Tunneling into 1D and Quasi-1D Conductors: Luttinger–Liquid Behavior and Effects of Environment

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Abstract

The paper addresses the problem whether and how is it possible to detect the Luttinger-liquid behavior from the IV curves for tunneling to 1D or quasi-1D conductors. The power-law non-ohmic IV curve, which is usually considered as a manifestation of the Luttinger-liquid behavior in nanotubes, can be also deduced from the theory of the Coulomb blockaded junction between 3D conductors affected by the environment effect. The two approaches predict different power-law exponents for conductance, but the difference becomes negligible for a large number of conductance channels.

Key words: Luttinger liquid, tunneling, nanotubes

In a 1D electron gas with arbitrarily weak interaction Landau's Fermi liquid (FL) theory breaks down, and the system is expected to behave as a *Luttinger liquid* (LL). In the Luttinger liquid, in contrast to FL, the fermion quasiparticle branch is absent and excited states of the system must be described by the boson collective excitations [1]. As a result of it, the IV curve of a tunnel junction between a normal FL and a LL conductor is described by a power law with an exponent depending on interaction strength. On the other hand, the power-law IV curve is also predicted by the theory of the Coulomb blockade in a junction between normal FL conductors affected by Environment Quantum Fluctuations (EQF) [2]. Since both EQF and LL pictures predict a power-law dependence, a problem arises, how, and whether it is possible at all, to discriminate these two pictures.

At $T = 0$ the current through the junction is:

$$I = \frac{1}{eR_T}\int_0^{eV} dE_1 \int_0^{eV} \rho(E_2)P(E_1 - E_2)\, dE_2 \ . \qquad (1)$$

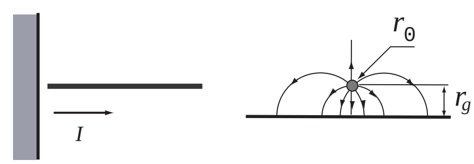

Fig. 1. Tunnel junction between 3D and 1D (or quasi-1D) conductor. On the right the cross-section of the 1D conductor is shown. Arrowed curves are electric-field lines in the space between the 1D conductor and the metallic ground.

Here $\rho(E)$ is the relative density of the state (DOS) for the right conductor (Fig. 1) normalized to the constant DOS of the normal Fermi-liquid, the latter being included into the definition of the junction conductance $1/R_T$. The left conductor is supposed to be always a FL conductor and its relative DOS is unity. If the right conductor is also a FL conductor then $\rho(E) = 1$, and neglecting the environment effect $P(E) = \delta(E)$. Then the IV curve is ohmic.

The EQF theory [2] assumes that both conductors are 3D FL conductors, *i.e.*, $\rho(E) = 1$, but takes into account phase fluctuations in the electric circuit. Then $P(E)$ is a Fourier transform of the phase correlator:

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$$P(E) = \frac{1}{2\pi\hbar} \int_{-\infty}^{\infty} \langle e^{i\hat{\varphi}(t)} e^{-i\hat{\varphi}(0)} \rangle e^{iEt/\hbar} \, dt \; . \qquad (2)$$

At E much smaller than the Coulomb energy e^2/C_T, where C_T is the junction capacitance, $P(E) \propto E^{\alpha_E - 1}$ is a power-law function with the exponent

$$\alpha_E = \frac{2Z}{R_K} \; , \qquad (3)$$

where $R_K = h/e^2 \approx 26$ kΩ is the quantum resistance, and Z is the low-frequency real impedance of the circuit. Since $P(eV) = (R_T/e)(d^2I/dV^2)$ the exponent for conductance $G(V) = dI/dV \sim V^{\alpha_E}$ is α_E.

In the LL theory the environment effects are absent, and $P(E) = \delta(E)$. But because of the electron-electron interaction $\rho(E)$ essentially different from unity, and for the end contact $\rho(E) \propto E^{\alpha_L - 1}$ [1], where

$$\alpha_L = \frac{1}{N}\frac{v_{pl}}{v_F} + \frac{N-1}{N} \; , \qquad (4)$$

N is the channel number, v_F is the Fermi velocity, and

$$v_{pl} = \sqrt{v_F^2 + \frac{2e^2 N v_F}{\pi\hbar} \ln \frac{r_g}{r_0}} \qquad (5)$$

is the velocity of the 1D plasmon. Here r_0 is the radius of the wire and r_g is the distance from the metallic ground (see Fig. 1). Now the exponent for conductance $G(V) \sim \rho(eV) = R_T(dI/dV) \sim V^{\alpha_L - 1}$ is $\alpha_L - 1$.

The DOS $\rho(E)$ is a Fourier transform of the averaged operator product $\langle \hat{\psi}(x,t)\hat{\psi}^\dagger(x,0) \rangle$ [1], whereas $P(E)$ is a Fourier transform of the correlator $\langle e^{i\hat{\varphi}(t)} e^{-i\hat{\varphi}(0)} \rangle$. Since the phase $\hat{\varphi}$ is an operator conjugate to the operator of the electron number, the operator $e^{-i\hat{\varphi}(t)}$ is a creation operator of the electron like $\hat{\psi}^\dagger(x,t)$. One should expect then similar functional dependencies for $\rho(E)$ and $P(E)$.

One can see this similarity considering the 1D plasmon mode as a wave along a lossless LC transmission line formed by a 1D conductor and a metallic ground. The inductance per unit length of the transmission line is determined by the kinetic energy of electrons, *i.e.,* is a kinetic inductance $l_l = R_K/2v_F$ for the case of one channel ($N = 1$). The capacitance $\tilde{c}$ per unit length must include the effect of the neutral-gas compressibility: $\tilde{c}^{-1} = c_l^{-1} + c_0^{-1}$, $c_0 = 2/R_K v_F$. While the geometric capacitance $c_l = 1/(2 \ln r_g/r_0)$ is related to the energy of the electric field between the wire and the metallic ground, the capacitance c_0 is related to the kinetic energy of the electron Fermi sea. The transmission line with these parameters supports the sound-like wave with the velocity $1/\sqrt{l_l \tilde{c}}$, which coincides with the plasmon velocity v_{pl} given by Eq. (5). Using the impedance $Z = \sqrt{l_l/\tilde{c}}$ of the infinite LC transmission line in Eq. (3) we obtain that $\alpha_E = \alpha_L$ for $N = 1$. On the other hand, the exponents of conductance in two approaches, α_E and $\alpha_L - 1$, differ by unity.

However, Matveev and Glazman [3] have received that for a large number N of channels both theories predict the same power law for conductance, i.e. $\alpha_E = \alpha_L - 1$. But then α_E and α_L cannot be equal. The reason for it is that in the LL approach [3] a quantum wire with N channels is modeled by N parallel transmission lines. They sustain a plasmon mode with the velocity v_{pl}, in which the total charge oscillates. The other $N - 1$ modes are neutral with the Fermi velocity v_F. The impedance $Z_L = Z + [(N-1)/N]R_K/2$ for such a system differs from the impedance Z for *one* transmission line with the only charged mode used by the EQF theory [4]. Thus $\alpha_L = 2Z_L/R_K = \alpha_E + (N-1)/N$, while the conductance exponents $\alpha_L - 1$ and α_E in the two approaches differ by $1/N$. The EQF theory ignores the neutral modes, which are important in the LL approach, but takes into account the single-particle excitations, which are absent in the LL approach. Eventually in the limit of large number of channels the difference in the impedance exactly compensates the difference in the exponents of conductance.

This means that it is difficult to detect the LL behavior from the IV power law. Even for single-wall nanotubes, which have four channels, the difference between the LL and EQF exponents is only $1/N$ =0.25. But to detect this difference is very important because of a conceptual difference between the EQF and the LL approaches. The LL theory for tunneling takes into account accurately the Coulomb interaction inside the LL conductor, but ignores the Coulomb energy e^2/C_T of the junction charge. Meanwhile, the junction capacitance C_T is quite small, and the recent experiment [5] gives evidences that IV curves of multiwall nanotubes are better described by the EQF picture.

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