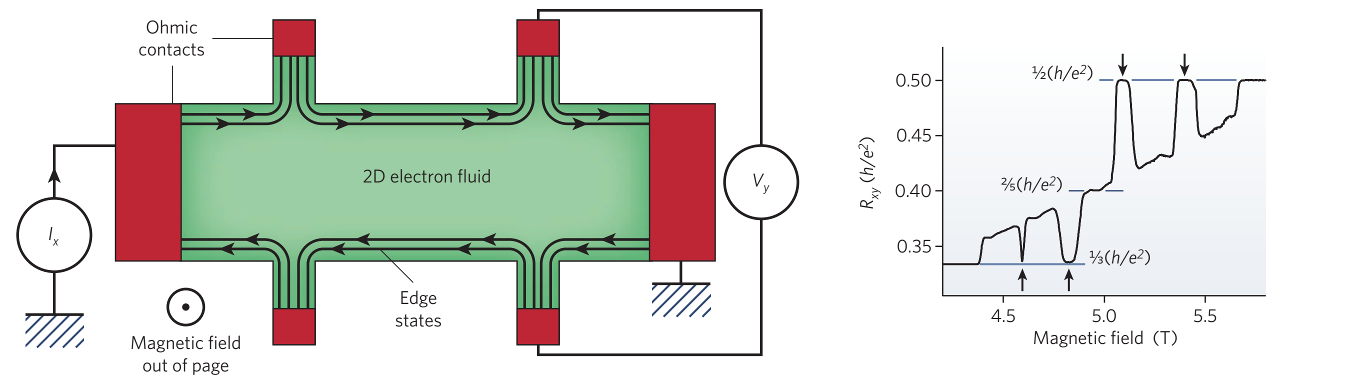
Box 1 | Integer and fractional quantum Hall systems



Two-dimensional electronic systems subject to a perpendicular magnetic field show the Hall effect, in which a current flow, I_x, is accompanied by a voltage, V_y, perpendicular both to the current and to the magnetic field (see figure, left, which shows a schematic of an experimental quantum Hall system). The ratio of this voltage to the current, the Hall resistance, R_{xy}, may be written as $h/e^2\nu$, where h is Planck's constant, e is the electron charge and ν is a dimensionless number. Classical considerations predict that $\nu = n\Phi_0/B$, where n is the electron density, $\Phi_0 = hc/e$ is the flux quantum, c is the speed of light and B is the magnetic field. At low enough temperature and for clean enough samples, quantum Hall states are formed. These states are characterized by quantized ν values, leading to plateaux in the Hall resistance as a function of magnetic field (see figure, right). Furthermore, these states are characterized by an energy gap in the bulk and a chiral flow of the current along the edges.

The integer quantum Hall states, for which ν is an integer, may be understood from a simple picture of non-interacting electrons under the effect of a magnetic field and a disordered potential. For clean systems, ν is roughly the number of filled Landau levels, that is, the number of highly degenerate energy states of non-interacting electrons in a magnetic field. The interaction between electrons is essential to the understanding of the fractional quantum Hall states, for which ν is a fraction (see figure, right). A useful tool for analysing how this interaction leads to the formation of fractional quantum Hall states is composite fermion theory, as discussed in the main text. (Right panel reproduced, with permission, from ref. 11.)

of non-Abelian states are based on the model of Majorana operators in a superconductor. Realizations of this model have been proposed in fractional quantum Hall systems[12,17], in p-wave superconductors and in hybrid systems of superconductors with materials in which spin–orbit coupling has a dominant role[30–33]. Non-Abelian states that are not described by this model are believed to exist in certain fractional quantum Hall states[18,28], where they are based on clusters larger than two fermions, and in certain spin models[19].

Fractional quantum Hall systems

The first system in which non-Abelian quasiparticles were predicted to exist[12], the quantum Hall system (Box 1), is still the richest arena for the search for non-Abelian states of matter. The fractional quantum Hall effect occurs in a 2D electronic system subject to a strong magnetic field, and is a consequence of the combination of the magnetic field and the interaction between the electrons. It is characterized by an energy gap in the bulk of the system, a gapless mode at its edge, a dissipationless flow of current along the edges and a quantization of the Hall resistivity.

There are good reasons to believe that the $\nu = 5/2$ fractional quantum Hall state is non-Abelian[9–27] and that the non-Abelian quasiparticles carry one-quarter of an electron charge. Originally, deep considerations of conformal field theories led Moore and Read[12] to propose a trial wavefunction (known as the 'Pfaffian' wavefunction) for the $\nu = 5/2$ state and to conclude that the state may be non-Abelian.

A more intuitive picture that leads to the same understanding is based on so-called composite fermion theory[17,35,36]. In this theoretical description, the problem of interacting electrons in a magnetic field B is mapped onto a problem of composite fermions in a magnetic field $B' = B - 2\Phi_0 n$, where $\Phi_0 = hc/e$ is the flux quantum and n is the electron density. A composite fermion is an electron to which two quanta of magnetic flux are attached. This mapping modifies the interaction between the particles: composite fermions interact both through their charges and through the magnetic flux they carry.

The $\nu = 5/2$ state is composed of two filled and inert Landau levels and a half-filled level. Composite fermion theory maps the half-filled Landau level ($\nu = 1/2$) of interacting electrons onto spin-polarized composite fermions at zero magnetic field ($B' = 0$). These composite fermions may then form a gapped state by pairing into Cooper pairs. For spin-polarized composite fermions, pairing is possible only if the relative angular momentum per pair is odd, with the simplest example being p-wave pairing. Vortices may be induced into the composite fermion superconductor by variation of the magnetic field B such that the filling fraction is shifted slightly away from $\nu = 5/2$. These vortices carry Majorana operators and are thus non-Abelian quasiparticles.

Numerical works[20–27] support these theories in several ways, of which I describe two. First, the ground state has been calculated numerically for a small number of particles, and the Pfaffian wavefunction has been found to approximate it remarkably well for a wide range of microscopic interactions. Second, the spectrum has been obtained for a series of Hamiltonians that slightly differ from one another in the microscopic interactions between the electrons. At one end of this series, the Hamiltonian was artificially constructed such that the interaction between its electrons makes the Pfaffian wavefunction its exact ground state. At the other end, the Hamiltonian had the realistic Coulomb interaction between the electrons built in. The intermediate Hamiltonians adiabatically connect between these two extremes. The energy gap was found not to vanish in all these cases, at least for the small systems that are computationally tractable. Because topological properties are robust as long as the energy gap does not close, this conclusion, if correct also for an infinite system, implies that the exact ground state has the same topological properties as the Pfaffian state.

If the $\nu = 5/2$ is indeed a non-Abelian state, the first topological qubit may be realized[8], by means of an electronic analogue to the Fabry–Pérot interferometer, as described below. It should be noted, however, that a Majorana-based qubit has a limited potential (it is 'non-universal'), as the unitary transformations that can be applied to this type of qubit through braiding of quasiparticles do not allow the system to reach to all possible ground states[7]. It may be possible to realize a universal topological qubit using other non-Abelian quantum Hall states, in which the clusters consist of more than two electrons.

***p*-wave superconductors**

If a p-wave superconductor of composite fermions such as the $\nu = 5/2$ state is a good candidate for a non-Abelian state of matter, a p-wave superconductor of less exotic particles, such as electrons or atoms, might also be expected to be one. Although relatively rare, superconductors of

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Box 2 | Majorana operators

Superconductivity results from the pairing of fermions into Cooper pairs. When described in the formalism of second quantization, a fermion at a point r in space is created by a creation operator $\hat{\psi}^+(r)$ and is annihilated by an annihilation operator $\hat{\psi}(r)$. The spectrum of a superconductor has excitations in which some Cooper pairs are broken. These excitations, which are separated by an energy gap from the ground state, are created by a set of creation operators of the form $\Gamma^+ = \int [g_1(r)\hat{\psi}(r) + g_2(r)\hat{\psi}^+(r)]\,dr$, where $g_1(r)$ and $g_2(r)$ are functions determined by the details of the system. The excitations are annihilated by a corresponding set of operators, Γ, that are the Hermitian conjugates of Γ^+. These excitations are unique to superconductors: to create an excitation one needs a superposition of operators creating a fermion and annihilating one.

For some superconductors, the presence of vortices allows Cooper pairs to be broken at no energy cost. When that happens, the operators that create and annihilate these zero-energy excitations have some unique properties. First, they are Majorana operators, meaning that $\Gamma^+ = \Gamma$ or, equivalently, $g_1(r) = g_2{}^*(r)$. Creating such an excitation is the same as annihilating it. Consequently, the zero-energy excitations that are described by these operators cannot be counted in the way particles are. Second, the functions $g_1(r)$ and $g_2(r)$ are localized within the cores of the vortices. Third, the phases of the functions $g_1(r)$ and $g_2(r)$ localized within the core of one vortex depend on the positions of all other distant vortices in a multiply valued way. As a consequence, when one vortex encircles another, the Majorana operators associated with both are modified. These zero-energy excitations are the reason for the degeneracy of the ground state. Their dependence on the position of the vortices is what makes them sensitive to braiding.

this symmetry are formed in helium-3 under certain conditions, and possibly also in electronic materials, such as $SrRuO_4$. They have also been conjectured to form from certain cold fermionic atoms[29]. Vortices in these superconductors may then be good candidates in which to observe non-Abelian statistics.

Unfortunately, none of these superconductors has so far been realized in two dimensions. The vortices that carry Majorana modes in these superconductors are generally not the lowest-energy vortices. Finally, the energy difference between the zero-energy Majorana states and other excitations within the cores of the vortices is likely to be very small, being of the order of Δ^2/E_F, where Δ is the superconductor's energy gap and E_F is its Fermi energy.

Hybrid systems

Another set of candidate systems for which Majorana modes are proposed as a means of observing non-Abelian statistics is based on a 2D conductor in which spin–orbit coupling — a term in the Hamiltonian that couples the orbital and spin degrees of freedom of electrons moving in the crystal field potential of a solid — has a crucial role[30–33]. This 2D conductor is to be positioned in proximity to a three-dimensional (3D) superconductor in such a way that the latter induces superconductivity in the former through the so-called proximity effect. The p-wave Cooper pairing originates in this case from the spin–orbit coupling in the 2D conductor. Conveniently, the 3D superconductor may be of the very common s-wave or d-wave pairing, rather than the rare p-wave type.

Perhaps the most intriguing example for this idea is one in which the normal conductor is the 2D metal formed on the surface of a 3D topological insulator (see page 194 for a discussion of these newly discovered materials). In this metal, spin–orbit coupling makes the electron spin lie in the plane of the metal and fixes its angle relative to the electron's linear momentum. Because Cooper pairs in a superconductor always comprise pairs of electrons with opposite linear momenta, a superconductor formed at the surface of a topological insulator would have Cooper pairs with electrons having a relative angular momentum of $\hbar$. The superconductor would therefore be of p-wave symmetry and vortices formed therein would carry Majorana operators, as discussed above. A similar situation should occur in semiconductors with strong enough spin–orbit coupling[27].

Detecting non-Abelian states

The difficulty of demonstrating that a many-body state is non-Abelian is almost inherent in its nature. In experiments, the system under study is usually perturbed, and then how it responds to perturbation is examined. However, the local perturbations used in experiments, such as electric fields, do not couple different ground states of a non-Abelian system, and therefore do not allow the multitude of ground states to be probed. Nevertheless, several experiments have been proposed as ways to probe non-Abelian states. Of these, I focus on those probing the $\nu = 5/2$ fractional quantum Hall state.

Predicted signatures of the $\nu = 5/2$ quantum Hall state

Most of the experimental effort directed at studying non-Abelian states has so far been focused on the $\nu = 5/2$ state. The motivation behind this effort is twofold. The first is the interest in the nature of the $\nu = 5/2$ state; the non-Abelian Moore–Read phase is but one of several candidate descriptions for this state, with Abelian and non-Abelian contenders[37]. The second is the desire to observe non-Abelian quasiparticles and see topological qubits realized.

The first of the four defining properties of a non-Abelian state, an energy gap between the ground state and the excitations, characterizes all quantum Hall states, including that with $\nu = 5/2$. The second characteristic to probe is the degeneracy of the ground state[38,39]. Being a property of the spectrum, it may in principle be observed in thermodynamic measurements, such as that of the heat capacity. In practice, the electronic contribution to the heat capacity is overwhelmed by non-electronic, low-energy degrees of freedom, such as phonons, nuclear spins and so on. The electronic entropy, which is related to the degeneracy of the ground state, would be better accessed through its effect on the temperature dependence of the electronic magnetization and chemical potential, as dictated by Maxwell relations. Measurements of these two thermodynamic quantities in 2D electronic systems have already been carried out[40,41], albeit not for the $\nu = 5/2$ state.

Braiding and interferometry

The most intriguing — and challenging — characteristic to probe is the unitary transformation applied by the braiding of quasiparticles. Quasiparticles winding around one another may be observed most directly through interferometry. The 'holy grail' of this line of study is the realization of a qubit[8], but an essential step along the way is a definitive experimental demonstration of the quasiparticles being non-Abelian. Generally, an interferometer interferes pairs of wave trajectories that enclose an interference loop. When the interfering particles are non-interacting electrons in a strong magnetic field, the relative phase between the paths is 2π times the number of flux quanta enclosed by the interference loop, as dictated by the Aharonov–Bohm effect.

In interferometers in the fractional quantum Hall regime (Fig. 2), the relative phase between the trajectories is affected also by the presence of localized quasiparticles trapped within the loop[42,43]. In particular, for the $\nu = 5/2$ Moore–Read state[44–47], no interference takes place when a non-Abelian quarter-charged quasiparticle interferes around an interference loop that encloses an odd number of similar quasiparticles. Interference does take place when that number is even, in which case one of two interference patterns will be seen, mutually shifted by a phase of π. The choice between these two patterns is determined by the particular ground state that the localized quasiparticles are in.

These general statements become concrete when two types of interferometer are considered. A Fabry–Pérot interferometer[42–47] is shown schematically in Fig. 2a. In the limit where the two constrictions introduce only a small amplitude for tunnelling between the edges, the probability of the incoming current being backscattered involves an interference of two trajectories only, one corresponding to each constriction. Ideally, the number of localized quasiparticles in the interference loop is controlled by the magnetic field, and the interference pattern is probed as a function of the loop's area, which is controlled by the application of voltage to a side gate. Therefore, if the $\nu = 5/2$ state is indeed the non-Abelian Moore–Read state, interference should be turned on and

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off periodically as the magnetic field is varied and the number of trapped quasiparticles alternates between even and odd. For the even case, the phase of the interference pattern may assume one of two possible values, depending on the ground state occupied by the trapped quasiparticles.

When the inter-edge coupling is made stronger, the interferometer becomes a quantum dot and the sinusoidal interference pattern becomes a series of so-called Coulomb blockade peaks. These are resonances in the transmission of the current through the dot that take place when the dot can accommodate another electron at no electrostatic energy cost. The signature of the Moore–Read state is then in two patterns of peaks: equally spaced peaks when an odd number of quasiparticles is trapped and peaks that are bunched into pairs when an even number of quasiparticles is trapped. Again, for the even case there are two possible patterns of peaks, depending on the ground state of the trapped quasiparticles[44,47].

A Fabry–Pérot interferometer enclosing two quasiparticles is the proposed $\nu = 5/2$ qubit[8] and a measurement of its interference pattern or the positions of its Coulomb blockade peaks as a function of its area serves as a read-out of its state. The strength of this qubit is in its insensitivity to noise, such as that from phonons or photons. As long as the noise is too weak to expel one of the localized quasiparticles from the interferometer, it will have no effect on the ground state occupied by these quasiparticles. To change this state, a winding is needed, this time a winding of an edge quasiparticle around an odd number of the localized ones.

A Mach–Zehnder interferometer[48,49] is shown schematically in Fig. 2b. In contrast to the Fabry–Pérot interferometer, its interference loop encloses one of the edges that separate the $\nu = 5/2$ state from the vacuum. The current enters the interferometer from the source located at the exterior edge, and ends up in one of the two drains. One drain is located at the interior edge and the other at the exterior edge. Whenever a quasiparticle tunnels from the exterior edge to the interior edge, it changes the parity of the number of quasiparticles within the interference loop, and affects the tunnelling probability for the quasiparticles that follow. The measured current is then a proper average over tunnelling rates that are history dependent. As a striking consequence, in the limit of weak tunnelling through the constrictions the current flows in batches of quasiparticles. The average charge in each batch oscillates with the magnetic flux through the interferometer, and varies between one-quarter and about three electron charges. This average, which may be observed in noise measurements, is limited to be less than or equal to one electron charge for single-edge quantum Hall states, such as the $\nu = 1$ and $\nu = 1/3$ states. Because the number of quasiparticles in the loop inherently varies in time, its thermal fluctuations do not affect the noise. Experiments carried out using a Mach–Zehnder interferometer in the regime of the integer quantum Hall effect conform closely to the ideal model, at least in the limit of small currents through the interferometer (the 'linear response limit')[50,51]. Technically, however, the Mach–Zehnder interferometer is complicated to realize, and has so far been used only for integer filling fractions, which are easier to study (see Fig. 3).

The non-Abelian nature of the $\nu = 5/2$ state may also be probed by a direct measurement of the edge, independent of the bulk and the localized quasiparticles that it contains. Possible probes include tunnelling of electrons into the edge from the outside, tunnelling between two edges and thermal transport[17,37,52–55]. The current–voltage characteristics of such transport, the associated current noise and the thermal Hall conductance all carry signatures of the nature of the $\nu = 5/2$ state.

Present experimental status of the $\nu = 5/2$ quantum Hall state

A realization of the various experimental tests described here is being vigorously attempted at present by many experimenters. Preliminary results support the identification of the $\nu = 5/2$ quasiparticles as carriers of one-quarter of an electron charge, a necessary condition for non-Abelian phenomena to be observed[56,57]. These results are, however, non-definitive, and are not fully understood.

A Fabry–Pérot interferometer has already been thoroughly studied for quantum Hall states with integer ν values, $\nu = 1/3$ and $\nu = 2/5$ (refs 58–61). The

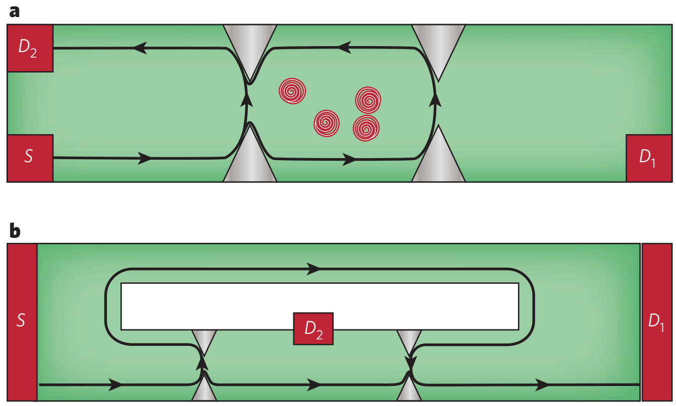

Figure 2 | Interferometric measurement setups in quantum Hall systems. **a**, In the context of the quantum Hall effect, the Fabry–Pérot interferometer is a Hall bar perturbed by two constrictions ('quantum point contacts', each represented by a pair of triangles). Current (black) flows chirally along the edges. The edge along which it moves to the right is put at a higher chemical potential than the edge along which it moves to the left. The point contacts introduce amplitudes t_1 and t_2 for inter-edge tunnelling. The presence of two point contacts makes the probability of backscattering the quantum Hall analogue of the probability of reaching the interference screen in a double-slit interference experiment. The backscattered current is, to lowest order, proportional to $|t_1 + t_2|^2$. The relative phase between the two amplitudes may be varied by varying the magnetic field and/or the area of the interference loop. The latter is implemented using a side gate that, to the crudest approximation, 'moves' the walls of the cell without introducing quasiparticles into the bulk. By contrast, the variation of the magnetic field leads to the introduction of localized quasiholes or quasiparticles. As explained in the text, if the $\nu = 5/2$ state is non-Abelian, the interference will be turned off when the number of quasiparticles localized in the bulk is odd, and turned on when it is even. S, source; D_1, D_2, drains. **b**, The Mach–Zehnder interferometer is another device that allows interference of trajectories of particles that are backscattered through two point contacts. In the Fabry–Pérot interferometer, the interference loop encloses only the cell between the two point contacts, whereas here the entire internal edge is part of the interference loop. The image shows the two trajectories leading from the source to one of the drains.

constraints on the sample quality and temperature needed to observe these states are less stringent than those needed for the $\nu = 5/2$ state, primarily as a result of their larger energy gaps. These studies showed that the magnetic field and the voltage on the side gate affect the interference in a way that is more complicated than that predicted by the idealized model described above (Fig. 3a). For most of the interferometers studied, the magnetic field and the gate voltage affect both the area of the interference loop and the number of localized quasiparticles[62]. Although these difficulties have to be understood in detail, they do not obscure the distinction, described above, between the types of interference corresponding to even and odd numbers of localized quasiparticles.

A Fabry–Pérot interferometer has also been realized for the $\nu = 5/2$ state. Recent studies yield encouraging, yet not definitive, results[63,64] (Fig. 3). The backscattering probability of the current, reflected in the interferometer's resistance, was observed to oscillate as a function of the voltage on a side gate, and the periodicity of the oscillations was observed to switch between two values. The oscillations were attributed to the effect of the side gate on the interferometer's area, and the switching between periodicities was attributed to its effect on the number of localized quasiparticles. In this interpretation, one periodicity corresponds to the interference of non-Abelian quarter-charged edge quasiparticles, and dominates when the number of localized bulk quasiparticles is even. The other periodicity corresponds to the interference of Abelian half-charged edge quasiparticles, and dominates when the number of localized bulk quasiparticles is odd and quarter-charged quasiparticles do not interfere[65].

Although the observed switching of periodicities is suggestive, it is not yet unambiguous. To make a conclusive identification, a two-pronged effort is likely to be required. On the experimental side, a mapping of

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the backscattered current in the two-parameter plane of gate voltage and magnetic field is probably the best way to establish the interpretation of the oscillations. On the theoretical side, a connection should be made between the ideal picture and the real world. In the ideal picture, quasiparticles are kept very far away from one another, their number is controlled and their positions may be braided at will. In the real world none of these fully holds. Moreover, energy splittings that are exponentially small cannot always be neglected, temperature may not be assumed to be zero and localized bulk quasiparticles may have tunnel couplings to the edge. Some of these issues have already been addressed in theoretical works[66–71], and others still need to be understood.

An example of the latter is the issue of spin polarization (refs 22, 72, 73 and T. D. Rhone and A. Pinczuk, personal communication). The original Moore–Read state is fully spin polarized, and numerical works support the assumption of full polarization of the ground state. Full polarization is, however, not a condition for non-Abelian quasiparticles to exist. Experiments indicate that in real samples spin polarization may not be complete, either as a property of the ground state or as a finite-temperature consequence of low-energy spin-reversed excitations. The effect of incomplete spin polarization on the attempts to study non-Abelian statistics in the $\nu = 5/2$ state and to use it for topological quantum computation is not fully understood yet.

Outlook

The experiments reviewed in the previous sections, those proposed and those attempted, are aimed at the observation of a non-Abelian state of matter. While this observation is awaited, researchers in the field actively study its theory.

In the context of known candidates for non-Abelian states of matter, much is still to be learned about probing states whose main defining property is their insensitivity to perturbations. The list of possible definitive tests for the identification of non-Abelian states is likely to be extended by future proposals, and the subtleties associated with interpreting experimental results will be better understood.

In the general context of non-Abelian states of matter, the theoretical challenge is wide open — it is the search for physical systems that may form non-Abelian states. Among the plethora of interacting systems that condensed-matter physics makes it possible to realize, it is desirable to identify those in which topology dominates the physics. It is to be hoped that, armed with such an understanding, the fine control that experimentalists have over the synthesis of new materials, the fabrication of electronic systems and the interaction between cold atoms in condensates can be used to design non-Abelian states of matter.

In the field of topological quantum computation, the potential of the special properties of non-Abelian states to help quantum computers over-

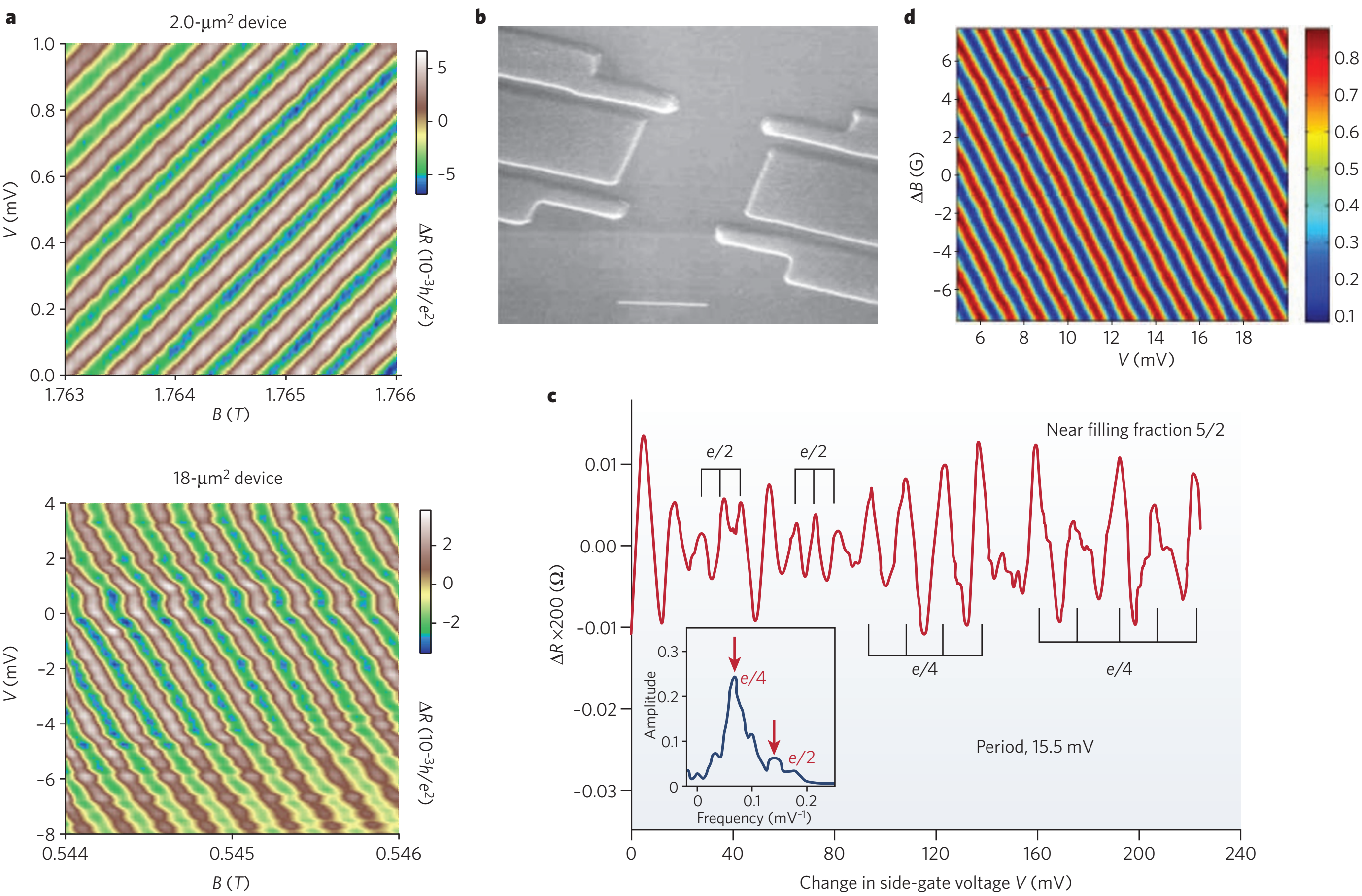

Figure 3 | Experimental results from interferometers. **a**, Fabry–Pérot interferometers were realized first in the integer[59,61] and Abelian fractional[61] quantum Hall states. The plots show the backscattered current (expressed in terms of the change in the sample's resistance, ΔR) as a function of magnetic field, B, and voltage on a side gate, V, for small and large areas of interference loops, for an integer quantum Hall state. The different directions of the constant phase lines are due to the variation of the interferometer area with magnetic field, which is crucial for small devices and negligible for large ones. (Image reproduced, with permission, from ref. 59.) **b**, Image of a $\nu = 5/2$ Fabry–Pérot interferometer. Scale, 1 µm. (Image reproduced from ref. 63.) **c**, Data from the $\nu = 5/2$ Fabry–Pérot interferometer. The change in the resistance is shown as a function of the change in side-gate voltage. The switching of periodicities may be an observation of effects associated with non-Abelian statistics. Inset, Fourier transform of the data in the main panel. (Panel reproduced from ref. 63.) **d**, Mach–Zehnder interferometers have already been realized, but only for states of the integer quantum Hall effect. The plot shows the probability of the current reaching from the source to the drain at the exterior as a function both of the variation of magnetic field, ΔB, around a value of 9 T, and of voltage applied to a side gate. (Data are unpublished data associated with ref. 50; panel courtesy of N. Ofek and M. Heiblum, Weizmann Institute of Science, Rehovot, Israel.)

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come decoherence is all but exhausted, even theoretically.

In conclusion, the past few decades have highlighted the surprisingly constructive interference of the subtlety of topology, the richness of quantum mechanics and the sophistication of materials science. In the next decade, it is to be hoped that this combination will express itself in making non-Abelian states a reality. ■

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