Scientific background for the 2021 Micius Quantum Prize: A brief history of superconducting quantum circuits leading to practical superconducting qubits

The field of quantum computation is making important strides, recently culminating in the demonstrations of certain computational tasks [1-3] that appear difficult even for state-of-the-art supercomputers. The corresponding advances in qubits and quantum operations involve quantum Josephson superconducting circuits, the development of which began four decades ago.

At the beginning of the 1980's, Leggett [4] proposed experiments to test whether or not macroscopic collective variables could behave quantum mechanically. He was questioning the traditional Copenhagen interpretation, according to which the world is divided into microscopic systems obeying quantum mechanics and macroscopic systems—including measurement apparatus—that behave classically. In particular, he understood that the macroscopic collective variable represented by the phase difference across a Josephson tunnel junction, essentially the integral of the voltage across it, could be sufficiently frictionless to lend itself to tests of the validity of quantum mechanics at the macroscopic level. En route to establishing the existence of two coherent macroscopic states an important intermediate step pointed out by Leggett was the existence of Macroscopic Quantum Tunneling (MQT), in which a collective macroscopic variable tunnels through a potential barrier.

In 1980, at Berkeley, Koch, Van Harlingen and Clarke showed theoretically that the white noise of a resistively shunted Josephson junction is limited by quantum fluctuations of the current through the shunt resistor [5], a macroscopic collective electrical variable [4] that is treated quantum mechanically, following the ideas of Leggett.

Subsequently, in 1984 again at Berkeley, Devoret, Martinis, Esteve and Clarke [6] invented the concept of resonant activation in the current-biased Josephson junction that enables one to measure *in-situ* the plasma frequency and damping of the zero-voltage state in the classical regime. This technique allowed one, for the first time, to compare experimental results of MQT with the Caldeira-Leggett theory with no fitted parameters and thus to eliminate possible artefacts.

In the following year, Martinis, Devoret and Clarke demonstrated the quantization of energy levels in the current-biased Josephson junction [7]. Later that year, Devoret, Martinis and Clarke [8] demonstrated that MQT obeys Leggett's theory with all relevant parameters measured *in situ* in the classical limit.

In 1997, Devoret's team (including Esteve) in Saclay realized the Cooper pair box [9], which became known later as the charge qubit, and showed its ground state was a quantum superposition of charge states [10]. They pointed out that this circuit constituted a superconducting qubit. Meanwhile, at NEC, Nakamura, Chen, and Tsai observed energy-level anti-crossing of the superconducting single electron transistor in microwave spectroscopy as evidence of the superposition of charge states [11]. A year later, Nakamura, Pashkin and Tsai, again at NEC, demonstrated Rabi oscillations between the ground and excited states of the Cooper pair box using the Cooper pair-quasiparticle cycle [12]. This experiment woke up the condensed matter physics world to the possibility of superconducting qubits with controllable dynamics.

In 2002, Devoret's group demonstrated Ramsey fringes in the quantronium qubit, as well as Rabi oscillations [13], by increasing the coherence time of the Cooper pair box by two orders of magnitude. In quantum information language, this achievement completed the full single-qubit control over the Bloch sphere.

The family of the superconducting qubits continues to expand, and in addition to the charge qubit [10, 11] and the quantronium [13] now includes the flux qubit [14], the phase qubit [15], the transmon [16] and the fluxonium [17]. In the past two and a half decades, the coherence time of superconducting qubits has been increased by as much as six orders of magnitude, making them an attractive candidate for implementation of large-scale quantum computation. The most frequently used design of the current superconducting devices is based on transmon qubits and circuit quantum electrodynamics [18, 19, 20] which were developed by Schoelkopf, Girvin, Devoret and their colleagues at Yale. Recently, expanding this Yale work, Martinis and his team at Google and the University of California, Santa Barbara made remarkable engineering progress in scaling up superconducting quantum devices. In 2019 they created a 53-qubit chip, nicknamed “Sycamore”, for the study of random circuit sampling [1].

The pioneering research led by Clarke, Devoret and Nakamura laid the foundations of the rich and rapidly evolving field of superconducting quantum circuits— artificial atoms probed by electrical wire connections—for quantum information processing. In recognition of this work, the selection committee has awarded them the 2021 Micius Quantum Prize.

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