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Probing many-body localization through the decay of a single photon

Down-conversion of a single photon as a probe of many-body localization
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Recommended with a Commentary by Steven M. Girvin, Yale University

Many-body systems can localize in Hilbert space [1–3] in a manner somewhat analogous to Anderson localization of a single electron (or gas of non-interacting electrons) in a disordered solid. Anderson localization can be defeated by decoherence associated with coupling to an external environment. Many-body localization (MBL) is extremely sensitive to such external coupling, making experimental observation challenging. Indeed, one can think of the MB localized phase as one in which the bulk of the medium which surrounds a given local region (self-consistently) fails to act as an equilibration bath for that local region, even when the energy of the system is well above the ground state. The analysis of this self-consistency is complicated by many-body resonances and avalanche instabilities [4]. Breakdown of ergodicity requires strong isolation of the entire system from the external environment, which raises experimental challenges.

The experiment of Mehta et al. gives a beautiful illustration of the essential concepts of MBL even though the initial state of the system consists of only a single microwave photon (with frequency in the GHz range) stored in a superconducting resonator. Just as in ordinary optics, one can detect the resonances of such a system by bouncing photons off it and detecting the rapid change in the phase shift as the frequency passes through each resonance. This however is not an ordinary linear resonator. One of the mirrors is actually a fluxonium qubit whose non-linearity (three-wave mixing) allows a single high-energy microwave photon at frequency ω_a to be down-converted into two photons whose energies obey $\omega_b + \omega_c = \omega_a$. Each generation of these 'daughter' photons can themselves down convert potentially leading to a divergent cascade.

The authors draw an analogy between this situation and the decay of a single electron above a Fermi sea in a quantum dot producing a cascade of particle-hole pairs due to the electron-electron interaction [5]. The random single-particle level spacing in the disordered dot can frustrate this process. Indeed, MBL is a competition between the closeness in energy of different many-body states and their distance in Hilbert space (which determines the matrix elements connecting them).

To properly understand the many-body cascade in the decay of a single microwave photon, we need to take into consideration the discreteness of the resonator spectrum. The free spectral range (FSR = level spacing) of this Fabry-Perot like resonator is less than 200 MHz, much smaller than one might initially guess given its length of only 6 mm. The resonator is a short length of transmission line comprised of a dense array of Josephson junctions whose large effective inductance (per unit length) reduces the speed of light (and thus the FSR) by two orders of magnitude. Naively the allowed mode frequencies are integer multiples of the fundamental, guaranteeing energy conservation for the production of the daughter photons if the sum of their mode indices matches the mode index of the parent photon. That is, a single photon in mode $k \gg 1$ would be degenerate with the energy of a pair of photons in modes m and $k - m$. The number of such degenerate states, $D = k - 1$, is large. More generally, a single photon in mode $k \gg 1$ would be degenerate with $D \sim k^{m-1}$ different states, each having m photons distributed appropriately over lower modes.

However, the massive degeneracy predicted by this simple picture does not take into account three facts. First, the lattice of Josephson junctions gives the transmission line dispersion. Second, one end of the resonator is terminated by a capacitance which causes the effective electrical length of the resonator to vary systematically with frequency. Finally, the other end of the resonator is terminated by a fluxonimum qubit which provides the three-wave mixing non-linearity but also contributes a linear response (similar to the capacitor at the other end of the resonator) that causes further dispersion. The strength of the non-linear coupling is very large–comparable to the FSR–further complicating the many-body spectrum (by generating the photon down-conversion cascade). All of these effects combine to yield pseudo-random disorder to the energy levels. Thus while the many-body states are not precisely degenerate, they are much denser in frequency and far more numerous than one might have first thought, given the large FSR of the harmonic part of the Hamiltonian.

By illuminating the resonator with a weak continuous microwave drive the authors are able to see a dense array of discrete many-body 'tunneling resonances' as a photon from the outside attempts to tunnel through the resonator mirror into one of the many-body eigenstates of the resonator. This appears to be the first experimental observation of this characteristic feature of MBL systems and was made possible by the low dissipation and strong photon-photon interactions available in circuit QED [6, 7] systems.

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