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The ABC of cQED

The combination of microwave photons with superconducting quantum circuits offers promise for quantum technologies and the fundamental study of quantum light–matter interactions. This month, a Focus issue explores this field of research.

The history of quantum mechanics is full of compelling stories. But it's often easy to fall into the trap of reducing more than a century of research down to a few clichés — usually centred on the scientific adventures of its pioneers.

We would do well to remember that for the generation of Einstein or Bohr, the idea of manipulating individual atoms (or anything that we'd call a qubit today) was closer to science fiction. Modern quantum technologies are precisely enabled by the ability to engineer devices that harness quantum effects at the level of individual qubits. But we often overlook the work that was required to take quantum physics from the blackboards of the 1920s to the future of quantum computing, a topic that even made it onto the agenda of the World Economic Forum in Davos last month.

Our current capability of handling individual quantum systems is the result of decades of research conducted in the second half of the twentieth century. Access to quantum effects requires well-isolated quantum systems that interact with their surroundings in a controllable manner. Only then can one use the state of the quantum system to encode information or for tasks such as sensing.

Historically, the first focus was on the most 'natural' qubits — atoms and photons. Indeed, it was in light–matter interactions between single atoms and photons in optical cavities, a research field known as cavity quantum electrodynamics (QED), that physicists saw the earliest and most vivid examples of quantum effects at the level of single quanta.

But qubits need not be limited to natural systems — in principle anything that behaves as a two-level quantum system, an artificial atom, will do. Superconducting circuits based on Josephson junctions are arguably the most popular artificial qubit at present, their success further increased by recent milestones on the road to quantum computing.

Just like atoms, superconducting qubits interact at the single quantum level with (microwave) photons. Such light–matter interaction at the circuit level is showing great promise, both as an instance for the study of fundamental quantum physics and with applications in mind. This month, we showcase this research field with a Focus issue on circuit QED — often referred to simply as cQED. This research field is also a shining example of the extent to which fundamental and applied quantum research have empowered each other in recent decades. At its origin, in fact, lies an instructive tale.

As they recount in a Comment in this issue, when John M. Martinis, Michel Devoret and John Clarke first showed the quantum behaviour of a Josephson junction circuit in 1985, their goal had originally been to probe a fundamental question: whether macroscopic degrees of freedom would obey quantum mechanics. It's an emblematic story that starts with the search for an answer to a decades-old question in physics and ends, for now, with newspapers celebrating quantum computing achievements at Google.

By the time physicists obtained sufficiently well-controlled access to the quantum states of superconducting circuits, cavity QED and light–matter interactions with atoms had already been under study for decades. Circuit QED, as the name suggests, built upon cavity QED results, and these two research fields have been complementary ever since. A historical Perspective on how such different platforms provide a window on the very same physics is provided by Serge Haroche and colleagues in this issue.

Looking at the present, our issue also includes three reviews on the current state of the art of circuit QED. They highlight the breadth of the research in this field, and anticipate future exciting developments into applied as well as fundamental areas of physics.

The Review Article by Alexandre Blais and colleagues also in this issue captures the heterogeneity of the research interests in the field. Their Review starts from the fundamental creation and manipulation of quantum states in circuit QED for the study of quantum information processing and quantum optics, and then goes on to discuss approaches for quantum error correction and scalable quantum computing architectures.

At its heart, circuit QED deals with a so-called hybrid quantum system: light and matter lose their individual identity and combine into something new. But it turns out that superconducting circuits and microwave resonators can further be efficiently interfaced with a wealth of other systems, for example mechanical resonators or spin ensembles. The possibilities offered by hybrid quantum systems based on circuit QED are the basis of a Review Article by Aashish Clerk and colleagues published in this issue.

Although circuit QED has been traditionally concerned with light–matter interactions at the level of a few quanta, steady improvements are opening a door onto many-body physics. Superconducting qubits become the means by which microwave photons can be made to interact with each other and simulate the physics of matter with light. Iacopo Carusotto and colleagues explain this recent idea and its first experimental realizations, as well as discuss what kind of many-body physics can be explored through circuit engineering, in another Review Article in this issue.

The prospect of a technology based on individual quantum systems must have looked very distant to the physicists of the 1920s. The fundamental study of quantum light–matter interactions has now made it a reality. The appetite for quantum technologies is likely to result in better qubits and experimental setups, which will hopefully in turn help physicists in their fundamental inquiries. ❐

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