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Published in: Physical Review Letters

DOI: 10.1103/PhysRevLett.81.1929

Exclusion Statistics for Non-Abelian Quantum Hall States

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(Received 13 March 1998)

We determine the exclusion statistics properties of the fundamental edge quasiparticles over a specific $\nu = \frac{1}{m}$ non-Abelian quantum Hall state known as the $g = 2$ Pfaffian state. The fundamental excitations are the edge electrons of charge $-e$ and the edge quasiholes of charge $+e/4$. We explicitly determine thermodynamic distribution functions and establish a duality which generalizes the duality for fractional exclusion statistics as described by F. D. M. Haldane.

PACS numbers: 73.40.Hm, 05.30.−d

Soon after the discovery of the fractional quantum Hall effect, Laughlin proposed the many body wave functions that have ever since served as the theoretical basis for the understanding of the phenomenon. It was quickly established that the fundamental quasiparticles over the Laughlin states are unusual in a number of ways: in particular, they have fractional charge and fractional braiding statistics.

The prediction of fractionally charged excitations has recently been confirmed in a number of independent experiments based on shot noise [1] and on the physics of the Coulomb blockade [2]. The fractional braiding statistics of Laughlin quasiparticles are harder to detect in a direct way. Braiding particles in a two-dimensional system is a theoretical notion that does not have a direct experimental counterpart.

To explore experimental consequences of fractional braiding statistics, one may as a first step try to translate this notion into a related notion of fractional exclusion statistics, i.e., into some generalization of the Pauli exclusion principle [3,4]. The exclusion statistics lead to a generalization of the Fermi-Dirac distribution, and from this one derives predictions for observable quantities.

In recent work [5,6], we have carried out part of the above program for the quasiparticles over the $\nu = \frac{1}{m}$ Laughlin state. In particular, we have linked the braiding statistics of these excitations to the exclusion statistics of the edge quasiparticles in the same system. The connection is established with the help of a conformal field theory (CFT) whose conformal blocks reproduce the wave functions for the quasiparticle excitations and whose finite size spectrum coincides with the spectrum of edge excitations. The braiding statistics of excitations over the Laughlin state are Abelian with statistics angle $\theta = \frac{2\pi}{m}$ for the charge $\pm \frac{e}{m}$ excitations and $\theta = m\pi$ for the excitations of charge $\pm e$ [7]. In [5,6] we established that the exclusion statistics of edge electrons (of charge $-e$) and edge quasiholes (of charge $+\frac{e}{4}$) are given by fractional exclusion statistics in the sense of Haldane [3], with statistics parameter $g = m$ and $g = \frac{1}{m}$, respectively, and no mutual statistics between the two. This result was established by a method based on recursion relations for truncated conformal spectra [5].

For a quantum Hall state with fundamental charged edge excitations of charge $q$ (measured in units of $e$) and distribution function $n(e)$ (generalizing the Fermi-Dirac distribution), the zero temperature Hall conductance is quickly shown to be

$$\sigma_H = q^2 n_{\text{max}}^2 \frac{e^2}{h},$$

with $n_{\text{max}}$ the maximum (reached for $e \rightarrow -\infty$) of $n(e)$. For Haldane $g$-ons one has $n_{\text{max}} = \frac{1}{g}$ and this gives the familiar result $\sigma_H = \frac{1}{m} \frac{e^2}{h}$, both for the edge electrons and the edge quasiholes over the $\nu = \frac{1}{m}$ Laughlin state. In this quasiparticle formalism, the fact that the Hall conductance does not depend on temperature comes about as a consequence of the duality between the statistics $g$ and $\frac{1}{g}$ distribution functions [8].

In the present Letter, we extend the above reasoning to the case of a quantum Hall state (the so-called $g = 2$ Pfaffian state) with excitations that obey non-Abelian braiding statistics. In this context, “non-Abelian” means that the wave function for a set of quasiparticle excitations at given positions has more than one component, and that the action of braiding (exchanging) two of those excitations is represented by a nondiagonal matrix acting on the multi-component wave function.

The issue addressed in this Letter is a fundamental one: we are exploring the consequences for thermodynamics and transport of the non-Abelian braiding statistics of a set of fundamental excitations in a condensed matter system. To our knowledge, a similar problem has not been addressed until now [9]. As a characteristic feature of “non-Abelian exclusion statistics,” we shall identify a nontrivial prefactor in the high-energy Boltzmann tail of a generalized distribution function.

After the experimental observation [10] of a quantum Hall effect at the even denominator filling fraction $\nu = \frac{5}{2}$, a number of candidate ground states with filling fraction $\nu = 1$ have been proposed. One of these is the so-called
lead to Abelian braiding statistics, with angles \((\text{OPE})\) of the electron and quasihole fields. The \text{OPE}'s ties of two-particle states. As such, they can be studied by linear states are Abelian and can be inferred from the proper structure of the braiding statistics of the quasihole excitations. As such, they can be studied by linear states are Abelian and can be inferred from the proper structure of the braiding statistics of the quasihole excitations. To derive quantitative results for the exclusion statistics of the edge excitations over the Pfaffian state, we employ the method of truncated conformal spectra [5]. The idea of this method is to establish an explicit quasiparticle basis of the CFT chiral finite size spectrum, and from there derive the statistics. In [6], this procedure was carried out in great detail for the Laughlin states and for the charged sector for more general hierarchical quantum Hall states (Jain series).

The complication that is new for the case of non-Abelian quantum Hall states is the occurrence of so-called fusion channels in the specification of a multi-\(\phi\) state. These have their origin in the following fusion rule for the spin field of the Ising CFT:

\[
[\sigma] \cdot [\sigma] = [1] + [\psi].
\]

Each time we apply a \(\phi\) mode to a state containing an odd number of \(\phi\) quanta, we have to specify a choice for either the first or the second term on the right-hand side of (4). For a state containing \(N\) quasiholes, the total fusion path is encoded in a Bratteli diagram, which is an arrowpath on the following grid:

\[
\begin{array}{cccccc}
\cdots & \cdots & \cdots & \cdots \\
N & \ldots & 4 & 3 & 2 & 1 \\
\end{array}
\]

with the vertical direction indicating the Ising sectors \(1, \sigma, \) and \(\psi\) and the horizontal index \(i = 1, \ldots, N\) labeling the \(\phi\) modes. The starting point of an arrow path is the CFT vacuum \(|0\rangle\). The multi-\(\phi\) states for a given fusion path are \([\phi(z)] = \sum_i \phi_{-\Delta_i \cdot \Delta_i - n_i}|l\rangle\), with integers \(n_1 \geq \ldots \geq n_2 \geq n_1 \geq 0\) and with increments \(\Delta_i\) determined by the Bratteli diagram according to

\[
\Delta_{i+1} = \Delta_i + \frac{1}{2} \quad \text{for} \quad i + 1 \quad \text{and} \quad i + 1
\]

with \(\Delta_1 = 0\). For example, the lowest energy fourquasihole states for the two possible fusion paths are

\[
\begin{align*}
\phi_{-3/8} \phi_{-3/8} \phi_{-1/8} \phi_{-1/8}|l\rangle, & \quad E = 1, \\
\phi_{-11/8} \phi_{-7/8} \phi_{-5/8} \phi_{-1/8}|l\rangle, & \quad E = 3.
\end{align*}
\]
In the construction of multielectron states the issue of fusion rules does not explicitly arise, but the details of the rules are different from what we had for the Laughlin states [6]. On the vacuum [0], we allow the following multielectron states [with \( G(z) = \sum \) ] of the chiral Hilbert space of the CFT, and thereby (up to certain projections, see [6]) of physical edge theories. The central claim of this Letter is that the union of all the
to the exclusion rules specified in the text. The symbols and are nonnegative integers.

We stress that the prefactor is a nonnegative integer. The rules specified above lead to the recursion relations

\[
X_l = X_{l-1} + qx^l (Y_l + Y_{l-1/2}),
\]

\[
Y_l = Y_{l-1} + qx^l X_{l-1/4}.\]

The initial conditions, which are sector dependent, follow from the information in Table I. The solution of (12) can be approximated as \( X_l \sim \prod_{l=1}^{\infty} \lambda (q' x)^l \), with \( \lambda (z_{qh}) \) the largest real solution of the equation

\[
(\lambda - 1) (\lambda^{1/2} - 1) = z_{qh}^2 \lambda^{3/4}.\]

This leads to a distribution function

\[
n_{qh}(\epsilon) = \left[ z_{qh} \partial_{\epsilon} \log (\lambda(\epsilon)) \right] (z_{qh} = e^{\beta (\mu - \epsilon)}) \]

for the qhino excitations. For the G quanta, the above rules are easily converted into a recursion relation for the quantity \( \Omega_l (y, q) \), which is the trace of \( y^{N_0} q^E \), with \( N_0 \) the number of G quanta and \( y = e^{\beta \mu + } \), over all multi-G states with modes \( l \leq \frac{1}{2} \). We find

\[
\Omega_l = \Omega_{l-1} + y q^{l-(1/2)} \Omega_{l-2} + y^2 q^{2l-2} \Omega_{l-4} - y^3 q^{3l-(13/2)} \Omega_{l-6}.\]

The corresponding distribution function is

\[
n_\epsilon(\epsilon) = \left[ \epsilon \partial_\epsilon \log (\mu +) \right] (z_\epsilon = e^{\beta (\mu - \epsilon)}) \]

with \( \mu + (z_\epsilon) \) the largest real solution of

\[
(\mu^4 - z_\epsilon^2) (\mu^2 - z_\epsilon) = \mu^5.\]

For temperature \( T = 0 \), the distribution functions \( n_{qh}(\epsilon) \) and \( n_\epsilon(\epsilon) \) are step-down functions with maximum \( n_{qh}^{\text{max}} = 8 \) and \( n_\epsilon^{\text{max}} = \frac{1}{2} \). At finite \( T \), the asymptotic behavior for \( \epsilon \to \infty \) is \( n_{qh} \sim \sqrt{2} e^{-\beta \epsilon} \) and \( n_\epsilon \sim e^{-\beta \epsilon} \). We stress that the prefactor \( \sqrt{2} \) is a direct manifestation of the non-Abelian nature of the exclusion statistics of the quasiholes. As an easy consequence of the above formulas, we establish the duality relation

\[
2n_\epsilon(\epsilon) = 1 - \frac{1}{8} n_{qh} \left( -\epsilon \right),\]

\[
\frac{1}{4}.
\]
provided $\mu_{qh} = -\frac{1}{4}\mu_c$. This result generalizes the duality for Haldane’s fractional exclusion statistics [8]. The duality allows us to interpret the spectrum in different ways. One picture has quasiholes with energies ranging from $-\infty$ to $\infty$, with the CFT vacuum and other reference states represented as filled seas of quasiholes. An alternative is a picture based on edge electrons, and then there is the “mixed” picture that we started from, with $\phi$ and $G$ quanta of positive energies only.

In the mixed picture, the total central charge $c = \frac{3}{2}$ of the edge CFT is established as the sum of a contribution $c^{+}_{qh}$ from the quasiholes and a piece $c^{+}_{e}$ from the electrons. Using MAPLE, we evaluated

$$c^{+}_{qh} = 1.059 \ldots, \quad c^{+}_{e} = 0.440 \ldots.$$  \hspace{1cm} (19)

To compute the Hall conductance, we insert $q_{qh} = \frac{1}{4}$ and $n_{qh}^{\text{max}} = 8$ or $q_{e} = -1$ and $n_{e}^{\text{max}} = \frac{1}{2}$ into (1), giving $\sigma_H = \frac{1}{2} e^2 / \pi$ as expected. The fact that this result is independent of temperature is guaranteed by the duality relation (18). We refer to [6] for the details of this way of computing and for further applications of the quasiparticle formalism.

In conclusion, we have established an appropriate generalization of the Pauli principle for a situation where electrons and quasiholes obey non-Abelian braiding statistics. We have also demonstrated a particle-hole duality in this non-Abelian theory. In a future publication, we shall give a more extensive treatment of exclusion statistics in CFT’s with non-Abelian braiding and give more examples. These will include the so-called parafermionic quantum Hall states, higher level Wess-Zumino-Witten theories, and a spinon representation for the SO(5)$_1$ CFT, which is relevant for SO(5) invariant ladders models for correlated electrons.

The author thanks P. Bouwknegt, N. Read, and R. A. J. van Elburg for discussions. Part of this work was done at the 1997 ITP Santa Barbara Workshop on Low-dimensional Field Theory: from Particle Physics to Condensed Matter. This research was supported in part by the foundation FOM of the Netherlands.

*Note added.*—The results presented here are easily generalized to the more general Pfaffian states with factor $(z_i - z_j)^q$ in (2). Equations (13) and (17) become

$$\left(\lambda - 1\right)\left(\lambda^{1/2} - 1\right) = \zeta_{qh}^{\lambda^{(3q-1)/(2q)}}$$
$$\left(\mu^{2q} - \zeta_{e}^{2}\right)\left(\mu^{q} - \zeta_{e}\right) = \mu^{3q-1}. \hspace{1cm} (20)$$

and the duality relation reads

$$qn_{e}(\epsilon) = 1 - \frac{1}{4q} n_{qh}\left(-\frac{\epsilon}{2q}\right). \hspace{1cm} (21)$$

After submitting this manuscript, we learned that S. B. Isakov (private communication; to be published) has determined the exclusion statistics for bulk quasiholes over the general $q$ Pfaffian state, and found results that are identical to those presented here for edge quasiholes.