Study sheds light on gauge invariance in ultrastrong-coupling cavity quantum electrodynamics

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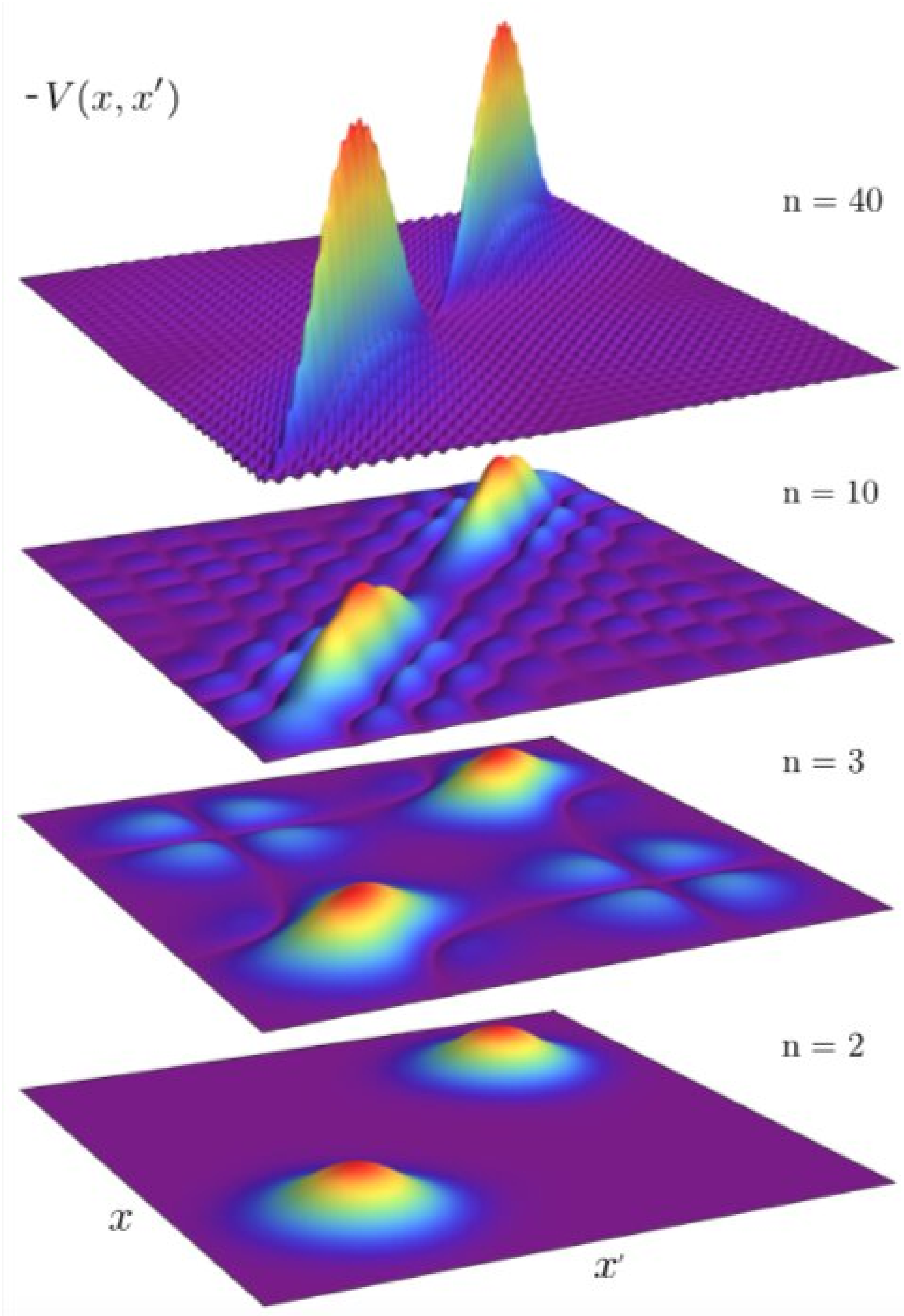

Credit: Di Stefano et al.

In quantum electrodynamics, the choice of gauge (i.e. specific mathematical formalism used to regulate degrees of freedom) can greatly influence the form of light-matter interactions. Interestingly, however, the "gauge invariance" principle implies that all physical results should be independent from a researcher's choice of gauge. The quantum Rabi model, which is often used to describe light-matter interactions in cavity-QED, has been found to violate this principle in the presence of ultrastrong light-matter coupling, and past studies have attributed this failure to the finite-level truncation of the matter system.

A team of researchers at RIKEN (Japan), Università di Messina (Italy) and the University of Michigan (U.S.) have recently carried out a study investigating this topic further. In their paper, published in *Nature Physics*, they identified the source of this gauge violation and provided a method to derive light-matter Hamiltonians in truncated Hilbert spaces, which can produce gauge-invariant physical results even in extreme light-matter interaction regimes.

"Ultrastrong coupling between light and matter has, in the past decade, transitioned from a theoretical idea to an experimental reality," Salvatore Savasta, one of the researchers who carried out the study, told Phys.org. "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. These regimes, besides enabling intriguing new physical effects, as well as many potential applications, represents an opportunity to deepen our understanding subtle aspects of the interaction of light and matter."

During an event organized by Prof. Franco Nori, who was also involved in the study, the rest of the team learned about the existence of two manuscripts that indicated a breakdown of gauge invariance of the quantum Rabi model. This breakdown occurred when considering the interaction between a two-level system and a single-mode electromagnetic resonator in the presence of a strong atom-field interaction.

"Since there is a fast-increasing interest in the ultrastrong-coupling regime of cavity QED and since gauge symmetry is the cornerstone of modern physics, we considered this situation to be very unsatisfying," Savasta said. "These gauge ambiguities determine a partial lack of predictability of key models in cavity QED, which is a central field in quantum optics and quantum technologies."

When the authors started discussing these problems, Savasta suddenly remembered one of his first research papers, as well as an older study carried out by his thesis supervisor Raffaello Girlanda in collaboration with Antonio Quattropani and Paolo Schwendimann . In this particular paper, the researchers showed that, in order to preserve the gauge invariance of multi-photon transition rates in solids, a corrective term needs to be added to the standard electron-photon interactions.

"We started applying these ideas to our goal, which was to derive a quantum description of light-matter interaction for arbitrary interactions strengths which would be free from gauge ambiguities, despite the unavoidable approximation which are usually introduced to manage calculations," Savasta said.

In physics, the "gauge principle" states that to each momentum component in the Hamiltonian of a matter system one needs to add the corresponding component of the field coordinate. This procedure is referred to as "minimal coupling replacement."

Savasta and his colleagues based their work on observations gathered by previous studies, which showed that approximations in the description of the matter system can transform the atomic local potential into a nonlocal one, which can be expressed as quantum operators depending on both its position and momentum. In this case, to satisfy the gauge principle, minimal coupling replacement needs to be applied to the potential as well.

"We used an operator technique, previously developed by one of the authors , which is able to work properly even if the actual nonlocal potential of the matter system is unknown," Savasta explained.

"Until now, the influence of nonlocal potentials on the interaction has been considered only up to the second order in the vector potential. We found that when the matter system is highly nonlinear and when the coupling strength is very high all orders have to be included."

The study carried out by Savasta and his colleagues offers very important insight for the field of quantum electrodynamics. Firstly and most importantly, their work shows that there is a simple way to attain a gauge-invariant description of light-matter interaction that remains valid despite approximations and with extreme interaction strengths.

"Our results shed light on gauge invariance in the non-perturbative and extreme-interaction regimes, as well as solving long-lasting controversies arising from gauge ambiguities in the quantum Rabi and Dicke models (an extension of the quantum Rabi model for many quantum emitters)," Savasta said. "In so doing, they allow a precise and unambiguous theoretical prediction/description of experimental results in ultrastong cavity QED."

The findings gathered by this team of researchers deepen the current understanding of subtle yet relevant quantum aspects of the interaction between light and matter. They might also help to solve ongoing controversies and debates arising from past observations of gauge ambiguities in the quantum Rabi and Dicke models. In the future, the extreme regimes that their study focused on could give rise to new physical effects and applications, while also challenging researchers' current knowledge of cavity-QED.

"When the interaction strength is so high, fundamental issues like the proper definition of subsystems and of their quantum measurements, the structure of hybrid light-matter ground states, or the analysis of time-dependent interactions are subject to ambiguities leading to even qualitative distinct predictions," Savasta said. "These problems offer an unprecedented chance to further deepen our understanding of quantum aspects of the interaction between light and matter. We are now actively working to solve these problems."

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