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Absorption spectra and localization aspects of a one-dimensional model with stretched exponential correlated disorder

Q1   J.L.L. dos Santos, M.O. Sales, F.A.B.F. de Moura *

Instituto de Física, Universidade Federal de Alagoas, Maceió - AL 57072-970, Brazil

HIGHLIGHTS

- Localization and correlated disorder.
- Dependence of the absorption spectrum on the degree of correlations.
- Direct relation between absorption spectrum intensity and the localization length.

ARTICLE INFO

ABSTRACT

In this paper, we numerically analyze the dynamics of a one-electron in a one-dimensional model with stretched exponential correlations in the diagonal disorder distribution. We analyze in detail the effect of this correlated disorder on the localization aspects and the optical absorption. We offer an estimate for the localization properties and its dependence on the intrinsic correlations in the disorder distribution. Our calculations of the optical absorption spectra suggest that as the disorder distribution becomes more correlated the absorption intensity decreases. We explain this behavior in detail by using heuristic arguments.

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1. Introduction

P.W. Anderson and co-workers proved by using scaling theory that extended eigenstates are absent in low-dimensional systems with uncorrelated disorder [1–5]. Since the end of the eighties, it was shown that low-dimensional disordered systems can support extended states or a localization–delocalization transition in the presence of short- or long-range correlations in the disorder distributions [6–30]. From the experimental point of view, V. Bellani et al. [16] and U. Kuhl et al. [19] have studied the effect of short- and long-range correlations on the transport properties of low-dimensional disordered systems. Moreover, it was suggested that an algorithm for generating random correlated sequences with desired mobility edges could be used in the manufacture of filters for electronic or optical signals [13]. Furthermore, the theoretical prediction that it is possible to *see* Anderson localization in a random multilayer filter [31] opened a wide field of investigations of effects of correlated disorder in optical systems.

In the recent years, a key problem in the context of condensed matter physics is to understand what is the effect of correlated disorder on the optical spectroscopy properties [32–42]. Usually, it is well known that optical spectroscopy fails in detecting localization–delocalization transitions. However, in Ref. [35] an anomalous behavior of the absorption

* Corresponding author. Tel.: +55 8299593909.
  E-mail address: fidelis@fis.ufal.br (F.A.B.F. de Moura).

spectrum in a one-dimensional (1d) lattice with long-range correlated diagonal disorder was reported. It was found that long-range correlated diagonal disorder promotes the appearance of an absorption spectrum profile with two peaks [35]. Moreover, it was proposed to use this double-peak absorption spectrum as a spectroscopic tool to monitor the Anderson transition [35]. Furthermore, in Ref. [39] a double-peak absorption spectrum was numerically observed in a 1d lattice with long-range off-diagonal correlated disorder. In Ref. [40], a detailed study of the optical properties in 1d models with heavy-tailed Levy disorder distribution was done. The authors found a broadening of the optical line and a non universal scaling of the distribution of exciton localization lengths. The scaling of the optical absorption bandwidth and the non universality of the localization length within models with Levy disorder distribution were re-visited in Ref. [41]. In general, the study of the dependence of the absorption spectrum on the properties of the disorder distribution give us key information that can be used to study the nature of eigenstates.

In this paper, we report further progress along these above lines. We will study the problem of one-electron localization and optical absorption spectrum in 1d systems with correlated disorder. Our calculations were carried out on open chains with stretched exponential correlations case in the disorder distribution. We perform exact numerical diagonalization to compute the participation number and the optical absorption spectrum. Our formalism provides an estimate for the dependence of the localization length on the type of correlated disorder considered here. In general, the localization length increases as the generalized correlation length is increased; however, we have not found a localization–delocalization transition. Our results for the optical absorption spectra reveal an interesting dependence of the absorption spectrum on the correlated disorder distribution. We observe that as the disorder distribution becomes more correlated the absorption intensity is decreased. We will explain this behavior in detail by using heuristic arguments. We obtain a simple relation between the optical absorption intensity and the localization length around the specific eigenstates with largest oscillator strength. Numerical calculations of the optical absorption and the localization length give support to our heuristic arguments.

2. Model and formalism

We consider the disordered Anderson model defined by the one-electron Hamiltonian [1,2,4,29]

$$H = \sum_{n=1}^{N} \epsilon_n |n\rangle\langle n| + t \sum_{\langle n,m \rangle} |n\rangle\langle m|, \tag{1}$$

where $|n\rangle$ is a Wannier state localized at site n and $\sum_{\langle n,m \rangle}$ represents a sum over nearest-neighbor pairs. Hereafter we will use energy units of $t = 1$. ϵ_n represents the on-site disorder distribution. We will consider open boundary conditions. In our work, we are interested in studying the nature of the eigenstates and the optical absorption spectrum by analyzing the above Hamiltonian in the presence of an on-site disorder distribution with stretched exponential correlations. The on-site potential ϵ_n with stretched exponential correlations will be generated by using the following formalism: initially we will calculate the sequence E_n defined by

$$E_n = \sum_{m=1}^{N} \eta_m * \exp(-|n-m|^{\gamma}/\zeta) \quad n = 1, \dots, N \tag{2}$$

where η_m are independent random numbers uniformly distributed in the interval $[-0.5, 0.5]$ and γ and ζ are tunable parameters that control the degree of correlations. The on-site potential ϵ_n is obtained by using the formula

$$\epsilon_n = [E_n - \langle E_n \rangle]/\sqrt{\langle E_n^2 \rangle - \langle E_n \rangle^2} \quad n = 1, \dots, N. \tag{3}$$

Therefore, the diagonal disorder displays zero mean value ($\langle \epsilon_n \rangle = 0$) and fixed standard deviation ($\sqrt{\langle \epsilon_n^2 \rangle - \langle \epsilon_n \rangle^2} = 1$). Let us discuss now some properties associated with the parameters γ and ζ. We will also discuss the values of γ and ζ that will be considered in our work. We can see that, for a fixed γ, the degree of correlations within the disorder distribution increases as ζ is increased. ζ is a type of generalized correlation length, and it can be used as a way to quantify the degree of correlation within the disorder distribution; however, formally, it is not the correlation length. Only for $\gamma = 1$ the ζ parameter has the status of the standard correlation length. We also emphasize that for $\gamma = 1$ the disorder distribution is exactly the same that was investigated in Ref. [29]. For a fixed value of $\zeta > 0$ and for $\gamma = 0$ there is no disorder at the sequence defined by Eq. (2). Therefore, the rescaling defined in Eq. (3) cannot be used in this case. In our study, we will focus our calculations on the disordered case ($\gamma > 0$). We observe that the internal correlations within the on-site energy distribution decrease substantially at the limit of large γ. From another side, for small γ, the decay of the correlation function becomes slower. Therefore, we will analyze the nature of the electronic eigenstates and the optical response at both limits: the case with weak correlations ($\gamma \gg 1$ and $\zeta \to 0$) and also the case with strong correlations ($0 < \gamma < 1$ and $\zeta \gg 0$). In Fig. 1(a) (left panel) we plot the on-site energy ϵ_n versus n for $N = 10^5$, $\zeta = 10$ and $\gamma = 0.25, 0.5, 0.75$ and 1.25. One can notice how the energy landscape becomes smooth as γ decreases. In order to compare some statistical properties of the above sequences, we compute the auto-correlation function ($C(r) = [1/(N-r)] * \sum_{n=1}^{N-r} \epsilon_n \epsilon_{n+r}$) of the potential landscape (see Fig. 1(b) (right panel)). Circles indicate the numerical calculation of $C(r)$ and the solid line represents