LETTER

Point-like topological defects in bilayer quantum Hall systems

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Abstract. Following a suggestion given in Cristofano \textit{et al} (2003 \textit{Phys. Lett.} B \textbf{571} 250; 2004 \textit{Nucl. Phys. B} \textbf{679} 621), we show how a bilayer quantum Hall system at fillings $\nu = m/(pm + 2)$ can exhibit a point-like topological defect in its edge state structure. Indeed our CFT theory for such a system, the Twisted Model (TM), gives rise in a natural way to such a feature in the twisted sector. Our results are in agreement with recent experimental findings of Deviatov \textit{et al} (2005 \textit{Phys. Rev.} B \textbf{72} 041305) which evidence the presence of a topological defect in the bilayer system.

Keywords: conformal field theory, conformal field theory (theory), fractional QHE (theory), fractional QHE (experiment)
The quantum Hall effect (QHE) is one of the most remarkable many-body phenomena that has been discovered in the last 25 years [3]–[5]. It takes place in a two-dimensional electron gas formed in a quantum well in a semiconductor host material and in the presence of a very high magnetic field [6,7], as a result of the commensuration between the number of electrons \( N \) and the number of flux quanta \( N_\Phi \). The electrons condense into distinct and highly non-trivial ground states (‘vacua’) formed at each integer (IQHE) [8] or rational fractional value (FQHE) [9] of the filling factor \( \nu = N/N_\Phi \). In particular at fractional fillings quasiparticles with fractional charge and statistics emerge, and new kinds of order parameters are considered [10]. The essential feature of such peculiar states is the existence of an excitation gap, so that the electron fluid is incompressible and flows rigidly past impurities in the sample without dissipation. As a result the conductivity tensor takes the universal form \( \sigma_{xx} = \sigma_{yy} = 0, \sigma_{xy} = -\sigma_{yx} = \nu (e^2)/h \). The presence of disorder in the samples is crucial for the observed phenomenology in order to localize topological defects and prevent dissipation.

Since the first observations of the FQHE [7] considerable experimental progress has been made in performing measurements with samples of higher mobility under stronger magnetic fields and at lower temperatures.

The experimental results relative to the sequence of filling factors \( \nu = p/(2p \pm 1) \) and \( \nu = p/(4p \pm 1) \) have given strong support to the idea first suggested by Jain [11] of looking at the FQHE for electrons as a manifestation of the integer effect (IQHE) for composite fermions, obtained by attaching to each electron an even number of flux units opposite to the external magnetic field. In fact the most prominent Hall plateaus have been observed at the fillings of the principal sequence \( p/(2p \pm 1) \) and the energy gaps measured for this sequence have been found to correspond to the cyclotron energies relative to the reduced magnetic field \( B - B_{1/2} \) [12]. Furthermore, Halperin et al [13], following a point of view closely related to Jain’s approach, stressed the role of the state at \( \nu = \frac{1}{2} \), computing an anomaly in surface acoustic wave propagation in agreement with experimental results [14].

The experimental evidence of a Hall plateau at filling \( \nu = \frac{5}{2} \) focused the attention of physicists on plateaus which do not fall into the hierarchical scheme [11]. To such an extent a pairing picture, in which pairs of spinless or spin-polarized fermions condense, has been proposed [15] for the non-standard fillings \( \nu = 1/q \), \( q > 0 \) and even. As a result the ground state has been described in terms of the Pfaffian (the so-called Pfaffian state) and the non-Abelian statistics of the fractional charged excitations evidenced [15]–[18].

Recent technological progress in molecular beam epitaxy techniques has led to the ability to produce pairs of closely spaced two-dimensional electron gases. Since then such bilayer quantum Hall systems have been widely investigated theoretically as well as experimentally [19,20]. Strong correlations between the electrons in different layers lead to new physical phenomena involving spontaneous interlayer phase coherence. In particular a spontaneously broken \( U(1) \) symmetry [21] has been discovered and identified and many interesting properties of such systems have been studied: the Kosterlitz–Thouless transition, the zero resistivity in the counter-current flow, a DC/AC Josephson-like effect in interlayer tunnelling as well as the presence of a gapless superfluid mode [22, 23]. Indeed, when tunnelling between the layers is weak, the quantum Hall bilayer state can be viewed as arising from the condensation of an excitonic superfluid in which an electron in one layer is paired with a hole in the other layer. The uncertainty principle makes it impossible to tell which layer either component of this composite boson is in. Equivalently the system
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may be regarded as a ferromagnet in which each electron exists in a coherent superposition of the ‘pseudospin’ eigenstates, which encode the layer degrees of freedom [24, 23]. The phase variable of such a superposition fixes the orientation of the pseudospin magnetic moment and its spatial variations govern the low energy excitations in the system.

Since Halperin’s work [25], the concept of edge states was introduced in order to describe transport phenomena in two-dimensional electron systems. They arise in a quantized magnetic field at the intersections of the Fermi level with different Landau levels, which are bent up by the edge potential. In particular the formation of a topological defect has been predicted to occur when two edge states with different spins locally switch their positions and thus cross each other at two or more points [26]. More interesting features take place in the transport properties of bilayer systems when pseudospin (related to the layer index) is also involved [23, 27]. Recently the presence of edge state crossings and thus of topological defects has been experimentally evidenced in such systems in a quasi-Corbino geometry [28] at filling $\nu = 3$ [2] by means of a selective population technique. In particular the application of a suitable gate voltage $V_g$ and of a magnetic field drives the bilayer in different pseudospin states in the gated and ungated regions, so producing a crossing of the edge states which has been detected in the transport characteristics. More precisely the gated region has filling $g$ while the ungated region is at filling $\nu - g$.

The net result is a linear $I-V$ characteristic for the electric transport between two different edges. Because the gate-gap width is smaller than the characteristic equilibration lengths in such a transport between the edge states, it has been argued that a defect must be present, which couples different edge states but only with the same spin in the gate-gap. Such a picture can be destroyed by an in-plane magnetic field component which washes out the above crossing; the $I-V$ curves become then strongly non-linear as a signal of the merging of a tunnelling process. All the above features in the $I-V$ characteristics appear to be the fingerprints of the presence of a topological defect induced by the different pseudospin configurations in bilayer quantum Hall systems [2].

In this letter we address theoretically the issue of the presence of topological defects in the conformal field theory (CFT) description of the edge states of bilayer quantum Hall systems in a wide class of filling factors, and in particular the paired states ones, in the framework of our TM approach [1]. In particular we show how such a feature arises in a very natural way in the twisted sector of our theory, as a result of the $m$-reduction technique [29, 30]. The transport properties of bilayer systems will be investigated by studying the properties under magnetic translations of the characters of the different sectors, which correspond to the different non-perturbative ground states of the TM. We point out that the results of this letter are very general and are relevant for different areas of condensed matter systems at low dimensions. In particular it has been shown that there is a close relation between the existence of topological defects and flux fractionalization in fully frustrated Josephson junction ladders [31]. Furthermore, topological defects have also been introduced in the description of dissipation in systems with magnetic impurities [1].

The $m$-reduction technique is based on the simple observation that for any CFT (mother) there exists a class of sub-theories parameterized by an integer $m$ with the same symmetry but different representations. The resulting theory (daughter) has the same algebraic structure but a different central charge $c_m = mc$. To obtain the generators of the algebra in the new theory we need to extract the modes which are multiples of the integer $m$. These can be used to reconstruct the primary fields of the daughter CFT. This
technique can be generalized and applied to any extended chiral algebra which includes the Virasoro one. Indeed the \( m \)-reduction preserves the commutation relations between the algebra generators but modifies the central extension (i.e. the level for the WZW models). In particular this implies that the number of primary fields gets modified. Its application to the QHE arises by the incompressibility of the Hall fluid droplet at the plateau, which implies its invariance under the \( W_{1+\infty} \) algebra at the different fillings, and by the property of the \( m \)-reduction procedure to obtain a daughter CFT with the same \( W_{1+\infty} \) invariance property of the mother theory. Thus the \( m \)-reduction automatically furnishes a mapping between different incompressible plateaus of the quantum Hall fluid (QHF).

The general characteristics of the daughter theory is the presence of twisted boundary conditions (TBCs) which are induced on the component fields. It is illuminating to give a geometric interpretation of that in terms of the covering on a \( m \)-sheeted surface or complex curve with branch-cuts; see figure 1. Indeed the fields which are defined on the left boundary have TBCs while the fields defined on the right one have periodic boundary conditions (PBCs). We point out that fields with TBCs elegantly describe the crossing between the layers as a consequence of the presence of a branch-cut. We find different sectors on the torus corresponding to different boundary conditions on the cylinder. Finally we recognize the daughter theory as an orbifold of the usual CFT describing the QHF at a given plateau. The two sheets simulate the two-layer system and the branch cut represents TBCs which emerge from the interaction with a localized defect on the edge. This is a key feature of our construction, as we will point out in the following.

In order to see how the \( m \)-reduction procedure works on the plane \cite{29} and on the torus \cite{30} and how it gives rise to the edge state coupling via a topological defect, let us focus on the paired states fillings in the special \( m = 2 \) case since we are interested in a system consisting of two parallel layers of a 2D electron gas in a strong perpendicular magnetic field. The filling factor \( \nu^{(a)} = 1/(2p + 2) \) is the same for the two \( a = 1, 2 \) layers, while the total filling is \( \nu = \nu^{(1)} + \nu^{(2)} = 1/(p + 1) \). We point out that our results can be generalized to any bilayer system. The simplest abelian quantum Hall state in the disc topology is written as a generalization of the analytic part of the Laughlin wave

\[ \text{Figure 1. The boundaries of the 2-covered cylinder can be viewed as different configurations of the QHF edges described by the 2-reduced CFT.} \]
function [25]:

\[ f(z_i^{(a)}) = \prod_{a=1,2} \prod_{i<j} (z_i^{(a)} - z_j^{(a)})^{2+2p} \prod_{i,j} (z_i^{(1)} - z_j^{(2)})^{p}; \]  

in particular, for \( p = 0 \) it describes the bosonic 220 state and, for \( p = 1 \), the fermionic 331 one. The CFT description for such a system can be given in terms of two compactified chiral bosons \( Q^{(a)} \) with central charge \( c = 2 \). A similar result can be obtained for filling \( \nu^{(a)} = 1/(2p + 1) \).

In order to construct the fields \( Q^{(a)} \) for the TM, let us start from the bosonic filling \( \nu = 1/2(p + 1) \), described by a CFT with \( c = 1 \) in terms of a scalar chiral field \( Q \) compactified on a circle with radius \( R^2 = 1/\nu = 2(p + 1) \) (or its dual \( R^2 = 2/(p + 1) \)). It is explicitly given by

\[ Q(z) = q - ip \ln z + i \sum_{n \neq 0} \frac{a_n}{n} z^{-n} \]  

with \( a_n, q \) and \( p \) satisfying the commutation relations \([a_n, a_{n'}] = n\delta_{n,n'}\) and \([q, p] = i\). From such a CFT (mother theory), using the \( m \)-reduction procedure, which consists in considering the subalgebra generated only by the modes in equation (2) which are a multiple of the integer \( m \), we get a \( c = 2 \) orbifold CFT (daughter theory, i.e. the TM) which describes the LLL dynamics. Then the fields in the mother CFT can be organized into components which have well defined transformation properties under the discrete \( Z_2 \) (twist) group, which is a symmetry of the TM. Its primary fields content can be expressed in terms of a \( Z_2 \)-invariant scalar field \( X(z) \), given by

\[ X(z) = \frac{1}{2}(Q^{(1)}(z) + Q^{(2)}(-z)), \]  

describing the electrically charged sector of the new filling, and a twisted field

\[ \phi(z) = \frac{1}{2}(Q^{(1)}(z) - Q^{(2)}(-z)), \]  

which satisfies the twisted boundary conditions \( \phi(e^{i\pi}z) = -\phi(z) \) and describes the neutral sector [29]. Such TBCs signal the presence of a topological defect which couples, in general, the \( m \) edges in an \( m \)-layer system. In the bilayer system \((m = 2)\) we get a crossing between the two edges as sketched in figure 2.

The chiral fields \( Q^{(a)} \), defined on a single layer \( a = 1, 2 \), due to the boundary conditions imposed upon them by the orbifold construction, can be thought of as components of a unique ‘boson’ defined on a double covering of the disc (layer) \((z_i^{(1)} = -z_i^{(2)} = z_i)\). As a
consequence of such a construction the two-layer system becomes equivalent to a one-layer QHF and the $X$ and $\phi$ fields defined in equations (3) and (4) diagonalize the interlayer interaction. In particular the $X$ field carries the total charge with velocity $v_X$, while $\phi$ carries the charge difference of the two edges with velocity $v_\phi$ i.e. no charge, the number of electrons being the same for each layer (balanced system).

The TM primary fields are composite operators and, on the torus, they are described in terms of the conformal blocks (or characters).

The defect is a topological one and in our formalism is induced by the different isospin configurations on the two layers, which naturally result from our $m$-reduction procedure. The effect of a topological defect in a QHF has been recently evidenced in experimental findings [2], as we will show in the following. In the presence of a localized defect two phenomena can take place. A tunnelling of edge quasi-particles at point $x_0$ can be described by a boundary term Hamiltonian such as

$$H_P = -t_P \cos(Q^{(1)} - Q^{(2)})\delta(x_0).$$

A second mechanism producing a current flow between the two edges can be addressed to a localized crossing of the edges, which can be represented by a boundary term:

$$H_\beta = \beta(Q^{(1)}\partial_t Q^{(2)} - Q^{(2)}\partial_t Q^{(1)})\delta(x_0),$$

where $\beta = 0(1/2)$ for PBCs (TBCs) respectively (see figure 2). The full Hamiltonian can be written as

$$H = \frac{1}{2} \sum_{a=1,2} \left[ (\Pi^{(a)})^2 + (\partial_x Q^{(a)})^2 \right] + H_P + H_\beta + eV\partial_t(Q^{(1)} - Q^{(2)}),$$

where $\Pi^{(a)}$ is the momentum conjugate to $Q^{(a)}$. We recognize a kinetic term for the two bosonic fields $Q^{(a)}$, $a = 1, 2$, a boundary tunnelling term which implements the locally applied gate voltage $V_g = t_P\delta(x_0)$, a boundary magnetic term [32] which couples the two fields introducing a topological defect (see [1] for details) and a voltage switching term between the two layers. The last term contains an irrelevant operator, so it does not change the central charge: it behaves as a boundary condition changing operator allowing for the flow from a boundary state to another one. Introducing the charged and neutral fields $X$ and $\phi$ defined in equations (3) and (4) we clearly see that the last term in the Hamiltonian is proportional to the neutral current, so it contributes to unbalance the system. Therefore edge-crossing can be described by a TBC on the $\phi$ field induced by the boundary magnetic term of equation (6).

The transport properties of such a system can be investigated by the application of different chemical potentials between the terminals of figure 2, that we represent by the matrix $V = \begin{pmatrix} V_{AC} & V_{AD} \\ V_{BC} & V_{BD} \end{pmatrix}$ with entries $V_{IJ}$, the potentials between the $I$ and $J$ terminals. Let us consider the following two cases: the one in which the transport of electrons is on the two independent edges through the points $A - C - A$, $B - D - B$ in the non-crossed case (PBCs; see figure 2(a)) and the one in which the transport is through the points $A - D - B - C - A$ in the crossed edge case (TBCs; see figure 2(b)). In both cases there is no tunnelling ($t_P = 0$) and they correspond respectively to the diagonal (i.e. $V_{AD} = V_{BC} = 0$) and to the anti-diagonal (i.e. $V_{AC} = V_{BD} = 0$) configurations. In a closed geometry, such as that of a torus, they can be induced by adiabatic magnetic flux insertion through a cycle of the torus (i.e. $A$ or $B$ cycle).
a flux quantum $hc/2e$ through the cycle $A$, an electromotive force is induced along it with a consequent transport of an electron along the $B$ cycle. In the torus topology the transport properties can be precisely described in terms of the action of magnetic translations on the conformal blocks of the untwisted and twisted sector respectively. Their explicit description can be realized by standard calculations on the characters of the TM given in [30]. In this letter we just recall that the characters are given in terms of the layer variables $w^{(1)}$, $w^{(2)}$ as $w_{c} = (w^{(1)} + w^{(2)})/2$ and $w_{n} = (w^{(1)} - w^{(2)})/2$ respectively.

So the two configurations, given above, without tunnelling are described on the torus by the following translations on the charged and neutral $w$ coordinate. In the non-crossed case (figure 2(a)) the potential $V_{AC}$ ($V_{BD}$) generates a translation along the first (second) layer, on the variable $w^{(1)}(w^{(2)}), and it results in $\Delta w_{c} \propto V_{AC} + V_{BD}$ and $\Delta w_{n} \propto V_{AC} - V_{BD}$, while in the crossed case (figure 2(b)) $\Delta w_{c} \propto V_{AD} + V_{BC}$ and $\Delta w_{n} \propto V_{AD} - V_{BC}$. Let us point out that a purely neutral translation $w_{p}$ with $w^{(1)} = -w^{(2)}$ creates the topological defect (and relates the edge switching to the large unbalance phenomenon predicted in [26]). Finally, in the presence of localized tunnelling ($t_{p} \neq 0$) between the layers hybridization takes place. In fact that experimentally corresponds to an equilibration process between the two edge states and results in a breaking of the symmetry of the balanced system described by the TM, due to the breaking of pseudospin symmetry. To take that into account the boundary CFT technology was used in [1], obtaining the characters of the system in the presence of both tunnelling and topological defects.

Let us now discuss the transport properties in these unbalanced cases, by describing the tunnelling as a small perturbation to the TM, and focus our attention on the terminal $AD$ in the crossed case. The working points are different for the untwisted and twisted configurations. In the first case the term in equation (5) for $t_{p} \ll 1$ is a weak perturbation of the background characterized by $V_{AD} = V_{BC} = 0$, while in the second one it has $V_{AC} = V_{BD} = 0$. The $I$–$V$ characteristics depend strongly on that. We obtain a different conductance for the two cases. In particular for TBCs in the absence of an in-plane magnetic field the driving voltage $V_{AD}$ puts the bilayer edges at different chemical potentials and then the ratio of the $AD$ terminal current to $V_{AD}$ is equal to the Hall conductance $\sigma_{H} = e^{2}/2h$ of the single layer. For general filling $\nu = 1/(p + 1)$, the Hall conductance for a single layer is expected to behave as $\sigma_{H} = e^{2}/2(p + 1)h$. Notice that the values of the slope just obtained refer to the layers population condition $g = \nu - g = 1/2(p + 1)$ (balanced case).

Conversely, when the two layers are coupled via the in-plane magnetic field, the tunnelling of the charge carriers results in a loss in the $AD$ terminal current. The net result is a negative contribution to the current which adds to the previous term, producing a total $AD$ terminal current, which for $p = 0$, can be exactly evaluated in a similar way.
as in [33], obtaining

$$I_{AD}(V_{AD}) = \frac{e^2V_{AD}}{2h} - \frac{e T_B}{h} \arctan \frac{e V_{AD}}{2 T_B},$$

where $T_B = C_1 t_P^{1/(1-\nu)}$ is the analogue of the Kondo temperature, depending on the external parallel magnetic field, $C_1$ is a non-universal constant and $\nu$ is the filling (see figure 3). In this case $\nu = \frac{1}{2}$ for the single layer, but the argument can be generalized to a wide class of fillings.

The non-linear behaviour of the tunnelling characteristics follows by standard analysis [33]. Indeed for $T_B = 0$ the characteristics have a linear behaviour, as for the transport in a single layer (see figure 3). Moreover, an in-plane magnetic field removes the twist (topological defect) and re-establishes the non-linear structure characterizing the tunnelling phenomenon. Let us notice also that our system is spinless (or fully polarized) while the experimental results in [2] are obtained for spin resolved systems. Therefore we reproduce only the negative branch of the curves given in [2]. No gap is obtained for positive $V_{AD}$.

In conclusion, the presence of topological defects in a double layer induces flux fractionalization described by the special $w_p$ translation and is responsible for linear conduction between different edges with a quantized value of the slope. We point out that the evidence of topological defects, resulting from TBCs, is theoretically indispensable for the consistency of our CFT approach to the QHE. It is implied by the $m$-reduction technique.

At the moment an application of the above ideas to the spin-1/2 linear chains with Mobius topology is under study.

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