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Ex nihilo: Dynamical Casimir effect in metamaterial converts vacuum fluctuations into real photons

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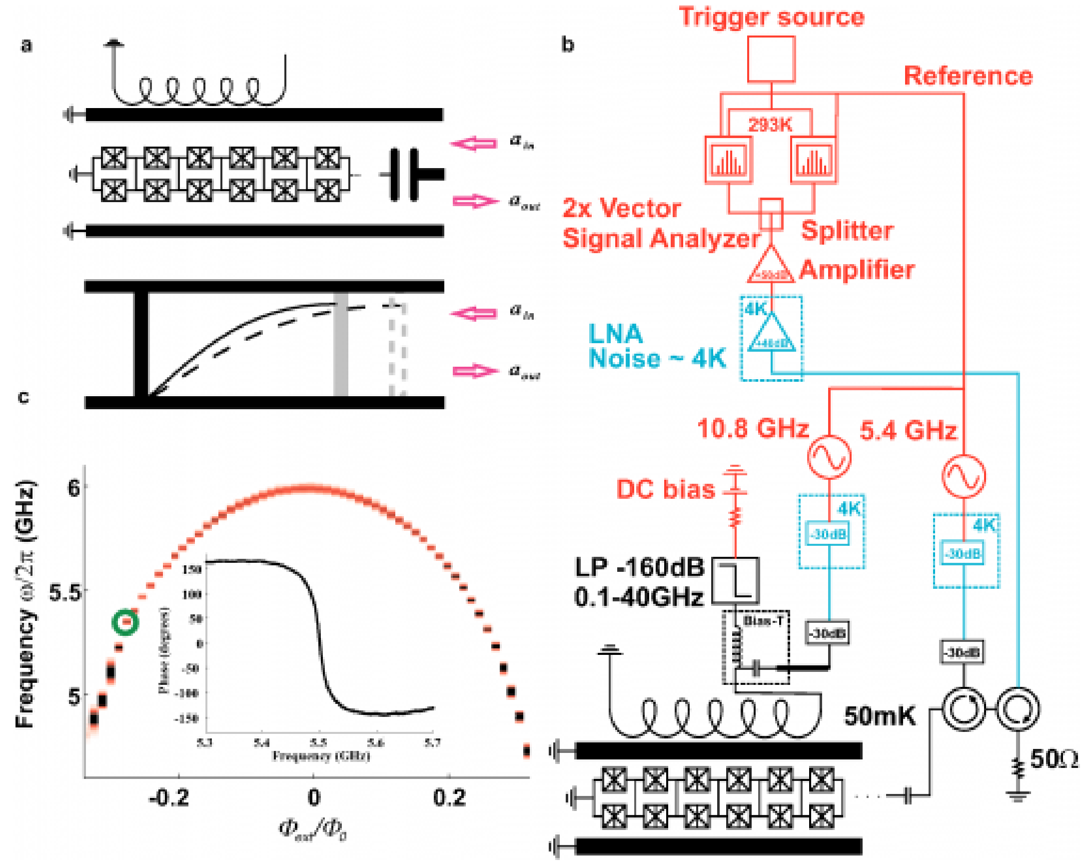

(a) Equivalent electrical and mechanical circuits: the modulation of the Josephson inductance in the metamaterial by a magnetic φext varies the wave length λ with respect to the cavity length, which is analogous to modulating the effective length d of the cavity by mechanical means. The coupling capacitor is equivalent to a semitransparent mirror. (b) Schematics of the measurement setup. The metamaterial sample is a 4-mm-long coplanar waveguide with 250 embedded SQUIDs, each junction having a critical current of ~ 10 µA. The modulation of the flux through the SQUIDs is realized through a lithographically fabricated spiral coil underneath the metamaterial. (c) Resonant frequency ωres/2π vs. reduced magnetic flux φext/φ0 without the pump signal; the DC operating point for DCE experiments is denoted by a green circle. The inset displays the measured phase of the scattering parameter S11 while sweeping frequency, which yields d arg(S11)/dφext = d arg(S11)/dfÍdf/dφext . The steepness of the variation in the phase arg(S11) governs the effective "movement of the mirrors". Copyright © PNAS, doi:10.1073/pnas.1212705110

(Phys.org) —In the strange world of quantum mechanics, the vacuum state (sometimes referred to as the quantum vacuum, simply as the vacuum) is a quantum system's lowest possible energy state. While not containing physical particles, neither is it an empty void: Rather, the quantum vacuum contains fluctuating electromagnetic waves and so-called virtual particles, the latter being known to transition into and out of existence. In addition, the vacuum state has *zero-point energy* – the lowest quantized energy level of a quantum mechanical system – that manifests itself as the *static Casimir effect,* an attractive interaction between the opposite walls of an electromagnetic cavity. Recently, scientists at Aalto University in Finland and VTT Technical Research Centre of Finland demonstrated the *dynamical Casimir effect* using a Josephson metamaterial embedded in a microwave cavity. They showed that under certain conditions, real photons are generated in pairs, and concluded that their creation was consistent with quantum field theory predictions.

Researcher Pasi Lähteenmäki discussed the challenges he and his colleagues – G. S. Paraoanu, Juha Hassel and Pertti J. Hakonen – encountered in their study. Regarding their demonstration of the dynamical Casimir effect using a Josephson metamaterial embedded in a microwave cavity at 5.4 GHz, Lähteenmäki tells Phys.org that the main challenge in general is to get high-quality samples. In addition, Lähteenmäki adds, they had to ensure that the origin of the noise is quantum and not some unaccounted source of excess noise, such as thermal imbalance between the environment and the sample, or possibly leakage of external noise.

Modulating the effective length of the cavity by flux-biasing the SQUID (superconducting quantum interference device) metamaterial had its challenges as well. "The pump signal needs to be rather strong, yet at the same time one wants to be sure that no excess noise enters the system through the pump line, Lähteenmäki notes, "and good filtering means high attenuation, which is a requirement contradictory to a strong signal. Also," Lähteenmäki continues, "at 10.8 GHz the pump frequency is rather high – and at that frequency range both the sample and the setup is rather prone to electrical resonances which can limit the usable frequencies." In short, the flux profile needs to be such that the pumping doesn't counteract itself. In addition, trapping flux in SQUID loops can also become a problem, limiting the range of optimal operating points and causing excess loss.

The researchers also showed that photons at frequencies symmetric with respect to half the modulation frequency of the cavity are generated in pairs. "In general, with frequency locked signal analyzers today the extraction of this correlation is not particularly problematic – especially since the low noise amplifier noise is not correlated at different frequencies," Lähteenmäki explains. That said, issues related to data collection and averaging include amplifier gain drift and phase randomization of the pump signal (relative to the detection phase) if the state of the generator is changed. "The noise temperature of the low noise amplifier sets some limits to the amount of data that needs to be collected, especially in the case where one is operating in the regime of low parametric gain."

Lastly, the team also found that at large detunings of the cavity from half the modulation frequency, they found power spectra that clearly showed the theoretically-predicted hallmark of the dynamical Casimir effect. "Large detunings imply low intensity of generated radiation," notes Lähteenmäki. "This means long averaging times, so the system should be kept stable for a long period. Also, the system needs to be fairly resonance-free over a large range of frequencies to get decent data – and/or one needs to know the characteristics of these resonances and noise temperature of the low noise amplifier rather well."

Lähteenmäki points out that addressing these issues required a number of insights and innovations. "We combated amplifier drift by continuously switching the pump on and off, and recording the difference in the observed output power, suitable operating points were searched for using trial and error, and trapping the photon flux was eliminated by applying a heat pulse to the sample and letting it cool down again. The researchers also magnetically shielded the sample with a superconductive shield, and minimized the effect of losses by changing the coupling of the existing samples by making different valued vacuum coupling capacitors with *focused ion beam* (FIB) cuts.

"However," Lähteenmäki stresses, "our biggest issue – ruling out the source of classical noise as opposed to quantum noise – was accomplished primarily by characterizing the sample and the environment well" Thermal imbalance was ruled out by the symmetry of the sparrow-tail shape of the noise spectrum.

It was essential for the scientists to clearly demonstrate that the observed substantial photon flux could not be assigned to parametric amplification of thermal fluctuations. "By characterizing the parametric gain with a network analyzer," Lähteenmäki notes, "we found that in order to explain the amount of noise one gets, the device would need to have significantly higher gain than is observed if the only source of noise was thermal." Moreover, confirming that photon pair creation is a direct consequence of the noncommutativity structure of quantum field theory was equally important. "Basically the experimental results fit the theoretical predictions rather well – and in the absence of other sources of noise, the theory implies that we should get no output from this sort of device. Since we see output consistent with the theoretical predictions, the conclusion was logical."

Moving forward, Lähteenmäki describes next steps in their research. "Instead of a continuous wave pump, we could have a straight flux line and feed it with a step-like flux pulse," Lähteenmäki says. "This would allow the creation of an analogue to a black hole event horizon. In fact," he adds, "we're hoping to create an artificial event horizon in a metamaterial similar to the one used in our current research and study Hawking radiation originating from it. Also, it would be nice to be able to run experiments on Bell's inequalities." His personal interests, Lähteenmäki says, are fundamental quantum mechanics, quantum information and properties of the vacuum itself.

"The obvious applications for these devices," he notes, "come from quantum computation, and in general they may serve as components for multitude of sensitive measurements. I believe the interest towards low loss metamaterials is high and the field is just getting started. Our results show that these devices have potential and can offer a fruitful platform for many experiments and perhaps practical devices as well. Improving such devices – especially eliminating the losses and making them function more robustly – would allow them to create a general purpose component suitable for creating entangled microwave photon pairs, low noise amplification, squeezed vacuum, and other functions that can be very useful for quantum computation and general experiments in the quantum mechanics and in studying the vacuum."

Another possibility, Lähteenmäki adds, is to create a metamaterial which would allow them to stop signal propagation in the material entirely and allow them to resume it later. "This would act as a kind of slow light memory that would store the photon for later use."

Other areas of research might benefit from their study as well, Lähteenmäki says. "There are some connections to cosmology, the big bang, cosmic inflation, and other areas. These metamaterials could possibly offer an analogy to such events and serve as a platform to simulate the evolution of such conditions. Who knows," he ponders, concluding that "perhaps we'd find clues to the mysteries of dark matter and dark energy or other fundamental questions from such systems."

More information: Dynamical Casimir effect in a Josephson metamaterial, *PNAS* Published online before print February 12, 2013, doi:10.1073/pnas.1212705110

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