Loophole-free Bell inequality violation with superconducting circuits

Anatoly Kulikov[1]
Simon Storz[1], Josua Schär[1], Paul Magnard[1], Philipp Kurpiers[1], Janis Lütolf[1], Theo Walter[1], Adrian Copetudo[1], Kevin Reuer[1], Abdulkadir Akin[1], Jean-Claude Besse[1], Mihai Gabureac[1], Graham J. Norris[1], Andres Rosario[1], Ferran Martin[2], José Martinez[2], Waldimar Amaya[2], Morgan W. Mitchell[3,4], Carlos Abellan[2], Jean-Daniel Bancal[5], Nicolas Sangouard[5], Baptiste Royer[6,7], Alexandre Blais[7,8], Andreas Wallraff[1,9]

[1]*Department of Physics, ETH Zurich, 8093 Zurich, Switzerland;* [2]*Quside Technologies, 08860 Castelldefels (Barcelona), Spain;* [3]*ICFO, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain;* [4]*ICREA, 08015 Barcelona, Spain;* [5]*Université Paris-Saclay, CEA, CNRS, Institut de Physique Théorique, 91191 Gif-sur-Yvette, France;* [6]*Department of Physics, Yale University, New Haven, CT 06520, USA;* [7]*Institut Quantique and Département de Physique, Université de Sherbrooke, Sherbrooke, Québec J1K 2R1, Canada;* [8]*Canadian Institute for Advanced Research, Toronto, Ontario M5G 1Z8, Canada;* [9]*Quantum Center, ETH Zurich, 8093 Zurich, Switzerland*
akulikov@phys.ethz.ch

One of the ultimate manifestations of the properties of nature as described by the laws of quantum physics is that measurements performed on entangled pairs of quantum systems can be shown to violate Bell's inequality[1,2], questioning and clashing with the principle of local realism[3]. This remarkable feature of quantum physics was first explored in seminal experiments performed with photons emitted in atomic cascade decay experiments[4,5]. Only several decades later, Bell tests with photons and nitrogen-vacancy centers have unequivocally experimentally confirmed -- in a manner free of additional assumptions called loopholes[6] -- that non-local quantum correlations cannot be described by any local realistic classical theories[7,8,9]. Here, we demonstrate a loophole-free violation of Bell's inequality with superconducting circuits. Performing such an experiment is particularly challenging due to the need of deterministically entangling qubits housed in distant cryogenic systems[10] and performing fast and high-fidelity measurements along randomly chosen bases. We address these challenges by assembling a unique 30-m-long cryogenic setup extending a prior 5-m-long one[11] and combining several state-of-the-art techniques. It allows performing a Bell test with a collective, macroscopic quantum degree of freedom using microwave frequency photons. We obtain an S-value[2] of $S_{CHSH} = 2.075$ and statistical significance (p-value) of $p = 10^{-108}$, thus violating the inequality with high certainty. Our experiment adds the resource of non-locality to the circuit QED platform, which was unavailable so far, and enables the implementation of device-independent quantum information processing algorithms.

References

[1] J. S. Bell, Physics (N. Y.), 1:195, 1964
[2] J. F. Clauser et al, Phys. Rev. Lett., 23(15):880–884, Oct 1969
[3] A. Einstein, B. Podolsky, and N. Rosen, Phys. Rev., 47(10):777–780, May 1935
[4] S. J. Freedman and J. F. Clauser, Phys. Rev. Lett., 28:938–941, Apr 1972.
[5] A. Aspect et al, Phys. Rev. Lett., 49:91–94, Jul 1982 and 49(25) 1804–1807, Dec 1982.
[6] N. Brunner et al, Rev. Mod. Phys., 86:419–478, Apr 2014
[7] B. Hensen et al, Nature, 526:682–686, Oct 2015
[8] M. Giustina et al, Phys. Rev. Lett. 115, 250401, Dec 2015
[9] W. Rosenfeld et al, Phys. Rev. Lett. 119, 010402, Jul 2017
[10] P. Kurpiers et al, Nature, 558:264–267, 2018
[11] P. Magnard et al, Phys. Rev. Lett., 125:260502, Dec 2020