Circuit-QED based spectroscopies of quantum impurities

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Quantum impurity problems describe a localized quantum system with a few degrees of freedom (the impurity), that is non-perturbatively coupled to a large system (the bath). These impurities can exist in many different forms in solid-state materials and nanostructures, such as charged [1] or magnetic impurities [2], while the bath is typically constituted by a Fermi sea. However, understanding the quantum dynamics and the entanglement properties of these many-body electronic systems remains a tremendous challenge, both experimentally and theoretically. The main underlying reason to this complexity lies in the presence of entanglement between the impurity and many modes of the bath that extend on a wide energy range, which prevents a brute force diagonalization of the full problem. In addition, in metallic devices such as artificial quantum dots, it has proved difficult experimentally to resolve or address electronic bath modes individually, due to internal losses of metallic islands. I will present a unique architecture based on superconducting circuits to tackle this challenging problem. It offers two main advantages: first, it allows to reach the multi-mode ultra-strong coupling regime allowing to build a strong hybridization between the quantum system and its bath; second, high quality factors of superconducting circuits enable to monitor spectroscopically the qubit and its bath at the same time. Our approach consists in coupling a superconducting artificial atom (namely a transmon qubit) to a meta-material made of thousands of SQUIDs [3,4,5]. The latter sustains many photonic modes and shows characteristic impedance close to the quantum of resistance. We succeeded in performing the full spectroscopy of the impurity plus bath system, which revealed strong hybridization of the transmon qubit with as many as ten modes of the bath. In this coupling regime, the common techniques used in circuit-QED (rotating wave approximation, exact diagonalization...) break down. To describe quantitatively our experimental data, we had to borrow a tool usually reserved to strongly interacting systems: the Self-Consistent Harmonic Approximation [6]. In the future, we plan to use this circuit to perform non-linear quantum optics experiments with a many-body system [4,7].

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