Anomalous charge tunneling at $\nu = 5/2$

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(Dated: March 1, 2011)

We explain effective charge anomalies recently observed for fractional quantum Hall edge states at $\nu = 5/2$ [M. Dolev, Y. Gross, Y. C. Chung, M. Heiblum, V. Umansky, and D. Mahalu, Phys. Rev. B. **81**, 161303(R) (2010)]. The experimental data of differential conductance and excess noise are fitted, using the anti-Pfaffian model, demonstrating that a peculiar agglomerate excitation with charge $e/2$, double of the expected $e/4$ charge, dominates the transport properties at low energies. We investigate the behavior of the finite frequency noise as a cross-check quantity to validate the depicted scenario.

PACS numbers: 71.10.Pm,73.43.-f,72.70.+m

Introduction.–Since its discovery [1], the fractional quantum Hall (FQH) state at filling factor $\nu = 5/2$ has been subject of intense investigations. Many proposals have been introduced in order to explain this exotic even denominator, ranging from an Abelian description [2] to more intriguing ones which support non-Abelian excitations, like the Moore-Read Pfaffian model [3–5] or its particle - hole conjugate, the anti-Pfaffian model [6, 7]. The possible applications for the topologically protected quantum computation of non-Abelian excitations aroused even more interest for this FQH state [8].

In these models the excitations have a fundamental charge $e^* = e/4$ (e the electron charge). This fact has been experimentally confirmed by bulk measurements [9] and by means of standard technique of current noise experiments through a quantum point contact (QPC) geometry [10], already used to measure fractional charges for other FQH states [11–13]. Very recently, were reported measurements [14] for $\nu = 5/$ where the $e/4$ charge value is only observed at high temperatures, while at low temperatures the measured charge reaches the unexpected value $e/2$. Analogous enhancements of the carrier charge has been already observed [13, 15] and theoretically explained [16–18] in other composite FQH states belonging to the Jain sequence. However, there is still no interpretation of this phenomenon in the $\nu = 5/2$ state.

In this letter we propose an explanation for these puzzling observations, demonstrating that a different kind of excitation with charge double (2-agglomerate) of the fundamental one dominate the transport at low energies. We will consider the anti-Pfaffian model despite, as we will see, the presented phenomenology could be also consistent with other models. In the anti-Pfaffian case three fields are involved, one charged and two neutral (one boson and one Majorana fermion). The key assumptions of our description are the finite velocity of neutral modes and the presence of interaction induced renormalizations [19–22]. Our predictions show an excellent agreement with experimental data for differential conductance and noise on a wide range of temperatures and voltages, demonstrating the presence of the 2-agglomerate at low temperatures. Note that this result cannot be simple interpreted as a bunching phenomena of two single-quasiparticle due to the non-Abelian nature of the excitations. We will also suggest the finite frequency noise [23, 24] as an independent quantity able to reinforce the above scenario.

Model.–We consider the disorder dominated phase of the anti-Pfaffian model [6, 7], that describes two completely filled inert Landau levels and an half filled one. The hidden symmetry associated to this phase decouples the two neutral modes and fixes their velocity to be equal [7]. The Lagrangian density is ($\hbar = 1$)

$$\begin{aligned}\mathcal{L} = &-\frac{1}{2\pi}\partial_x\varphi_c\left(\partial_t\varphi_c + v_c\partial_x\varphi_c\right)\\ &-\frac{1}{4\pi}\partial_x\varphi_n\left(-\partial_t\varphi_n + v_n\partial_x\varphi_n\right) +\\ &-i\psi\left(-\partial_t\psi + v_n\partial_x\psi\right).\end{aligned} \quad (1)$$

The charged bosonic mode $\varphi_c(x)$ is related to the electron number density $\rho(x) = \partial_x\varphi_c(x)/2\pi$, the neutral counter-propagating modes are a bosonic one ($\varphi_n(x)$) and the Majorana fermion ($\psi(x)$). The commutators rules are $\left[\varphi_{c/n}(x), \varphi_{c/n}(y)\right] = i\pi\nu_{c/n}\mathrm{sgn}(x-y)$ with $\nu_c = 1/2$ and $\nu_n = -1$, with the Majorana fermion that commutes with both. With v_c and v_n we indicate the propagation velocities of the modes. Numerical calculations suggest $v_n < v_c$ [25]. Related to these velocities, there are the energy bandwidths $\omega_{c/n} = v_{c/n}/a$, with a a finite length cut-off. The charged mode bandwidth ω_c corresponds to the greatest energy in our model, and is assumed to be of the order of the gap.

Excitations.–A generic operator destroying an excitation along the edge can be written as [7]

$$\Psi_{\chi,m,n}(x) \propto \chi(x) e^{i\left(\frac{m}{2}\varphi_c(x) + \frac{n}{2}\varphi_n(x)\right)} \quad (2)$$

here, the integer coefficients m, n and the Ising field χ define the admissible excitations. In the Ising sector χ can be I (identity operator), ψ (Majorana fermion) or σ (spin operator). The operator σ, due to the non-trivial operator product expansion $\sigma \times \sigma = I + \psi$, leads to the non-Abelian statistics of the excitations [8]. The single-valuedness properties of the operators force m, n to be even integers for $\chi = I, \psi$ and odd integers for $\chi = \sigma$. The charge associated to the operator in Eq. (2) is $e^*_{\chi,m,n} = (m/4)e$ depending on the charged mode only. In the following we will indicate an $(m/4)e$ charged excitation as m-agglomerate [16]. The scaling dimension [26] of the operators in Eq. (2) is

$$\Delta_{\chi,m,n} = \frac{1}{2}\delta_\chi + \frac{g_c}{16}m^2 + \frac{g_n}{8}n^2, \qquad (3)$$

with $\delta_I = 0$, $\delta_\psi = 1$ and $\delta_\sigma = 1/8$ [8]. Here, the renormalization parameters $g_{c,n} \geq 1$ are introduced in order to take into account non-universal effects due to coupling with the external environment [19, 20], edge reconstruction [21] or interactions with the completely filled Landau levels [22]. Note that, as far as we know, there are no proposed mechanisms for renormalizations of the fields in the Ising sector, therefore we assume them as unrenormalized. Inspection of Eq. (3) allows for the determination of the more relevant excitations. Among all the single-quasiparticle (qp), with charge $e^* = e/4$, the most dominant are $\Psi^{(1)} = \Psi_{\sigma,1,\pm1}$ with scaling dimensions $\Delta^{(1)} = \Delta_{\sigma,1,\pm1} = (g_c + 2g_n + 1)/16$. The other most relevant excitation is the 2-agglomerate with charge $2e^* = e/2$ and operator $\Psi^{(2)} = \Psi_{I,2,0}$ with scaling dimension $\Delta^{(2)} = \Delta_{I,2,0} = g_c/4$. It is worth to note that also the operator $\Psi_{\psi,2,0}$ has a charge $e/2$, but it is less relevant because of its scaling dimension is increased by the Majorana fermion contribution. All other excitations are less relevant and will be neglected in the following.

In the unrenormalized case ($g_c = g_n = 1$) the single-qp ($\Psi^{(1)}$) and the 2-agglomerate ($\Psi^{(2)}$) have the same scaling dimension, equal to $1/4$. Renormalization effects qualitatively change the above scenario. In particular, for $g_c < (1 + 2g_n)/3$, the 2-agglomerate becomes the most relevant excitation at low energies opening the possibility of a crossover between the two excitations, in agreement with experimental observations.

Note that due to the peculiar fusion rules of the σ operator, the 2-agglomerate cannot be simply created combining two single-qp without introducing also an excitation with a Majorana fermion in the Ising sector. This fact suggests that, in the non-Abelian models, the 2-agglomerate is not simply given by a bunching of two quasiparticles.

Transport properties.–In the QPC geometry tunneling of excitations between the two side of the Hall bar is allowed, and can be described through the Hamiltonian $H_T = \sum_{m=1,2} t_m \Psi_R^{(m)\dagger}(0)\Psi_L^{(m)}(0) + \text{h.c.}$ where R and L indicate respectively the right and the left edge and t_m ($m = 1, 2$) are the tunneling amplitudes. Without loss of generality, we assume the tunneling occurring at $x = 0$. At lowest order in H_T the backscattering current is $I_B = \sum_{m=1,2} I_B^{(m)}$ with

$$I_B^{(m)} = me^*\left(1 - e^{-\frac{me^*V}{k_BT}}\right)\Gamma_m(me^*V) \qquad (4)$$

being V the bias, T the temperature and

$$\Gamma_m(E) = |t_m|^2 \int_{-\infty}^{+\infty} dt e^{iEt} G^<_{m,R}(-t) G^>_{m,L}(t) \qquad (5)$$

the tunneling rate. Here $G^>_{m,j}(t) = \langle \Psi_j^{(m)}(t)\Psi_j^{(m)\dagger}(0)\rangle = (G^<_{m,j}(t))^*$ indicates the Green's function of the quasiparticle operators on the edge $j = R, L$. Note that the tunneling rate in Eq. (5) is not affected by the non-abelian nature of the excitations [4]. The differential backscattering conductance is given by $G_B = \sum_{m=1,2} G_B^{(m)}$ with $G_B^{(m)} = dI_B^{(m)}/dV$.

Finite frequency noise [23, 24] is another relevant quantity in order to provide information on the m-agglomerate excitations. At lowest order in the tunneling, it is simply given by the sum of the two contributions $S_B(\omega) = \sum_{m=1,2} S_B^{(m)}(\omega)$ with

$$S_B^{(m)}(\omega) = (me^*)\sum_{\epsilon=\pm} \coth\left[\frac{\epsilon\omega + m\omega_0}{2k_BT}\right] I_B(\epsilon\omega + m\omega_0) \qquad (6)$$

where $\omega_0 = e^*V$. At zero frequency one can introduce the excess noise $S_{\text{exc}} = S_B(0) - 4k_BTG_{B,0}$ with $G_{B,0}$ the total linear conductance. This quantity could be directly compared with the noise measurements carried out in the weak backscattering regime.

Results–In this part we present our theoretical predictions and we compare them with the experimental data for the differential conductance and the excess noise in the extreme weak backscattering regime, taken from Ref. 14. In the shot noise regime $k_BT \ll e^*V$ the current in Eq. (4) follows specific power-laws $I_B \propto V^{\alpha-1}$. An analogous power-law behavior also appears in the excess noise $S_{\text{exc}} \propto V^{\alpha-1}$. The exponent α changes varying the voltages and it is related to the scaling dimensions in Eq. (3). In particular it is $\alpha = g_c$ at very low energy, where the 2-agglomerate dominates. At higher voltages, where the single-qp dominates, it is possible to distinguish two different regimes. For $e^*V \ll \omega_n$, where the neutral modes contribute to the dynamics, one has $\alpha = g_c/4 + g_n/2 + 1/4$, while for $e^*V \gg \omega_n$ the neutral modes are uneffective and the exponent reduces to $\alpha = g_c/4$. The possibility to resolve all these regimes crucially depends on the bandwidth ω_n and the tunneling amplitudes.

In thermal regime $k_BT \gg e^*V$ the conductance is independent on the voltage and scales with temperature like $G_{B,0} \propto T^{\alpha-2}$ while $S_{\text{exc}} \propto V^2$. In Fig. 1 we show experimental data and theoretical predictions for the backscattering differential conductance (top) and excess noise (bottom) at different temperatures. All curves are

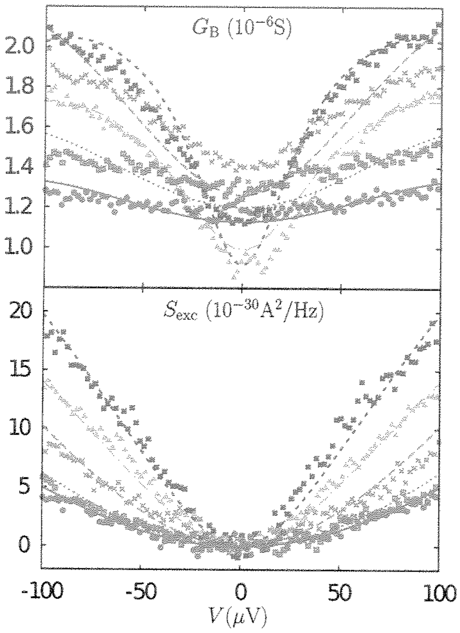

FIG. 1. Differential conductance G_B (top) and excess noise S_{exc} (bottom) as a function of voltage. Symbols represent the experimental data, corresponding to the sample indicated with the full circles in Fig. 5 of Ref. [14], with courtesy of M. Dolev. Different styles indicate different temperatures: $T = 27$ mK (asterisks, short-dashed blue), $T = 41$ mK (triangles, dashed-dotted cyan), $T = 57$ mK (crosses, long-dashed green), $T = 76$ mK (squares, dotted magenta), $T = 86$ mK (circles, solid red). Fitting parameters are: $g_c = 2.8$, $g_n = 8.5$, $\omega_c = 500$ mK, $\omega_n = 150$ mK ($k_B = 1$). $\gamma_1 = |t_1|^2/(2\pi v_c)^2 = 3.1\cdot 10^{-2}, 3.3\cdot 10^{-2}, 5.6\cdot 10^{-2}, 4.9\cdot 10^{-2}, 4.2\cdot 10^{-2}$ and $\gamma_2 = |t_2|^2/(2\pi v_c)^2 = 1.2\cdot 10^{-2}, 7.6\cdot 10^{-3}, 1.7\cdot 10^{-3}, 4.9\cdot 10^{-5}, 4.2\cdot 10^{-5}$.

obtained by fitting with the same values for the renormalization parameters ($g_c = 2.8, g_n = 8.5$) and neutral mode bandwidth ($\omega_n = 150$ mK). We also assume that the tunneling coefficients associated to the single-qp (γ_1) and the 2-agglomerate (γ_2) could vary with temperature. The fitting has been validated by means of the standard χ^2 test and shows an optimal agreement with the whole sets of data. Notice that the value of the neutral mode bandwidth is lower than $\omega_c = 500$ mK, which is of the order of the gap, according with the conclusion of Ref. [25].

The backscattering differential conductance always presents a minimum at zero bias which is the signature of the 'mound-like' behavior generally observed for the transmission in the QPC geometry at very weak backscattering [10]. For low enough temperatures, i.e. blue (short dashed) and cyan (long dashed) lines, one can see the dominance of the 2-agglomerate for low bias $V \lesssim 50$ μV and a crossover region related to the dominance of the single-qp increasing voltages. At higher temperatures, where the single-qp contribution becomes relevant, the curves appear quite flat and voltage independent (dotted magenta and solid red lines). This is a signature of the fact that the system is ohmic in the thermal regime $e^*V \ll k_BT$. Notice that the presence of renormalizations for the charged and neutral modes is crucial in order to fit the experimental data.

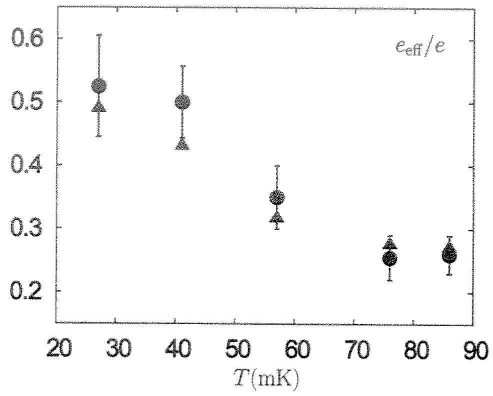

FIG. 2. Effective charge, in unit of the electron charge, as a function of temperature. Circles with error bars are the experimental data of Fig. 5 of Ref. [14], with courtesy of M. Heiblum. Triangles are the effective charges obtained from the theoretical curves of excess noise in Fig.1.

Let us discuss now the excess noise curves. At high temperature (low bias) they present an almost parabolic behavior as expected for the thermal regime. Nevertheless this behavior is also present for $e^*V \gg k_BT$. This effect is not universal and it is due to the peculiar scaling dimension of the 2-agglomerate and to the value of the charge mode renormalization. At high bias ($V \approx 100$ μV) the lowest temperature curve deviates from the quadratic behavior as a consequence of the single-qp contribution.

In Fig. 2 we compare the effective charge e_{eff} (triangles), calculated from our theoretical curves using the same fitting procedure adopted in Ref. [14] with the experimental results (circles with error bars). Our results are in accordance with the evolution of the effective charge as a function of the temperature.

A possible way to validate the above scenario is by means of the finite frequency noise [23]. This quantity has been considered for other FQH states in Refs. [24, 27] and for $\nu = 5/2$ in the case of the Pfaffian model in Ref. [28]. At zero temperature, the spectral density noise $S_B(\omega)$ presents signatures of tunneling charges as a function of frequency $S_B(\omega) \underset{\omega\to m\omega_0}{\approx} (\omega - m\omega_0)^{4\Delta^{(m)}-1}$ with $m\omega_0$ the Josephson frequency associated to the m-agglomerate charge me^*. The presence of peaks or dips, depending on the scaling dimensions $\Delta^{(m)}$, could indicate specific values of carrier charges. Unfortunately these structures can be hidden by thermal smearing. In Fig. 3 we show the spectral density noise at different temperatures assuming different values of the renormalizations. In particular in the unrenormalized case ($g_c = g_n = 1$) at zero

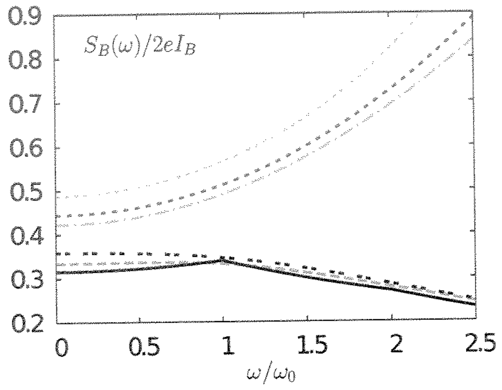

FIG. 3. Normalized finite frequency noise $S_B(\omega)/2eI_B$ as a function of ω/ω_0. The three lower curves represent the unrenormalized anti-Pfaffian case $g_c = g_n = 1$, while the three upper curves the renormalized anti- Pfaffian case with $g_c = 2.8$, $g_n = 8.5$. Temperatures are $T = 0$ mK (solid black, dashed gray), $T = 27$ mK (long dashed green, dashed blue) and $T = 41$ mK (dotted black, dotted-dashed cyan) . Parameters are the same of Fig. 1 and $\omega_0/e^* = V = 30$ μV.

temperature (black solid line) one can distinguish the Josephson resonances corresponding to the single-qp (ω_0) and the 2-agglomerate ($2\omega_0$). At finite temperature these resonances are practically not detectable both for the unrenormalized (lowest three curves) and the renormalized case (upper three curves). Nevertheless the behavior in the two cases is very different, indeed the unrenormalized case is slowly decreasing with the frequency, conversely the renormalized one strongly grows with frequency. Therefore a measurement of this quantity could give important information about the presence of renormalizations validating our initial assumptions.

Conclusions.– We fit recent experimental data on differential backscattering conductance and excess noise in a quantum point contact geometry for filling factor $\nu = 5/2$, demonstrating that the tunneling excitation has a charge double of the fundamental one at low temperatures. Our results are in accordance with the evolution of the effective charge as a function of temperatures starting from $e/2$ at low temperatures and going to $e/4$ at higher values. One of the key assumption, in order to fit the experimental data, is the presence of interactions which renormalize the scaling behavior for the two bosonic modes. The presented phenomenology is also consistent with other models for the $\nu = 5/2$ state, by properly changing the definition of the renormalization parameters and mapping the different expressions of the scaling dimensions. We also propose the finite frequency noise as an independent quantity in order to shed light on interaction induced effects and consequently on the discussed behavior.

Acknowledgements. We thank Y. Gefen, Y. Oreg, A. Cappelli and G. Viola for valuable discussions. A particular acknowledge is for the experimental group of M. Heiblum for providing us the raw data of their experiment and for the kind hospitality of one of us (A.B.). We acknowledge the support of the CNR STM 2010 programme and the EU-FP7 via ITN-2008-234970 NANOCTM.

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28 Febbraio 2010

Report del PROGRAMMA SHORT TERM MOBILITY (ANNO 2010)

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Report

The study of the current noise of a quantum point contact (QPC) in a quantum Hall bar is one of the best method to investigate the peculiar properties of fractional quantum hall (FQH) fluids. In particular the noise in QPC was fundamental to demonstrate the existence of the phenomena of charge fractionalization[1, 2, 3]. More recently experiments have shown anomalous enhancements of the noise, at very low temperatures, those correspond to an increased carrier charge in comparison to the expected values for the fundamental charges[4, 5, 6]. In the CNR Unit a possible explanation, for these peculiar results obtained by the group of Prof. Heiblum, was recently proposed, at least for filling factor in the Jain sequence $\nu = p/(2np+1)$ [7, 8, 9]. The italian group proposed indeed that the observed enhancement are indeed determined by the crossover between the dominance in the transport of the single quasiparticle (qp) toward to excitations with the charge multiple of the single qp, i.e. agglomerates.
The first issue of the visit was indeed to compare the experimental data for the Jain sequence, taken in the last year, with the theory. The results of the comparison confirmed the good agreement between theory and experiments as already anticipated in the first publications on the topic[7, 8, 9]. The theory of the italian group gave for the first time a clear and simple

explanation of the variation of the measured effective charges as a function of the temperatures in terms of a crossover between single-qps and agglomerates. From the physical point of view probably one of the most important implication of the theory was the clear identification, at least at indirect level, of the existence of propagating neutral modes[8]. It was also clarified that the transport measurement could potentially extract information about the neutral modes. It is relevant to observe, given the evanescent role of the neutral modes since that time, that there were also theories where neutral modes were taken topological, not propagating at all[10].
The theory of the italian group, giving a sort of indirect proof of the existence of neutral modes, seems just to anticipate the revolutionary observation done in the 2010 by the group of M. Heiblum where indeed neutral modes were for the first time observed. In that year, indeed, the experimental group have showed indeed that for FQH with $\nu = 2/3$ neutral modes indeed exist, they are counterpropagating (in agreement with some version of the low energy effective theories) and they have important consequence in the transport[11]. During the visit the italian researcher has acquired some data and information on that recent experiment and he has started to investigate from the theoretical point of view that experiment with particular attention to the still unexplained observations.
During the visit the italian researcher investigated also the case of $\nu = 5/2$ where a similar phenomenology of an increased effective charge $e/2$ was indeed observed, at very low temperatures, instead of the predicted value of $e/4$, only observed only at high temperatures[6]. This analogy with the phenomenology discussed before was investigated in detail during the visit. The main difference between FQH fraction with even denominator, such as $\nu = 5/2$, with the more common fractions at odd denominator, such as the Jain sequence $\nu = p/(2np + 1)$, is that some of the accepted theories developed to explain them require the existence of qp with non-Abelian statistics[12]. This unique properties has been suggested as an unique resource to create a new paradigm of quantum computation scheme that is called topological protected quantum computation i.e. protected against decoherence by the clever usage of the non- Abelian statistics[12].
The investigation of QPC transport in the edge states calculated in term of Abelian and non-Abelian low energy effective theory has shown that also for the non-Abelian case the crossover between single-qp and agglomerate dominance could explain well the experimental observations of the Prof. Heiblum 's group. We have recently collected those results in a recent paper[13] (attached documentation).
During the visit we have also explored the possibility to use the skewness and the finite frequency noise measurements to better address some of the previous issues, such as for example to measure

the carrier charges with an independent method. Unfortunately, on the experimental side, nowadays techniques are still not able to measure those quantities in the FQH for many technical reasons. Even if we cannot predict nowadays if those type of measurements will be done in FQH surely it has been demonstrated how those informations could be extremely helpful to shine light on some of the most interesting poen issues in the FQH fluids[13, 14, 15].
In conclusion the research visit of Dr. Alessandro Braggio to the Weizmann Institute has opened some new and interesting line of research and enforced the collaboration between the CNR and this prominent institution in the field of FQH and in general in the field of condensed matter. The italian group is developing an intense scientific exchange with the Prof. Heiblum's group opening the possibility of a research collaboration in the field of FQH with one of the most important experimental group of the field.

Pubblications

- *Anomalous charge tunneling at $\nu = 5/2$*
  M. Carrega, D. Ferraro, A. Braggio, N. Magnoli, M. Sassetti
  submitted to Phys. Rev. Lett. see also arXiv:1102.5666

- *Effective charge evolution with neutral current*
  A. Braggio, D. Ferraro and N. Magnoli
  in preparation.

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