Transferring spin polarization in disordered long-range interacting spin chains

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Regular arrays of interacting qubits or spins are paradigmatic systems for quantum simulations and computations. In any realistic system, the spins interact with each other via a finite range potential, and transferring quantum states or spin polarization requires quantum communication channels that can withstand certain degree of disorder. The main goal of the current project is to transfer spin polarization in a finite, disordered, one-dimensional spin chain with long-range interactions.

The magnetic dipolar interaction we consider falls of as $\propto 1/r^3$ and the Hamiltonian of an N-site chain that describes the dynamics of one spin excitation, is given by the following equation:

$$H_{dd} = \sum_{i=1}^{N} \varepsilon_i c_i^\dagger c_i + \sum_{i=1}^{N} \sum_{j \neq i} \frac{J(1-3\cos^2\theta)}{|\overrightarrow{r}_j - \overrightarrow{r}_i|^3} (c_i^\dagger c_j + c_j^\dagger c_i) \tag{1}$$

where ε_i are the onsite energies, J the coupling strength between nearest-neighbors, $\overrightarrow{r}_i$ the position vector of the i-th site and θ the angle between the quantization axis and the position vector.

The most common approach towards introducing static disorder on this system is to assign random values either on the onsite energies ε_i (diagonal disorder) or on the coefficient of the second term of Eq. 1 (off-diagonal disorder). For the case of diagonal disorder, we do this in the following way: $\varepsilon_i = \varepsilon_i(1+\sigma_\varepsilon \delta\varepsilon_i)$ corresponds to the strength of the disorder and $\delta\varepsilon_i$ to independent random variables taken from a gaussian distribution with mean $\mu = 0$ and standard deviation $\sigma = 1$. For the case of off-diagonal disorder, we consider the spin chain's sites to be positioned on the $x-y$ plane, thus our system is quasi one-dimensional. Therefore, imposing gaussian noise on the x and y coordinates of each site, we effectively induce off-diagonal disorder on our system. Depending on whether the randomness is diagonal or off-diagonal, the system behaves differently in terms of the localization properties of its' eigenstates, therefore we review the two cases separately. Furthermore, for the case of the off-diagonal disorder, we also consider how the effective degree of off-diagonal disorder changes when we change the quantization axis orientation and therefore change the θ angle on the second term of Eq. 1.

In general, it is known that diagonal or off-diagonal disorder induce the localization of the chain's eigenstates and therefore the transfer probability gets degraded.

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We investigate when, to which extent and how we can circumvent the aforementioned undesirable degradation. To this end, we employ numerical methods in order to track down the system's extended eigenstates and suitably exploit them. More specifically, we consider the following situation: We assume that we have complete control (onsite energies and couplings) over two sites which will be referred to as sender and receiver. Initially, the spin excitation is localized on the sender site which is disconnected from the spin chain. The receiver on the other hand, is connected to the last site of the chain. If the system has some eigenstates that remain extended in the presence of disorder, we can tune the onsite energies of the sender and receiver to be resonant with the extended state's energy. Then, if we slowly turn on the coupling between the sender and the first site of the spin chain, while at the same time turn off the coupling between the receiver and the last site, we want to examine whether we can efficiently transfer the polarized spin excitation from the sender to the receiver "through" the extended state.

Our work addresses the following research questions, given a particular type and strength of disorder: What are the characteristics of the "good" extended eigenstates and in which cases they are not particularly useful for transfer? How does the transfer time scales as the system size is increased and how long is best to wait? What is the maximum length of the chain that we can use to achieve a given mean transfer probability?