Nonlinear Transport in One-Dimensional Mott Insulator in Strong Electric Fields

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Abstract

Time-dependent Schrödinger’s equation is integrated for a one-dimensional strongly-correlated electron system driven by large electric fields. For larger electric fields, many-body Landau-Zener tunneling takes place at anticrossings of the many-body energy levels. The nonlinear I-V characteristics as well as the time dependence of the energy expectation value are obtained. The energy of the Mott insulator in electric fields shows a saturation, which suggests a dynamical localization in energy space of many-body wave functions.

Key words: Mott insulator, I-V characteristics, non-equilibrium phenomenon

Introduction

Strongly-correlated electron systems should be an interesting test-bench for nonequilibrium phenomena. Specifically, we can ask how the nonlinear transport properties of Mott insulators are distinct from those of band insulators. It has been experimentally shown that a quasi-one-dimensional cuprate exhibits a dielectric breakdown that remains when extrapolated to zero temperature[1]. This suggests that the origin of the breakdown is quantum mechanical. Indeed, a many-body version of the Landau-Zener transition for correlated electron systems has been proposed by the present authors[2]. In the present paper we make a further analysis of the many-body Landau-Zener breakdown of the one-dimensional Mott insulator in strong electric fields to elucidate how its nature differs from those of the conventional Zener breakdown of band insulators.

I-V characteristics

We study the time evolution of wave functions for a one-dimensional Mott insulator in a static electric field $F$ turned on at $t = 0$. The electric field is here induced by a time-dependent Aharonov-Bohm(AB) flux $\phi(t) = \Phi(t)/\Phi_0 = FLt/h$ pierced through the system in a periodic boundary condition, so the evolution is governed by the time-dependent Schrödinger equation with a time-dependent Hamiltonian,

$$H(\phi(t)) = -\frac{w}{4} \sum_{i\sigma} \left( e^{i2\pi \phi(t)/L} c_{i+1\sigma} d_{i\sigma} + \text{H.c.} \right) + U \sum_i n_i \sigma n_{i+1} + \frac{\Delta}{2} \sum_i (-1)^i n_i.$$

When the system is half-filled, the groundstate is a band insulator for the level offset $\Delta > 0$ with the Hubbard $U = 0$, and becomes a Mott insulating when $U > 0$ with $\Delta = 0$.

We first look at the I-V characteristics (Fig.1) of the Mott insulating phase ($U > 0$, $\Delta = 0$), where the current is defined as a time-averaged $\langle J \rangle \equiv \frac{1}{T} \int_0^T \langle J(t) \rangle dt$. The current is suppressed until the field strength exceeds a threshold, $F(U)$, whose value depends on $U$. The threshold can be estimated from the Landau-Zener formula, and we predict an $F(U) \propto [\Delta E(U)]^2$ dependence on the charge gap $\Delta E(U)$ as confirmed numerically[2]. Above the threshold, Landau-Zener tunneling from the ground state to excited states is activated.

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What distinguishes the breakdown of Mott insulators from those for band insulators is how the system becomes out of equilibrium in electric fields above the threshold. In order to quantify this, we plot the long-time behavior of the energy expectation value $\langle H(t) \rangle$ for a Mott insulator as compared with that for a band insulator (Fig. 2).

**Small $F$ regime:** When the Landau-Zener tunneling is ineffective, the wave function approximately evolves adiabatically along the ground state of the time-dependent Hamiltonian $H(\phi(t))$. The ground-state energy shows an AB-oscillation for a finite system.

**Large $F$ regime:** $\langle H(t) \rangle$ of band insulators diverges in the long-time limit, which is not apparent in Fig. 2(a), but the long-period oscillation seen in the figure has a periodicity $\Delta \phi \sim N$, so the amplitude as well as the periodicity diverge for $N \to \infty$. This is in sharp contrast with the saturated behavior of $\langle H(t) \rangle$ of Mott insulators.

The divergence of $\langle H(t) \rangle$ in the band insulator can be readily understood. The Landau-Zener tunneling produces free electron-hole pairs, which are accelerated by static electric fields. Since there is no dissipation for the present clean and isolated system nor electrode to absorb the energy, the energy increases indefinitely.

On the other hand, $\langle H(t) \rangle$ in the Mott insulator is seen to saturates to a value that depends on the electric field, which is quite an interesting and nontrivial behavior. For noninteracting but disordered systems, Gefen and Thouless explained such a saturation in terms of a *dynamical localization*, i.e., Anderson’s localization in energy space[3]. We can extend the notion of the dynamical localization to a (clean) many-body system.[4] This takes place on many-body adiabatic spectra typically depicted in Fig. 3. We can see that, while a band insulator has a single level anticrossing separated by a gap between the ground state and the state excited with one electron-hole pair, a Mott insulator has many (actually a macroscopic number of) anticrossings among the excited levels. At each level anticrossing the Landau-Zener tunneling takes place and the probability amplitude bifurcates.

**Conclusion**

So, while the disorder gives rise to a saturated behavior in the current-time characteristics in one-body systems, this is replaced by the quantum mechanical tunneling across many level repulsions caused by the electron-electron interaction in many-body systems. We have identified this as the reason why the strong field behaviors are quite different between band insulators and Mott insulators.

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**References**

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