Theoretical prediction and subsequent observation of the dynamical Casimir effect in a superconducting circuit.

Franco Nori
RIKEN, Saitama, Japan; and the University of Michigan, Ann Arbor, USA

We theoretically investigated [1-5] the dynamical Casimir effect (DCE) in electrical circuits based on superconducting microfabricated waveguides with tunable boundary conditions. We proposed implementing a rapid modulation of the boundary conditions by tuning the applied magnetic flux through superconducting quantum-interference devices that are embedded in the waveguide circuits. We considered two circuits: (i) An open waveguide circuit that corresponds to a single mirror in free space, and (ii) a resonator coupled to a microfabricated waveguide, which corresponds to a single-sided cavity in free space. We analyzed the properties of the DCE in these two setups by calculating the generated photon-flux densities, output-field correlation functions, and the quadrature squeezing spectra. We showed that these properties of the output field exhibit signatures unique to the radiation due to the DCE, and could, therefore, be used for distinguishing the DCE from other types of radiation in these circuits. We also discussed the similarities and differences between the DCE, in the resonator setup, and the down-conversion of pump photons in parametric oscillators.

We observed [2] the dynamical Casimir effect in a superconducting circuit consisting of a coplanar transmission line with a tunable electrical length. The rate of change of the electrical length can be made very fast (a substantial fraction of the speed of light) by modulating the inductance of a superconducting quantum interference device at high frequencies (>10 gigahertz). In addition to observing the creation of real photons, we detected two-mode squeezing in the emitted radiation, which is a signature of the quantum character of the generation process.

1. J.R. Johansson, G. Johansson, C.M. Wilson, F. Nori, *Dynamical Casimir effect in a superconducting coplanar waveguide,* Phys. Rev. Lett. **103**, 147003 (2009). [PDF][Link][arXiv]. *Featured in Physics, Editors' Suggestion*

2. J.R. Johansson, G. Johansson, C.M. Wilson, F. Nori, *Dynamical Casimir effect in superconducting microwave circuits,* Phys. Rev. A **82**, 052509 (2010). [PDF][Link][arXiv]

3. C.M. Wilson, G. Johansson, A. Pourkabirian, J.R. Johansson, T. Duty, F. Nori, P. Delsing, *Observation of the dynamical Casimir effect in a superconducting circuit,* Nature **479**, 376-379 (2011). [PDF][Link][arXiv]. The supplementary material is here [PDF][Link]. Featured in a Nature "News & Views" [PDF][Link]. Physics World top five Physics breakthroughs of the year 2011 [PDF][Link]. According to Nature, coverage of our work on Nature News was "The most read news story of 2011". [PDF][Link]

4. P.D. Nation, J. Johansson, M. Blencowe, F. Nori, *Stimulating uncertainty: Amplifying the quantum vacuum with superconducting circuits,* Rev. Mod. Phys. **84**, 1-24 (2012). [PDF][Link].

5. J.R. Johansson, G. Johansson, C.M. Wilson, P. Delsing, F. Nori, *Nonclassical microwave radiation from the dynamical Casimir effect,* Phys. Rev. A **87**, 043804 (2013). [PDF][Link][arXiv].

PDF files of our publications are available via this link: *https://dml.riken.jp/pub/*