Tunnelling between edge states of a 2D topological insulator and a Fermi liquid lead through a quantum dot

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received 6 August 2011; accepted in final form 27 October 2011
published online 30 November 2011

PACS 72.10.Bg – General formulation of transport theory
PACS 73.40.Gk – Tunneling
PACS 71.10.Pm – Fermions in reduced dimensions (anyons, composite fermions, Luttinger liquid, etc.)

Abstract – In this paper we study a non-equilibrium resonant tunnelling problem where a non-interacting quantum dot is connected to two leads, one being the edge of an interacting 2D topological insulator (Luttinger liquid) and the other being a usual Fermi liquid. We show that the current passing through the system can be expressed in terms of a non-equilibrium local single-particle Green’s function of the Luttinger liquid lead which can be analysed using standard bosonization-renormalization group (RG) technique. In particular, some exact results can be extracted in the small-bias limit with repulsive electron-electron interaction. A simple formula which captures the qualitative feature of the \( I-V \) relation over the whole temperature and voltage bias range is proposed and studied.

The discovery of topological insulators [1,2] has generated much interests and activities in the condensed-matter physics community. In the case of 2D topological insulators (quantum spin-Hall systems), helical edge states respecting time-reversal symmetry [3] exist and provide an example of interacting Luttinger liquid which can be studied experimentally up to room temperature. The transport properties of interacting one-dimensional systems have been studied extensively in the literature [4–6], especially after the discovery of edge states in fractional quantum Hall (FQH) liquids [7] (chiral Luttinger liquids). For example, the problem of a non-interacting quantum dot connected to leads of FQH edge states was studied by de Chamon and Wen [8], and later by Furusaki [9] at temperatures higher than the tunnelling strength.

The emergence of topological insulators makes these 1D theoretical models realizable. In this paper we study a simple model of a non-interacting quantum dot connected to two leads, one being the edge of a 2D topological insulator with electron-electron interaction, the other being a normal Fermi liquid lead (fig. 1). We show here that the non-linear \( I-V \) relation of the system can be expressed in terms of a non-equilibrium local single-particle Green’s function of the topological insulator lead which can be analyzed in the limit of small voltage bias and low temperature using a conventional renormalization group (RG) approach. A few exact results are extracted from the RG analysis and a simple formula which captures the qualitative feature of the \( I-V \) relation over the whole temperature and voltage bias range is proposed and studied.

We start with the model Hamiltonian \( H = H_{01} + H_{02} + H_{0d} + H_{T}, \) where

\[
H_{01} = -iv_F \int dx (\bar{\psi}_{1R,\uparrow}^{+}(x) \partial_x \psi_{1R,\uparrow}(x) \\
-\bar{\psi}_{1L,\downarrow}(x) \partial_x \psi_{1L,\downarrow}(x)) \\
+ \frac{g}{2} \int dx (\bar{\psi}_{1R,\uparrow}^{+}(x) \psi_{1R,\uparrow}(x) \\
+ \bar{\psi}_{1L,\downarrow}(x) \psi_{1L,\downarrow}(x))^2
\]  

\( (1a) \)}

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and
\[ H_{02} = \sum_{k,\sigma} \varepsilon_{2k} c_{2k,\sigma}^{\dagger} c_{2k,\sigma} \]  
(1b)
describe the edge states of a 2D topological insulator \((H_{01})\) and the states in the Fermi liquid lead \((H_{02})\), respectively; \(\psi_{1,R/L,\sigma}(x)\), \(\psi_{1,R/L,\sigma}(x)\) and \(\hat{c}_{2k,\sigma}^{\dagger} \hat{c}_{2k,\sigma}\) are the corresponding electron field operators in the topological insulator lead and Fermi liquid lead (in momentum representation), respectively.

\[ H_{0d} = \varepsilon_0 \sum_{\sigma} \hat{d}_{\sigma}^{\dagger} \hat{d}_{\sigma} \]  
(1c)
describes the single-particle state on the quantum dot where \(\hat{d}_{\sigma}^{\dagger}, \hat{d}_{\sigma}\) are the corresponding electron operators and
\[ H_T = T_1 \{ \psi_{1,R}^{\dagger}(0) \hat{d}_{\uparrow} + \psi_{1,L}^{\dagger}(0) \hat{d}_{\downarrow} + \text{h.c.} \} 
+ T_2 \{ \psi_{2,R}^{\dagger}(0) \hat{d}_{\uparrow} + \psi_{2,L}^{\dagger}(0) \hat{d}_{\downarrow} + \text{h.c.} \} \]  
(1d)
describes electron tunnelling between the dot and the leads. We note that since the propagation and spin directions of electrons in the topological insulator lead are tied together (helical edge), we can forget its spin suffix and the helical edges states of topological insulator behave like a spinless Luttinger liquid [10,11].

\(H_{01}\) can be transformed to a free boson system by the standard bosonization technique [12] where the fermion correlation function \(g_1(t, t') = -i \langle T_C \psi_{1,\sigma}(0,t) \psi_{1,\sigma}^{\dagger}(0,t') \rangle_H \) can be computed straightforwardly [13]. In the bosonization theory a Luttinger liquid is usually characterized by the interaction strength parameter \(K \equiv (1 + \frac{\beta}{\pi \nu})^{-1/2}\); here we further define \(\beta \equiv \frac{1}{2}(K + \frac{1}{K} - 2)\) which is a parameter we shall use frequently in the following.

The DC current \(I\) flowing from lead 1 to lead 2 in the above system can be expressed as [14]

\[ I = -I_2 = e \int d\sigma \left\langle \sum_{\sigma} \left\{ \frac{dN_{\sigma \sigma}}{dt} \right\} \right\rangle 
= -ieT_2 \sum_{\sigma} \left\{ \psi_{2,\sigma}^{\dagger}(0,t) \hat{d}_{\sigma}(t) - \hat{d}_{\sigma}^{\dagger}(t) \psi_{2,\sigma}(0,t) \right\}, \]  
(2)

where \(I_2\) is the current flowing from lead 2 to the quantum dot. Since lead 2 is non-interacting, we can eliminate the lead-2 electron operators through their equation of motion. Following ref. [14] we obtain after some straightforward algebra
\[ \begin{align*} 
I &= -e|T_2|^2 \sum_{\sigma} \int d\varepsilon \rho_2(\varepsilon) [2f(\varepsilon - \mu_2) \text{Im}\{G_{dd,\sigma}(\varepsilon)\} 
+ \text{Im}\{G_{dd,\sigma}^{<}(\varepsilon)\}] 
\end{align*} \]  
(3)
where \(G_{dd,\sigma}(\varepsilon)\) and \(G_{dd,\sigma}^{<}(\varepsilon)\) are the Fourier transform of the “retarded” and “less” components of the onsite (Keldysh) Green’s function of the quantum dot, \(G_{dd,\sigma}(t, t') = -i \langle T_C \hat{d}_{\sigma}(t) \hat{d}_{\sigma}^{\dagger}(t') \rangle\), where \(t\) and \(t'\) are time ordered along a closed time contour from \(t = -\infty\) to \(t = \infty\) and then back to \(t = -\infty\). \(\rho_2(\varepsilon)\) and \(\mu_2\) are the density of states (which will be taken to be a constant later) and the chemical potential of lead 2, respectively. \(f(\varepsilon)\) is the Fermi-distribution function. Notice that the current is expressed solely in terms of a (non-equilibrium) local single-particle Green’s function of the system. This result is possible because lead 2 is non-interacting.

To calculate \(G_{dd,\sigma}(t, t')\), we follow the Keldysh path integral formalism [15]. The action of the system is [16]
\[ S = \int_C dt \left[ \int dx \sum_{\sigma} \left\{ \bar{\psi}_{1,\sigma}(x,t) (\partial_t + \sigma v_F \partial_x) \psi_{1,\sigma}(x,t) \right\} 
- \frac{g}{2} \int dx \left\{ \bar{\psi}_{1,\sigma}(x,t) \psi_{1,\sigma}(x,t) \right\}^2 
+ \sum_{k,\sigma} \bar{c}_{2k,\sigma}(t)(i\partial_t - \varepsilon_{2k})c_{2k,\sigma}(t) 
+ \sum_{\sigma} \{ T_1 \bar{\psi}_{1,\sigma}(0,t) d_{\sigma}(t) + T_2 \bar{\psi}_{2,\sigma}(0,t) d_{\sigma}(t) + \text{c.c.} \} 
+ \sum_{\sigma} d_{\sigma}(t)(i\partial_t - \varepsilon_0) d_{\sigma}(t) + \sum_{\sigma} \{ \xi_{\sigma}(t) d_{\sigma}(t) + \text{c.c.} \} \right], \]  
(4)
where \(\sigma = \pm 1\) and we have suppressed the propagation direction indices of the helical edge states for brevity. \(\{\xi_\sigma, \xi_\rho\}\) are external source fields introduced to generate \(G_{dd,\sigma}(t, t')\). Integrating out the fermionic fields \(\{c_{2k,\sigma}, \bar{c}_{2k,\sigma}\}\) and \(\{d_{\sigma}, \bar{d}_{\sigma}\}\) we obtain
\[ S_{eff} = \int_C dt \left[ \int dx \sum_{\sigma} \left\{ \bar{\psi}_{1,\sigma}(x,t) (\partial_t + \sigma v_F \partial_x) \psi_{1,\sigma}(x,t) \right\} 
- \frac{g}{2} \int dx \left\{ \bar{\psi}_{1,\sigma}(x,t) \psi_{1,\sigma}(x,t) \right\}^2 \right] 
- \sum_{\sigma} \int dt_1 dt_2 [\xi_{\sigma}(t_1) + T_1 \bar{\psi}_{1,\sigma}(0,t_1)] g_{D\sigma}(t_1, t_2) \]  
(5)
which is an effective action for lead-1 electrons only. \(g_{D\sigma}(t, t')\) is the Green’s function of the quantum dot evaluated under the “dot+lead 2” action with
\[ g_{D\sigma}^{R/A}(\omega) = \frac{1}{\omega - \varepsilon_0 \pm i\Gamma_2}, \]  
(6)
\[ g_{D\sigma}(\omega) = \frac{2i\Gamma_2 f(\omega - \mu_2)}{(\omega - \varepsilon_0)^2 + \Gamma_2^2}, \]
where \(\Gamma_2(\omega) = \pi \rho_{1,2}(T_1(2)^2\omega)\) is the tunnelling width from the dot to lead 1 (2). \(G_{dd,\sigma}(t, t')\) can be obtained by taking functional derivatives of the generating functional with respect to the \(\{\xi_\sigma, \xi_\rho\}\) fields; we obtain
\[ G_{dd,\sigma}(t, t') = g_{D\sigma}(t, t') + |T_1|^2 \int_C dt_1 dt_2 g_{D\sigma}(t_1, t_2) \]  
(7)
\[ I = -e|T_1|^2|T_2|^2 \sum_\sigma \int d\omega \rho_2 \text{Im} \left\{ \frac{2(f(\omega - \mu_2) - f(\omega - \mu_1))g_{00}^R(\omega) - |g_{00}^R(\omega)|^2}{1 - g_{00}^R(\omega) g_{00}^R(\omega)^*} \left( \Sigma_{\sigma,T}^R(\omega) + 2f(\omega - \mu_2)\Sigma_{\sigma,T}^R(\omega) \right) \right\}. \]  

(10)

where

\[ g_{1\sigma \text{eff}}(t,t') = -i \left\langle T_C \hat{\psi}_{1,\sigma}(0,t) \hat{\psi}_{1,\sigma}^+(0,t') \right\rangle_{\text{eff}} \]

is the Green’s function of lead-1 electrons evaluated at \( x = 0 \) according to the effective action (5) in the absence of the external source terms. Different Keldysh components of \( G_{dd,\sigma} \) can be extracted from (7) using Langreth’s sum rules [17]. Combining eqs. (6) and (7), we obtain for the tunnelling current (3),

\[ I = -e|T_1|^2|T_2|^2 \sum_\sigma \int d\omega \rho_2 \left[ \frac{1}{(\omega - \varepsilon_0)^2 + \Gamma_2^2} \times \{ \text{Im} g_{1\sigma \text{eff}}^R(\omega) + 2f(\omega - \mu_2)\text{Im} g_{1\sigma \text{eff}}^R(\omega) \} \right], \]

(8)

where the only unknown is the effective Green’s function \( g_{1\sigma \text{eff}}(t,t') \).

To evaluate \( g_{1\sigma \text{eff}}(t,t') \) we express it in the form of a standard Dyson’s equation

\[ g_{1\sigma \text{eff}}(t,t') = g_{1\sigma}(t,t') + \int_C dt_1 dt_2 g_{1\sigma}(t,t_1) \Sigma_{\sigma,T}(t_1,t_2) \times g_{1\sigma \text{eff}}(t_2,t'), \]

(9)

where \( g_{1\sigma}(t,t') \) is the Green’s function of lead-1 electrons at \( x = 0 \) evaluated at \( T_1 = 0 \), and is the standard \( x = 0 \) Green’s function of spinless Luttinger liquid with interaction strength \( K \) [12]. The self-energy term in (9) represents correction coming from the tunnelling term (last term in eq. (5)). The tunnelling current (8) can be expressed in terms of the Fourier-transformed self-energy \( \Sigma_{\sigma,T}(\omega) \) as see eq. (10) above.

We observe that the tunnelling current is completely determined by the self-energy function \( \Sigma_{\sigma,T}(\omega) \). In the absence of electron-electron interaction \( \Sigma_{\sigma,T}(\omega) = \Sigma_{\sigma,T}^{(0)}(\omega) = |T_1|^2 g_{D\sigma}(\omega) \) and our main job here is to understand how \( \Sigma_{\sigma,T}(\omega) \) is renormalized by the electron-electron interaction.

In the following we shall study \( \Sigma_{\sigma,T}(\omega) \) in the small-bias, low-temperature limit \( T, |\mu_1 - \mu_2| \ll \Gamma_1(2) \) using a standard bosonization-RG analysis [4]. In this limit we may keep only the long-time behavior of \( g_{D\sigma}(t) \) in eq. (5) and forget about the more complicated intermediate time behaviors, i.e. we approximate

\[ g_{D\sigma}^{R(A)}(t) = e^{i\varphi_0 - \Gamma_2 t} |t| \rightarrow \infty \rightarrow 0, \]

\[ g_{D\sigma}^{R(A)}(t) \sim 2i \frac{\Gamma_2}{\varepsilon_0^2 + \Gamma_2^2} e^{i\mu_0 t}/t. \]

(11)

To proceed further we compare the present problem with the problem of directly tunnelling between a Luttinger liquid and a Fermi liquid through a simple tunnelling junction barrier \( \Sigma \). The Fermi liquid fields can be integrated out as what we have done to derive eq. (5). The only difference in the direct tunnelling problem is that \( g_{D\sigma}(t) \) in eq. (5) is replaced by \( g_{D\sigma}^{R(A)}(t) \sim \mp i\pi N(0)\delta(t) \) and \( g_{D\sigma}(t) \sim 2iN(0)e^{i\mu_0 t}/t \), where \( N(0) \) is the density of states on the Fermi surface. Comparing with eq. (11) we see that the resonant tunnelling problem reduces to the direct tunnelling problem in this limit if we replace the dimensionless tunnelling parameter \( \Sigma N(0) \rightarrow T_1 \frac{\Gamma_2}{\varepsilon_0^2 + \Gamma_2^2} \) and the scaling behavior of the self-energy in the present problem can be inferred from the corresponding direct tunnelling problem which has been analyzed using well-developed bosonization-RG technique. We obtain immediately

\[ T_1(E) \sim T_1(E/E_F)^{1-K_{eff}}, \]

in this approximation, where \( K_{eff} = 2K/(1 + K) \) [9]. In particular for repulsive interaction \( K < 1 \), \( T_1(E \rightarrow 0) \rightarrow 0 \) and the self-energy scales to zero in the infrared regime, which makes perturbative RG applicable. In this case it is sufficient to approximate \( \Sigma_{\sigma,T} \sim \Sigma_{\sigma,T}^{(0)} \) with \( T_1 \rightarrow T_1(E) \). Physically, the vanishing of self-energy is an alternative way to express the well-known result that the tunnelling between the Luttinger liquid lead and the Fermi liquid lead vanishes in the infrared limit [4,9]. We emphasize here that the renormalization of \( T_1 \) is restricted only to the self-energy term and does not appear in other places in the current expression. With this approximation we obtain

\[ I \sim -2e|T_1|^2 \Gamma_2 \sum_\sigma \int d\omega (f(\omega - \mu_2) - f(\omega - \mu_1)) \times \text{Im} g_{D\sigma}^{R(A)}(\omega)/|\omega - \varepsilon_0 + i\Gamma_2 - T_1(E)2g_{D\sigma}^{R(A)}(\omega)|^2, \]

(12)

where \( E = \max\{T_1, |\omega - \mu_1|\} \). Equation (12) is expected to be reliable in both the low-temperature, small-bias limit \( (T, |\mu_1 - \mu_2|) \ll \Gamma(2) \) and in the high-temperature, large-bias limit \( (T, |\mu_1 - \mu_2|) \sim E_F \), where \( T_1(E) \rightarrow T_1 \) and the renormalization of \( T_1 \) becomes unimportant. We shall analyze the current using this approximate formula in the following.

To study the tunnelling characteristics, we define \( eV \equiv \mu_2 - \mu_1 \) and \( \varepsilon \equiv \varepsilon_0 - \mu_1 \) and look at the differential conductance \( dI/dV \) as a function of \( V \) at different temperature regimes. The high- and low-temperature regimes
are defined by comparing the width of the Fermi function $f(\omega - \mu_2) - f(\omega - \mu_1) \sim \frac{2f(\omega - eV)}{\delta}$ and the spectral function $\text{Im}[\tilde{g}^R_{1\sigma}(\omega)] \sim \frac{\omega - \epsilon_0 + iT_1(\omega)^2\tilde{g}^R_{1\sigma}(\omega)}{\delta}$. The Fermi function has width $\sim T$, whereas the spectral function has width $\sim \Gamma_{1,2}$. In the high-temperature regime $T \gg \Gamma_{1,2}$ we approximate the spectral function by a $\delta$-function. Using the result $\tilde{g}^R_{1\sigma}(\omega) \sim E^0$ and $T_1(\omega) \rightarrow T_1$ at this regime, we find that $\frac{\partial f}{\partial V}$ scales with temperature as $T^{\gamma-1}$ in the high-temperature regime, in agreement with Furusaki’s result [9].

The low-temperature regime $T \ll \Gamma_{1,2}$ can be subdivided into two regions: when $eV \ll T$, $\frac{df(\omega - eV)}{dV}$ is non-zero only at a range of frequency $\omega \sim T$ and

$$\frac{df}{dV} \sim \frac{\text{Im}[\tilde{g}^R_{1\sigma}(T)]}{(T - \epsilon - [T_1(T)]^2\text{Re}[\tilde{g}^R_{1\sigma}(T)])^2 + (\Gamma_2 - [T_1(T)]^2\text{Im}[\tilde{g}^R_{1\sigma}(T)])^2}. \quad (13)$$

Expanding the expression at small $T$, we find that linear differential conductance scales as $T^\delta(1 + a' T^\gamma)$, where $\gamma = \min\{1, \theta + 2(1 - K_{eff})\}$ and $a$ is a temperature-independent constant; but when $(\Gamma_{1,2} \gg eV) \rightarrow T \rightarrow 0$, $\frac{df(\omega - eV)}{dV} \sim \delta(\omega - eV)$ and the current-voltage relation becomes non-linear at small $|V|$ (see discussion below). The different scaling behaviors (at fixed voltage $V$) are summarized in fig. 2.

Next we consider (non-linear) differential conductance at low-temperature regime $eV \gg T \rightarrow 0$. Replacing $T$ by $eV$ in eq. (13), we observe that in the off-resonance region ($|eV| \ll \Gamma_{1,2}, \epsilon$), the differential conductance goes as $|V|^\delta(1 + a' |V|^\gamma)$, where $a'$ (different from $a$) is a temperature-independent constant. The first term $|V|^\delta$ is in agreement with previous result [8] and the second term $|V|^\delta + \gamma$ is the leading correction coming from the scaling of $T_1$. Our RG analysis suggests that the leading and sub-leading order scalings we derived here are exact as long as perturbative RG is applicable, which is the case for repulsive electron-electron interaction.

We also observe a resonance peak of differential conductance located around $eV \sim \epsilon$ and the differential conductance at $V = 0$ is always zero as long as lead 1 is interacting (see fig. 3(a)). The width of resonance is of order $\Gamma_{1,2}$. The vanishing of differential conductance at $V = 0$ is a character of Luttinger liquids which is very different for non-interacting electrons ($K = 1$), where $\frac{df}{dV}|_{V=0}$ approaches a constant. Notice that, strictly speaking, the resonant peak is not of Lorentzian form and the peak height is not a monotonic function of the Luttinger interaction parameter $K$ because of the non-analytic form of the spectral function for $K \neq 1$. The $dI/dV$ curve becomes monotonic in $K$ only when far from resonance. Finally, we note that when $V$ is far away from the resonant point ($|eV| \gg \max(\Gamma_{1,2}, \epsilon)$), the differential conductance falls as $|V|^{\delta - 2\times \max\{1, \theta + 2(1 - K_{eff})\}}$. The $dI/dV$ curve at small $\Gamma_2 = 0.1\Gamma_1$ for various values of $K$ is also shown in fig. 3(b) where the non-analytic character of the spectral function at $K \neq 1$ is clear from the figure. Notice that $\frac{dI}{dV}|_{\Gamma_2}$ diverges at $eV \rightarrow \epsilon$ for $K \neq 1$ when $\epsilon = 0$ and $\Gamma_2 \rightarrow 0$.

To conclude, we have extended Meir-Wingreen’s current formula to the case with one interacting lead in this paper.
and have used it to calculate the tunnelling current from the edge of a 2D topological insulator through a quantum dot to a normal Fermi liquid lead. The formulation allows us to construct a current expression in terms of the self-energy of a local Green’s function. The differential conductance in different temperature regimes is analyzed using perturbative RG in this paper, which is believed to be reliable when both temperature and voltage bias are much smaller than $\Gamma_{1(2)}$ and if the electron-electron interaction in lead 1 is repulsive. Based on the RG result, an approximate formula for the current qualitatively valid over the whole temperature/voltage range is proposed. The formula reproduces results of earlier works at high temperature and produces new, exact results at low temperature for repulsive electron-electron interaction and small bias. For attractive interaction the scaling breaks down at low enough energy $E$ suggesting that qualitatively new $dI/dV$ behavior is expected at low energy. Our approach offers a new theoretical tool for analysing (non-equilibrium) DC transports which can be extended to other systems with both Luttinger and Fermi liquid leads.

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We thank K. T. Law, Z. Liu and C. Chan for useful discussions. This work is supported by HKRGC grant HKUST3/CRF/09.

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