

# Spectral properties of a disordered insulating lattice under nonlinear electric field

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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-Abraham's expression [33],

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

where  $\xi$  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  $Vg(\epsilon_F)\Delta\epsilon$ , where  $V \sim R^d$  is the volume and  $g(\epsilon_F)$  is the density of states of disordered levels at the Fermi level  $\epsilon_F$ . 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

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

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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# Spectral Properties Of Disordered

**N. Hannay**



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**Spectral Properties of Disordered Chains and Lattices** Syracuse University, 1968      **Spectral properties of disordered chains and lattices** J. Hori, 1968      **Spectral Properties of Disordered Chains and Lattices** Jun'ichi Hori, 1968      **Schrödinger Operators The Quantum Mechanical Many-Body Problem** Erik Balslev, 2005-08-11 In these proceedings basic questions regarding n body Schrödinger operators are dealt with such as asymptotic completeness of systems with long range potentials including Coulomb a new proof of completeness for short range potentials energy asymptotics of large Coulomb systems asymptotic neutrality of polyatomic molecules Other contributions deal with different types of problems such as quantum stability Schrödinger operators on a torus and KAM theory semiclassical theory time delay radiation conditions magnetic Stark resonances random Schrödinger operators and stochastic spectral analysis The volume presents the results in such detail that it could well serve as basic literature for seminar work      **Models of Disorder** J. M. Ziman, 1979-09-06 Originally published in 1979 this book discusses how the physical and chemical properties of disordered systems such as liquids glasses alloys amorphous semiconductors polymer solutions and magnetic materials can be explained by theories based on a variety of mathematical models including random assemblies of hard spheres tetrahedrally bonded networks and lattices of spins The text describes these models and the various mathematical theories by which the observable properties are derived Techniques and concepts such as the mean field and coherent approximations graphical summation percolation scaling and the renormalisation group are explained and applied This book will be of value to anyone with an interest in theoretical and experimental physics      **Disordered Solids** Baldassare Di Bartolo, 2013-03-09 This book presents an account of the course Disordered Solids Structures and Processes held in Erice Italy from June 15 to 29 1987 This meeting was organized by the International School of Atomic and Molecular Spectroscopy of the Ettore Majorana Centre for Scientific Culture The objective of this course was to present the advances in physical modelling mathematical formalism and experimental techniques relevant to the interpretation of the structures of disordered solids and of the physical processes occurring therein Traditional solid state physics treats solids as perfect crystals and takes great advantage of their symmetry by means of such mathematical formalisms as the reciprocal lattice the Brillouin zone and the powerful tools of group theory Even if in reality no solid is a perfect crystal this theoretical approach has been of great usefulness in describing solids deviations from perfect order have been treated as perturbations of the ideal model A new situation arises with truly disordered solids where any vestige of long range order has disappeared The basic problem is that of describing these systems and gaining a scientific understanding of their physical properties without the mathematical formalism of traditional solid state physics While some of the old approaches may occasionally remain valid e.g. chemical bonding approach for amorphous solids the old ways will not do Disorder is not a perturbation with disorder something basically new may be expected to appear      *The Chemical Structure of Solids* N. Hannay, 2012-12-06      Disordered

Pharmaceutical Materials Marc Descamps, 2016-03-28 A one stop resource for researchers developers and post graduate students in pharmaceutical science This handbook and ready reference provides detailed but not overloaded information presenting the topic without unnecessarily complex formalism As such it gives a systematic and coherent overview of disordered materials for pharmaceutical applications covering fundamental aspects as well as preparation and characterization techniques for the target oriented development of drug delivery systems based on disordered crystals and amorphous solids Special attention is paid to examine the different facets and levels of disorder in their structural and dynamic aspects as well as the effect of disorder on dissolution and stability Chapters on processing induced disorder and on patenting issues round off the book As a result the book helps overcoming the challenges of using these materials in the pharmaceutical industry For pharmaceutical and medicinal chemists materials scientists clinical physicists and pharmaceutical laboratories looking to make better and more potent pharmaceuticals Coulomb and Interference Effects in Small Electronic Structures D. C. Glattli, M. Sanquer, J. Thanh Van Tran, 1994 **Dynamical Mean-Field Theory for Strongly Correlated Materials** Volodymyr Turkowski, 2021-04-22 This is the first book that provides a detailed summary of one of the most successful new condensed matter theories dynamical mean field theory DMFT in both static and dynamical cases of systems of different sizes DMFT is one of the most successful approaches to describe the physical properties of systems with strong electron electron correlations such as bulk materials multi layers surfaces 2D materials and nanostructures in both metallic and insulating phases Strongly correlated materials usually include partially filled localized d or f orbitals and DMFT takes into account crucial for these systems time resolved interaction between electrons when they meet on one atom and occupy one of these orbitals The First Part of the book covers the general formalism of DMFT as a many body theory followed by generalizations of the approach on the cases of finite systems and out of equilibrium regime In the last Chapter of the First Part we discuss generalizations of the approach on the case when the non local interactions are taken into account The Second Part of the book covers methodologies of merging DMFT with ab initio static Density Functional Theory DFT and Time Dependent DFT TDDFT approaches Such combined DFT DMFT and DMFT TDDFT computational techniques allow one to include the effects of strong electron electron correlations at the accurate ab initio level These tools can be applied to complex multi atom multi orbital systems currently not accessible to DMFT The book helps broad audiences of students and researchers from the theoretical and computational communities of condensed matter physics material science and chemistry to become familiar with this state of art approach and to use it for reaching a deeper understanding of the properties of strongly correlated systems and for synthesis of new technologically important materials

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