Gauge principle and gauge invariance issues in the ultrastrong coupling regime

Omar Di Stefano

Università di Messina, Viale F. Stagno D'alcontres, Messina, Italy

The interaction between quantized electromagnetic fields in cavities and natural or artificial atoms has played a crucial role in developing our understanding of light-matter interactions and quantum technologies. New regimes for light-matter coupling of cavity-QED have been explored in several settings, wherein the light-matter coupling rate becomes comparable to (ultrastrong coupling) or even exceeds (deep-strong coupling) the photon frequency. These coupling regimes can give rise to new physical effects and applications, and they challenge our understanding of cavity QED. Fundamental issues like the proper definition of subsystems, their quantum measurements, the structure of light-matter ground states, and the analysis of time-dependent interactions are subject to gauge ambiguities that can lead to even qualitatively distinct predictions. The resolution of these ambiguities is important for understanding and designing next-generation quantum devices that can operate in extreme coupling regimes. In the last few years, solutions to these ambiguities with different procedures and approaches have been presented [1, 2, 3]. In particular it is possible to obtain a modified quantum Rabi model able to provide gauge-invariant physical results (e.g., energy levels, expectation values of observables, quantum probabilities) in any interaction regime. Moreover, it can be shown that this model is analogous on that obtained with the implementation in two-state systems of the gauge principle (the guiding principle in quantum field theory) [2]. Following this approach it is possible to investigate and solve several physical effects that present gauge issues and provide solutions to such a problem. Finally, I will present a theory of pure dephasing in cavity-QED systems which provides correct and gauge-invariant results at any light-matter coupling strength.

[1] O. Di Stefano, A. Settineri, V. Macr'ı, L. Garziano, R. Stassi, S. Savasta, and F. Nori, Nat. Phys. 15, 803 (2019).

[2] S. Savasta, O. Di Stefano, A. Settineri, D. Zueco, S. Hughes, and F. Nori, Phys. Rev. A 103, 053703 (2021).

[3] A. Settineri, O. Di Stefano, D. Zueco, S. Hughes, S. Savasta, and F. Nori, Phys. Rev. Research 3, 023079 (2021).