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Ultrastrong Light-Matter Coupling in Circuit QED

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Abstract:

In circuit quantum electrodynamics (QED) effective light-matter interactions can be studied in terms of superconducting two-level systems (``artificial atoms'') coupled to microwave resonators. Compared to regular cavity QED systems with atoms and optical photons, the achievable coupling strengths in such artificial systems can be enhanced by many orders of magnitude and even exceed the bare energies of the photons and atoms. In this so-called ultra-strong coupling (USC) regime the simple physics of the Jaynes-Cummings model is no longer valid and new exotic phenomena emerge.

This thesis addresses the physics of circuit and cavity QED systems beyond the standard description based on the Dicke model. First of all, a rigorous derivation of the effective circuit QED Hamiltonian is presented, which shows that the Dicke model is no longer valid in the USC regime of circuit QED. Instead, a new model, the Extended Dicke model (EDM), is identified as a physically consistent description. In the remainder of the thesis, the physics of the EDM is studied, first in the case of non-interacting qubits. From this analysis a new ground state phase, the subradiant phase, is found, where the qubits decouple from the photons, but at the same time they are strongly entangled with each other. In a next step the cases of repulsively and attractively interacting qubits are discussed. From this analysis it can be shown that the origin of the usual superradiant phase transition is related to the presence of attractive qubit-qubit interactions and not to the presence of a cavity mode, as commonly understood. In the successive parts of the thesis also the excited states of the EDM are discussed, in particular in the low-photon-frequency regime. In this limit the photons behave as effective particles moving in a potential landscape determined by the coupling to the qubits. Several symmetry-breaking transition in the qubit excited states are found and ways to probe them are discussed. Finally, as an application of these new USC effects a scheme to extract entanglement from the subradiant vacuum and a quantum simulation scheme of the EDM with trapped ions are proposed and analyzed.