# 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 $\Delta\varepsilon$ depends on the spatial overlap between localized states separated by $R$ as, similar to the Miller-Abraham's expression [33],

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

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 $\Delta\varepsilon$. To achieve this, he proposed a statistical approach where the number of states within a $d$—dimensional sphere of radius $R$ and energy width $\Delta\varepsilon$ is given as $V g(\varepsilon_F)\Delta\varepsilon$, where $V \sim R^d$ is the volume and $g(\varepsilon_F)$ is the density of states of disordered levels at the Fermi level $\varepsilon_F$. 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

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

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

# Spectral Properties Of Disordered

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**Spectral Properties Of Disordered:**

    <u>Spectral Properties of Disordered Chains and Lattices</u> Syracuse University,1968    **Spectral Properties of Disordered Chains and Lattices** Jun'ichi Hori,1968    **Spectral properties of disordered chains and lattices** J. Hori,1968

    <u>Models of Disorder</u> 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    **Investigation of the Spectral Properties of Disordered Alloys and Superconductors** Gary Michael Batt,2008    *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    *Stochastic Aspects of Classical and Quantum Systems* S. Albeverio,P. Combe,M. Sirugue-Collin,2007-01-05    **Schrödinger Operators The Quantum Mechanical Many-Body Problem** Erik Balslev,2005-08-11 In these proceedings basic questions regarding n body Schr dinger 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 withdifferent types of problems such as quantum stability Schr dinger operators on a torus and KAM theory semiclassical theory time delay radiation conditions magnetic Stark resonances random Schr dinger operators and

stochastic spectral analysis The volume presents the results in such detail that it could well serve as basic literature for seminar work     <u>Dynamical Mean-Field Theory for Strongly Correlated Materials</u> 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     **Coulomb and Interference Effects in Small Electronic Structures** D. C. Glattli,M. Sanquer,J. Thanh Van Tran,1994     *Interpolation Theory, Systems Theory and Related Topics* Daniel Alpay,Israel Gohberg,Victor Vinnikov,2012-12-06 This volume is dedicated to Harry Dym a leading expert in operator theory on the occasion of his sixtieth birthday The book opens with an autobiographical sketch a list of publications and a personal account of I Gohberg on his collaboration with Harry Dym The mathematical papers cover Krein space operator theory Schur analysis and interpolation several complex variables and Riemann surfaces matrix theory system theory and differential equations and mathematical physics The book is of interest to a wide audience of pure and applied mathematicians electrical engineers and theoretical physicists     *Interacting Stochastic Systems* Jean-Dominique Deuschel,2005-01-12 The Research Network on Interacting stochastic systems of high complexity set up by the German Research Foundation aimed at exploring and developing connections between research in infinite dimensional stochastic analysis statistical physics spatial population models from mathematical biology complex models of financial markets or of stochastic models interacting with other sciences This book presents a structured collection of papers on the core topics written at the close of the 6 year programme by the research groups who took part in it The structure chosen highlights the interweaving of certain themes and certain

interconnections discovered through the joint work This yields a reference work on results and methods that will be useful to all who work between applied probability and the physical economic and life sciences    *Mesoscopic Physics of Electrons and Photons* Eric Akkermans,Gilles Montambaux,2007-05-28 Quantum mesoscopic physics covers a whole class in interference effects related to the propagation of waves in complex and random media These effects are ubiquitous in physics from the behaviour of electrons in metals and semiconductors to the propagation of electromagnetic waves in suspensions such as colloids and quantum systems like cold atomic gases A solid introduction to quantum mesoscopic physics this book is a modern account of the problem of coherent wave propagation in random media It provides a unified account of the basic theoretical tools and methods highlighting the common aspects of the various optical and electronic phenomena involved and presenting a large number of experimental results With over 200 figures and exercises throughout the book was originally published in 2007 and is ideal for graduate students in physics electrical engineering applied physics acoustics and astrophysics It will also be an interesting reference for researchers    Analysis on Graphs and Its Applications Pavel Exner,2008 This book addresses a new interdisciplinary area emerging on the border between various areas of mathematics physics chemistry nanotechnology and computer science The focus here is on problems and techniques related to graphs quantum graphs and fractals that parallel those from differential equations differential geometry or geometric analysis Also included are such diverse topics as number theory geometric group theory waveguide theory quantum chaos quantum wiresystems carbon nano structures metal insulator transition computer vision and communication networks This volume contains a unique collection of expert reviews on the main directions in analysis on graphs e g on discrete geometric analysis zeta functions on graphs recently emerging connections between the geometric group theory and fractals quantum graphs quantum chaos on graphs modeling waveguide systems and modeling quantum graph systems with waveguides control theory on graphs as well as research articles    The Chemical Structure of Solids N. Hannay,2012-12-06

**Supersymmetry and Trace Formulae** Igor V. Lerner,Jonathan P. Keating,David E. Khmelnitskii,2012-12-06 The motion of a particle in a random potential in two or more dimensions is chaotic and the trajectories in deterministically chaotic systems are effectively random It is therefore no surprise that there are links between the quantum properties of disordered systems and those of simple chaotic systems The question is how deep do the connec tions go And to what extent do the mathematical techniques designed to understand one problem lead to new insights into the other The canonical problem in the theory of disordered mesoscopic systems is that of a particle moving in a random array of scatterers The aim is to calculate the statistical properties of for example the quantum energy levels wavefunctions and conductance fluctuations by averaging over different arrays that is by averaging over an ensemble of different realizations of the random potential In some regimes corresponding to energy scales that are large compared to the mean level spacing this can be done using diagrammatic perturbation theory In others where the discreteness of the quantum spectrum becomes important such an

approach fails A more powerful method devel oped by Efetov involves representing correlation functions in terms of a supersymmetric nonlinear sigma model This applies over a wider range of energy scales covering both the perturbative and non perturbative regimes It was proved using this method that energy level correlations in disordered systems coincide with those of random matrix theory when the dimensionless conductance tends to infinity *Recent Advances in Differential Equations and Mathematical Physics* Nikolai Chernov,2006 Surveys topics in differential equations that are associated with mathematical physics This book includes such topics as asymptotic formulas for the ground state energy of fermionic gas J self adjoint Dirac operators and spectral theory of Schrodinger operators It is suitable for mathematicians and physicists

    *Collective Dynamics of Nonlinear and Disordered Systems* Günter Radons,Wolfram Just,Peter Häussler,2005-01-12 Phase transitions in disordered systems and related dynamical phenomena are a topic of intrinsically high interest in theoretical and experimental physics This book presents a unified view adopting concepts from each of the disjoint fields of disordered systems and nonlinear dynamics Special attention is paid to the glass transition from both experimental and theoretical viewpoints to modern concepts of pattern formation and to the application of the concepts of dynamical systems for understanding equilibrium and nonequilibrium properties of fluids and solids The content is accessible to graduate students but will also be of benefit to specialists since the presentation extends as far as the topics of ongoing research work

    <u>Disordered Pharmaceutical Materials</u> 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 *Seasonal Affective Disorder* Timo Partonen,S. R. Pandi-Perumal,2010 Seasonal affective disorder SAD or winter depression is a mood disorder related to the change in the seasons and lack of exposure to daylight It affects 1 in 100 adults in western countries SAD is a rare example of a psychiatric disorder with a clear identifiable biological cause The new edition of this award winning book brings together distinguished scientists and opinion leaders to discuss the current and anticipated developments in the study and care of Seasonal Affective Disorder Highlighting the clinical diagnosis and management of Seasonal Affective Disorder SAD this book provides a valuable resource for all whom are involved in the health care for patients with SAD This book deals with the

range of therapeutic measures that are available for the treatment of SAD In addition this book elucidates potential areas of research that have emerged such as the study of the circadian pacemaker and the night time sleep structure and their interaction that influences mood

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