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Spectral properties of a disordered insulating lattice under nonlinear electric field

Kunal Mozumdar, Herbert F. Fotso, and Jong E. Han*
Department of Physics, University at Buffalo, SUNY, Buffalo NY 14260
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Quenched disorder in a solid state system can result in Anderson localization where electrons are exponentially localized and the system behaves like an insulator. In this study, we investigate the effect of a DC electric field on Anderson localization. The study highlights the case of a one-dimensional insulator chain with on-site disorder when a DC electric field is applied throughout the chain. We study spectral properties of an Anderson localized system in equilibrium and out-of-equilibrium using a full lattice nonequilibrium Green's function method in the steady-state limit. Tuning the disorder and the electric field strength results in the creation of exponential Lifshitz tails near the band edge by strongly localized levels. These Lifshitz tails create effects like insulator-to-metal transitions and contribute to non-local hopping. The electric field causes gradual delocalization of the system and Anderson localization crossing over to Wannier Stark ladders at very strong fields. Our study makes a comparison with the coherent potential approximation (CPA) highlighting some major differences and similarities in the physics of disorder.

I. INTRODUCTION

Disordered solid-state systems have been a problem of great interest in condensed matter physics. Seminal work by P. W. Anderson in 1958 [1] showed that in a regular lattice with disordered potential, there is the absence of diffusion of the electronic wave-functions, which get confined in certain regions of the lattice irrespective of the underlying distribution of disorder. The Anderson localization (AL) arises from the quantum interference of electronic wavefunctions mixing at random energy levels. This groundbreaking concept, primarily discussed in the context of electronic systems [2–8], has since been extended to various wave phenomena [9], including acoustic [10], electromagnetic [11–15], gravitational waves[16]. It is relevant for applications in electronic devices [17] and photonic materials [18], etc. Almost a decade after Anderson's paper, Neville Mott argued that Anderson localization is the mechanism of disorder driven metal to insulator transition called the Anderson Transition [19–21], which happens over a mobility edge, the energy scale below which a particle is localized. Fluctuations in the random disordered potential allow localized levels to appear near the band-edge which form Lifshitz tails [22–24] and the mobility edge separates these localized states from the delocalized extended states.

A much less studied problem is the effect of a DC electric field on Anderson localization. In disordered materials, the electric field influences the phase coherence lengths that can affect Anderson localization [25, 26]. Various theoretical methods using different levels of approximations have been developed. Some earlier analytic studies [27, 28] have reported that in a weak field there is a power-law localization instead of Anderson localization. At some stronger critical field there is a mobility edge beyond which the states are extended. Other approaches [29] calculate the electron density fluctuation and relaxation dynamics showing delocalization in the presence of strong fields. In a weakly disordered two-dimensional electronic system, it was claimed that a very small electric field can disrupt localization [30, 31]. One question we address in this work is how an electric field delocalizes a disordered system and how we can learn signatures of the localization–delocalization crossover from spectral properties in an electronic lattice system.

To motivate the study, we first summarize the concept of variable range hopping (VRH) transport in equilibrium, following Mott's argument [32]. We consider electron transport through hops in disordered levels on a lattice. The probability of hops between nonlocal sites with the level difference $\Delta\epsilon$ depends on the spatial overlap between localized states separated by R as, similar to the Miller-Abrahams's expression [33],

$$W = W_0 \exp\left[-\frac{2R}{\xi} - \frac{\Delta\epsilon}{k_B T}\right] \tag{1}$$

where ξ is the localization length and T is the temperature. Mott proposed that the most probable hops are those that maximize the exponent in the hopping probability, effectively balancing the distance R and the energy difference $\Delta\epsilon$. To achieve this, he proposed a statistical approach where the number of states within a $d-$dimensional sphere of radius R and energy width $\Delta\epsilon$ is given as $V g(\epsilon_F)\Delta\epsilon$, where $V \sim R^d$ is the volume and $g(\epsilon_F)$ is the density of states of disordered levels at the Fermi level ϵ_F. Assuming that there is at least one state available to hop in this volume and the energy range, we relate the probable level spacing given by the range of hopping as

$$\Delta\epsilon \sim \frac{1}{g(\epsilon_F)R^d} \tag{2}$$

Now substituting this term to Eq. (1) and maximizing the exponent gives us a generalized equation for the conductivity which is also known as Mott's law of variable

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1. Understanding the eBook Spectral Properties Of Disordered
    - The Rise of Digital Reading Spectral Properties Of Disordered
    - Advantages of eBooks Over Traditional Books
2. Identifying Spectral Properties Of Disordered
    - Exploring Different Genres
    - Considering Fiction vs. Non-Fiction
    - Determining Your Reading Goals
3. Choosing the Right eBook Platform
    - Popular eBook Platforms
    - Features to Look for in an Spectral Properties Of Disordered
    - User-Friendly Interface
4. Exploring eBook Recommendations from Spectral Properties Of Disordered
    - Personalized Recommendations
    - Spectral Properties Of Disordered User Reviews and Ratings
    - Spectral Properties Of Disordered and Bestseller Lists
5. Accessing Spectral Properties Of Disordered Free and Paid eBooks
    - Spectral Properties Of Disordered Public Domain eBooks

    - Spectral Properties Of Disordered eBook Subscription Services
    - Spectral Properties Of Disordered Budget-Friendly Options
6. Navigating Spectral Properties Of Disordered eBook Formats
    - ePub, PDF, MOBI, and More
    - Spectral Properties Of Disordered Compatibility with Devices
    - Spectral Properties Of Disordered Enhanced eBook Features
7. Enhancing Your Reading Experience
    - Adjustable Fonts and Text Sizes of Spectral Properties Of Disordered
    - Highlighting and Note-Taking Spectral Properties Of Disordered
    - Interactive Elements Spectral Properties Of Disordered
8. Staying Engaged with Spectral Properties Of Disordered
    - Joining Online Reading Communities
    - Participating in Virtual Book Clubs
    - Following Authors and Publishers Spectral Properties Of Disordered
9. Balancing eBooks and Physical Books Spectral Properties Of Disordered
    - Benefits of a Digital Library
    - Creating a Diverse Reading Collection Spectral Properties Of Disordered
10. Overcoming Reading Challenges
    - Dealing with Digital Eye Strain
    - Minimizing Distractions
    - Managing Screen Time
11. Cultivating a Reading Routine Spectral Properties Of Disordered
    - Setting Reading Goals Spectral Properties Of Disordered
    - Carving Out Dedicated Reading Time
12. Sourcing Reliable Information of Spectral Properties Of Disordered
    - Fact-Checking eBook Content of Spectral Properties Of Disordered
    - Distinguishing Credible Sources
13. Promoting Lifelong Learning
    - Utilizing eBooks for Skill Development
    - Exploring Educational eBooks

14. Embracing eBook Trends
    - Integration of Multimedia Elements
    - Interactive and Gamified eBooks

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