Light-matter Interaction in the Ultra-strong Coupling

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Ultrastrong coupling between light and matter has, in the past decade, transitioned from a theoretical idea to experimental reality. It is a new regime of quantum light-matter interaction, which goes beyond weak and strong coupling to make the coupling strength comparable to the transition frequencies in the system [1]. I review the theory of quantum systems with ultrastrong coupling, discussing entangled ground states with virtual excitations and new avenues for quantum nonlinear optics [2,3]. I also briefly overview the multitude of experimental setups, including superconducting circuits, organic molecules, semiconductor polaritons, and optomechanical systems, that have now achieved this extreme regime of interaction.
This regime offers an unprecedented possibility to investigate, subtle, although, relevant quantum aspects of light-matter interaction. Recently, it has been shown that the quantum Rabi model, describing the dipolar coupling between a two-level atom and a quantized electromagnetic field, violates the gauge principle [4,5]. Very recently, we identified the origin of these gauge ambiguities and showed that a careful application of the gauge principle is able to restore gauge invariance even for extreme light-matter interaction regimes [6]. Finally, I will briefly describe some recent results on optomechanical systems with ultra-high-frequency oscillators approaching the ultrastrong optomechanical interaction regime [7-9].

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