Non-Hermitian Anderson Transport

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Abstract: We predict and experimentally verify a novel non-Hermitian transport mechanism in which a stochastic energy exchange with the environment leads to localization of all eigenstates, while simultaneously enabling particles to travel via ultra-far jumps. © 2020 The Author(s)

It was a major breakthrough for the understanding of conductance in solids when Anderson derived that stochastic imperfections in crystalline lattices can result in self-trapping of a single electron via quantum interference. This phenomenon, known as Anderson localization [1], relies on the wave nature of quantum particles, and explains how disorder can turn conductors into insulators. Its discovery sparked decades of lively theoretical and experimental studies [2], such that disorder is nowadays a highly discussed subject. Yet, one major condition is commonly excluded in these considerations: The disorder is given by random changes only in the real part of the potential, hence neglecting any interaction with the environment.

In our work, we illuminate the subject from a different perspective: As every physical system is subject to interaction with its environment, it seems natural to ask whether the concepts of localization and transport hold true within the more general context of open (i.e. non-Hermitian) systems, where disorder is caused by the surrounding environment. To this end, we consider a different type of disorder, which is given by random changes also in the imaginary part of the potential. As such, it corresponds to a stochastic energy exchange with the environment. We discover a novel non-Hermitian transport mechanism in which all eigenmodes are exponentially localized while particles can still move via intriguing spatial jumps. We employ light propagation in large-scale 1D photonic lattices with precisely tuneable dissipation (Fig. 1a) as a model for the evolution of quantum particles in open systems. The ability to adjust the strength of dissipation at will enables us to implement nearly arbitrary complex potentials. The experimental implementation is based on the propagation of classical light in coupled optical fiber loops [3] as shown in Fig. 1b. The model system can be considered as a linear chain of nearest neighbor-coupled sites, and, with its numerous degrees of freedom, represents a simple yet powerful experimental framework. To characterize localization and transport, it is common to study the propagation that arises from a single-site excitation. In solid state physics, the evolution of the probability density of an electron, that initially resides at a specific atom, is described this way. In our photonic analogue, optical waves account for the wave nature of quantum particles and the evolution of an initially localized light excitation is considered. In homogeneous, disorder-free lattices, a single-site excitation yields the well-known ballistic spreading of the wave function. As a result, the quantum particle quickly becomes delocalized and acquires a high probability to be found far away from its initial position, as shown by our experimental data (Fig. 1c left). Now we consider two distinct cases with disorder. In the conventional Hermitian case, disorder is commonly realized by randomly varying on-site energies (i.e. the real part of the potential) [4]. In accordance to previous studies [5], a single-site excitation of the disordered lattice undergoes repeated scattering at the potential fluctuations, leading to a superposition of destructively interfering waves in such a way that previously extended states localize at the initial position (Fig. 1c center). This process is at the heart of Anderson localization: From the perspective of solid-state physics, the electron is trapped and as a result, the initially conducting material turns into an insulator. In contrast, for the non-Hermitian disorder model, the linear chain itself is again perfectly ordered, while the lattice is now coupled to its environment. Disorder comes into play by a stochastic energy exchange, i.e. random changes in the imaginary part of the potential. We experimentally realize the imaginary potential fluctuations by tailoring the dissipation, and find both theoretically and in the experiment, that a single-site excitation localizes due to the non-Hermitian disorder (Fig. 1b right), because all eigenmodes of the system are exponentially localized [6]. However, against all intuition, instead of remaining trapped at the initial position, transverse jumps can be observed. Even more surprising, the distances spanned by these jumps can far exceed the localization length. In other words, despite the fact that only exponentially localized eigenstates are occupied, the quantum particle can nevertheless travel along the chain of sites, and thereby...
still facilitate transport. This “Anderson transport” is driven by disorder in the imaginary part of the potential, and exhibits a striking scaling of the participation number that is identical to the Hermitian Anderson case [6]. From extensive experimental and numerical studies we extract further remarkable features of the Anderson transport, such as an intriguing restoration of ballistic spreading. In addition, we provide a theoretical explanation by giving the analytical solution for a corresponding chain model. Moreover, we show that the Hatano-Nelson model [7] is analytically solvable for non-Hermitian disorder and that the extracted solution covers the key findings of our experiment.

To conclude, we take a barely explored perspective within the study of disordered systems by considering localization and transport in the more general context of open systems where disorder manifests as random changes also in the imaginary part of the potential. Our theoretical and experimental findings reveal the non-Hermitian Anderson transport: The stochastic energy exchange with the environment not only leads to a fully localized eigenmode spectrum as in the Hermitian case, but also drives surprising transport dynamics that are characterized by ultra-far jumps and a restoration of ballistic spreading. Beyond the experimental observation of this “Anderson Transport”, we provide a thorough theoretical explanation. Our findings are not limited to our experimental platform and open up a whole new perspective on localization and transport in open quantum systems or wave systems in general.

Figure 1. Anderson Transport: Model and Experiment. (a) A linear chain of coupled sites (top) is realized with a 1D quantum walk (bottom). While the different arrow widths correspond to different dissipations, different shades of green correspond to different real parts of the potential. (b) Light propagation in the experimental fiber loop arrangement can be mapped onto the lattice in (a). Two unequally long optical fiber loops are connected by a variable beam splitter (VBS), corresponding to the splitter in (a). Acousto-optical modulators (AOM) control the dissipation while a phase modulator (PM) controls the real part of the potential. A photo detector measures the temporal light evolution. (c) The experimental propagation shows the mode jumping of Anderson transport (right) compared to Anderson localization (center) and ballistic spreading (left).

References

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