

Experimental Violation of Bell-like Inequalities By Electronic Shot Noise

Jean-Charles Forgues,^{*} Christian Lupien,[†] and Bertrand Reulet[‡]

Département de Physique, Université de Sherbrooke, Sherbrooke, Québec J1K 2R1, Canada

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We report measurements of the correlations between electromagnetic field quadratures at two frequencies $f_1 = 7$ GHz and $f_2 = 7.5$ GHz of the radiation emitted by a tunnel junction placed at very low temperature and excited at frequency $f_1 + f_2$. We demonstrate the existence of two-mode squeezing and violation of a Bell-like inequality, thereby proving the existence of entanglement in the quantum shot noise radiated by the tunnel junction.

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Electrical current flowing in a conductor always fluctuates in time, a phenomenon usually referred to as “electrical noise.” At room temperature, one way this can be described is using a time-dependent current $I(t)$. While the dc current corresponds to the average $\langle I(t) \rangle$, current fluctuations are characterized by their statistical properties such as their second order correlator $\langle I(t)I(t') \rangle$, where the brackets $\langle \dots \rangle$ represent the statistical average. An alternate approach is to consider that this time-dependent current generates a random electromagnetic field that propagates along the electrical wires. Both of these descriptions are equivalent. For example, the equilibrium current fluctuations (Johnson-Nyquist noise [1,2]) correspond to the blackbody radiation in one dimension [3]. More precisely, the power radiated by a sample at frequency f in a cable is proportional to the spectral density $S(f)$ of current fluctuation which, at high temperature and at equilibrium (i.e., with no bias), is given by $S_0(hf \ll k_B T) = 2k_B T/R$ where T is the temperature and R is the electrical resistance of the sample [4].

In short samples at very low temperatures, electrons obey quantum mechanics. Thus, electron transport can no longer be modeled by a time-dependent, classical number $I(t)$, but needs to be described by an operator $\hat{I}(t)$. Current fluctuations are characterized by correlators such as $\langle \hat{I}(t)\hat{I}(t') \rangle$. Quantum predictions differ from classical ones only when the energy hf associated with the electromagnetic field is comparable with energies associated with the temperature $k_B T$ and the voltage eV . Hence for $hf \gg k_B T$, eV , the thermal energy $k_B T$ in the expression of $S_0(f)$ has to be replaced by that of vacuum fluctuations, $hf/2$. Some general link between the statistics of current fluctuations and that of the detected electromagnetic field is required beyond the correspondence between the spectral density of current fluctuations and radiated power [5–8]. In particular, since the statistics of current fluctuations can be tailored by engineering the shape of the time-dependent bias voltage [9], it may be possible to induce nonclassical correlations in the electromagnetic field generated by a quantum conductor. For example, an ac bias at frequency f_0 generates

correlations between current fluctuations at frequencies f_1 and f_2 , i.e., $\langle \hat{I}(f_1)\hat{I}(f_2) \rangle \neq 0$, if $f_1 \pm f_2 = nf_0$ with n integer [10–12]. This is responsible for the existence of correlated power fluctuations [13] and for the emission of photon pairs [14] recently observed. For $f_1 = f_2$, $\langle \hat{I}^2(f_1) \rangle \neq 0$ leads to vacuum squeezing [15,16]. In this Letter, we report measurements of the correlations between electromagnetic field quadratures at frequencies f_1 and f_2 when the sample is irradiated at frequency $f_0 = f_1 + f_2$. By analyzing these correlations, we show that the electromagnetic field produced by electronic shot noise can be described in a way similar to an Einstein-Podolski-Rosen (EPR) pair: when measuring fluctuations at only one frequency, i.e., one mode of the electromagnetic field, no quadrature is preferred. But when measuring two modes, we observe strong correlations between identical quadratures. These correlations are stronger than what is allowed by classical mechanics as proven by their violation of Bell-like inequalities.

Entanglement of photons of different frequencies has already been observed in superconducting devices engineered for that purpose in Refs. [17–19], where frequencies f_1 and f_2 are fixed by resonators and the entanglement comes from a nonlinear element, a Josephson junction. What we show here is that any quantum conductor excited at frequency f_0 emits entangled radiation at any pair of frequencies f_1, f_2 such that $f_0 = f_1 + f_2$. This property is demonstrated using a tunnel junction but our results clearly stand for any device that exhibits quantum shot noise. The key ingredient for the appearance of entanglement is the following: noise at any frequency f_1 modulated by an ac voltage at frequency f_0 gives rise to sidebands with a well defined phase. These sidebands, located at frequencies $\pm f_1 \pm nf_0$ with n integer, are correlated with the current fluctuations at frequency f_0 . The particular case $f_2 = -f_1 + f_0$ we study here corresponds to the maximum correlation.

Experimental setup.—(See Fig. 1). We use a $R = 70 \Omega$ Al/Al₂O₃/Al tunnel junction in the presence of a magnetic field to insure that the aluminum remains a normal metal

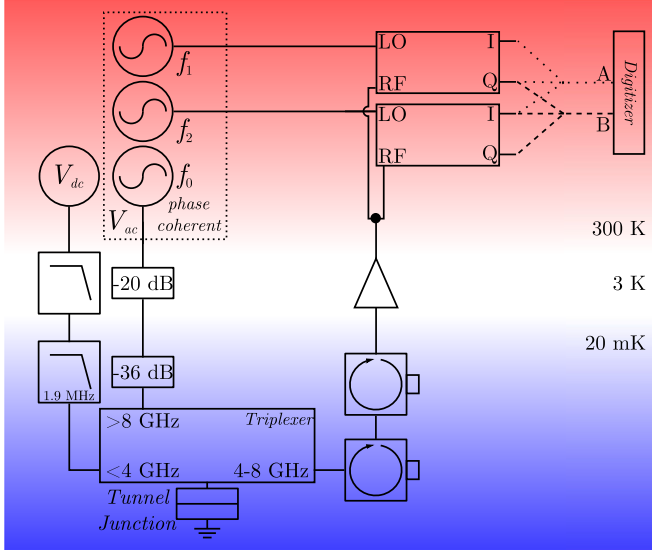


FIG. 1 (color online). Experimental setup. See details in text.

at all temperatures. It is cooled to ~ 18 mK by a dilution refrigerator. A triplexer connected to the junction separates the frequency spectrum in three bands corresponding to the dc bias (< 4 GHz), the ac bias at frequency f_0 (> 8 GHz), and the detection band (4–8 GHz). Low-pass filters are used to minimize the parasitic noise coming down the dc bias line and attenuators are placed on the ac bias line to dampen noise generated by room-temperature electronics. The signal generated by the junction in the 4–8 GHz range goes through two circulators, used to isolate the sample from the amplification line noise, and is then amplified by a high electron mobility transistor amplifier placed at 3 K.

At room temperature, the signal is separated in two branches, each entering an I/Q (in phase/quadrature) mixer. One mixer is referenced to a local oscillator at frequency f_1 and the other at frequency $f_2 = f_0 - f_1$. All three microwave sources at frequencies f_0, f_1 , and f_2 are phase coherent. The two IQ mixers take the signal emitted by the junction and provide the in-phase $X_{1,2}$ and quadrature $P_{1,2}$ parts relative to their references with a bandwidth of 80 MHz. Similar setups have already been used to determine statistical properties of radiation in the microwave domain [20–24]. We chose to work at $f_0 = 14.5$ GHz, $f_1 = 7$ GHz $\Rightarrow f_2 = 7.5$ GHz so that f_1 and f_2 are far enough to suppress any overlap between the frequency bands. Any two quantities A, B among X_1, X_2, P_1 , and P_2 can be digitized simultaneously by a two-channel digitizer at a rate of 400 MS/s, yielding a 2D probability map $\mathcal{P}(A, B)$. From $\mathcal{P}(A, B)$, one can calculate any statistical quantity, in particular the variances $\langle A^2 \rangle, \langle B^2 \rangle$, as well as the correlators $\langle AB \rangle$.

Calibration.—The four detection channels must be calibrated separately. This is achieved by measuring the variances $\langle X_{1,2}^2 \rangle, \langle P_{1,2}^2 \rangle$ in the absence of rf excitation. These should all be proportional to the noise spectral

density of a tunnel junction at frequency $f_{1,2}$, given by $S(f, V) = [S_0(f + eV/h) + S_0(f - eV/h)]/2$, where $S_0(f) = (hf/R) \coth(hf/2k_B T)$ is the equilibrium noise spectral density at frequency f in a tunnel junction of resistance R . By fitting the measurements with this formula, we find an electron temperature of $T = 18$ mK and an amplifier noise temperature of ~ 3 K, which are identical for all four channels. The small channel cross talk was eliminated using the fact that $\langle A_1 B_2 \rangle = 0$ when no microwave excitation is present.

Results.—We begin our analysis by illustrating the effect of microwave excitation and dc bias on the current fluctuations. We show in Fig. 2 the difference $\Delta\mathcal{P}$ between the probability distribution $\mathcal{P}(A, B)$ in the presence of $V_{dc} = 29.4 \mu\text{V}$ and $V_{ac} = 37 \mu\text{V}$ bias and $\mathcal{P}(A, B)$ for $V_{dc} = V_{ac} = 0$. Figures 2(b) and 2(c), which correspond to $\Delta\mathcal{P}(X_1, P_2)$ and $\Delta\mathcal{P}(P_1, X_2)$, are almost invariant by rotation. This means that the corresponding probability $\mathcal{P}(X, P)$ depends only on $X^2 + P^2$.

As an immediate consequence, one expects $\langle X_1 P_2 \rangle = \langle P_1 X_2 \rangle = 0$: X_1 and P_2 are uncorrelated, as are X_2 and P_1 . In contrast, Figs. 2(a) and 2(d), which show, respectively, $\Delta\mathcal{P}(X_1, X_2)$ and $\Delta\mathcal{P}(P_1, P_2)$, are not invariant by rotation: the axes $X_1 = \pm X_2$ and $P_1 = \pm P_2$ are singular; for a given value of X_1 the probability $\Delta\mathcal{P}(X_1, X_2)$ is either maximum or minimum for $X_2 = X_1$, whereas for a given value of P_1 , the probability $\Delta\mathcal{P}(P_1, P_2)$ is either maximum or minimum for $P_2 = -P_1$. These indicate that it is possible to observe correlations or anticorrelations between X_1 and X_2 on one hand, and between P_1 and P_2 on the other hand. Data in Figs. 2(a) through 2(d) correspond to two frequencies f_1 and f_2 that

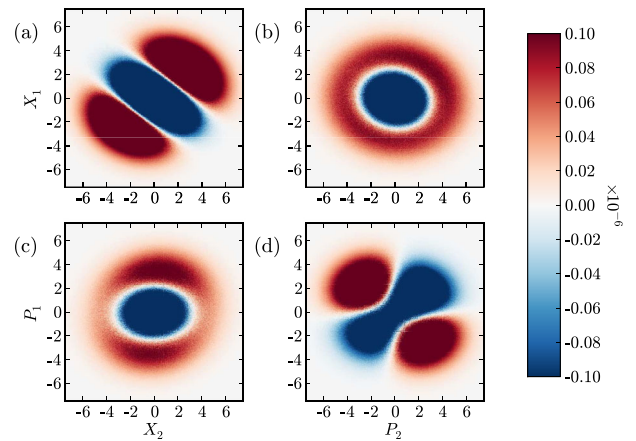


FIG. 2 (color online). $\Delta\mathcal{P} = \mathcal{P}(A, B)_{V_{dc}, V_{ac}} - \mathcal{P}(A, B)_{0,0}$ (unitless): (a)–(d) difference between the normalised 2D current fluctuation distributions of the tunnel junction at $V_{dc} = 29.4 \mu\text{V}$, 18 mK, under 14.5 GHz, $V_{ac} = 37 \mu\text{V}$ microwave excitation and without excitation at $V_{dc} = 0$. X and P represent two quadratures of the observed signal while numbers 1 and 2 represent fluctuations of frequency 7 and 7.5 GHz in arbitrary units. Each distribution is made up of 2×10^{11} samples.

sum up to f_0 , all three frequencies being phase coherent. If this condition is not fulfilled, no correlations are observed between any two quadratures, giving plots similar to Figs. 2(b) or 2(c) (data not shown). The effect of frequencies on correlations between power fluctuations has been thoroughly studied in Refs. [13,14].

To be more quantitative, we show in Fig. 3 the $\langle AB \rangle$ correlators as a function of the dc bias voltage for a fixed V_{ac} . Clearly, $\langle X_1 P_2 \rangle = \langle P_1 X_2 \rangle = 0$ while $\langle X_1 X_2 \rangle = -\langle P_1 P_2 \rangle$ is nonzero for $V_{dc} \neq 0$. These results are presented in temperature units (K), using the usual unit conversion $T_{\text{noise}} = RS/2k_B$ for the measured noise spectral density S of a conductor of resistance R .

Theory.—We now compare our experimental results with theoretical predictions. In order to link the measured quantities to electronic properties, we will first define the quadrature operators, following Refs. [8,16],

$$\hat{X}_{1,2} = \frac{\hat{I}(f_{1,2}) + \hat{I}(-f_{1,2})}{\sqrt{2}},$$

$$\hat{P}_{1,2} = \frac{\hat{I}(f_{1,2}) - \hat{I}(-f_{1,2})}{i\sqrt{2}},$$

where $\hat{I}(f)$ is the current operator at frequency f . In the absence of rf excitation, the currents observed at two different frequencies are uncorrelated, $\langle \hat{I}(\pm f_1) \hat{I}(\pm f_2) \rangle = 0$. The excitation at frequency $f_0 = f_1 + f_2$ induces correlations so that $\langle \hat{I}(f_1) \hat{I}(f_2) \rangle = \langle \hat{I}(-f_1) \hat{I}(-f_2) \rangle \neq 0$.

More precisely, one has [10–12]

$$\langle \hat{I}(f) \hat{I}(f_0 - f) \rangle = \sum_n \frac{\alpha_n}{2} [S_0(f_{n+}) - S_0(f_{n-})], \quad (1)$$

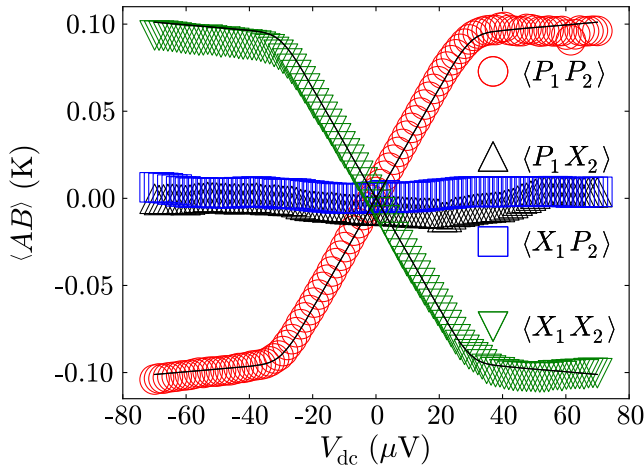


FIG. 3 (color online). Quadrature correlators of electromagnetic field at frequencies $f_1 = 7$ GHz, $f_2 = 7.5$ GHz generated by a 70Ω tunnel junction at 18 mK under 14.5 GHz, $V_{ac} = 37 \mu\text{V}$ microwave excitation. Symbols represent experimental data and lines are theoretical expectations. Symbol sizes represent experimental uncertainty.

where $f_{n\pm} = f + nf_0 \pm eV_{dc}/h$ and $\alpha_n = J_n(eV_{ac}/hf_0)J_{n+1}(eV_{ac}/hf_0)$ with J_n the Bessel functions of the first kind. From this we can calculate the theoretical predictions for all the correlators, which are represented as black lines in Fig. 3, showing a very good agreement between theory and experiment.

Two-mode squeezing.—Squeezing is best explained using the dimensionless operators

$$\hat{x}_k = \frac{\hat{X}_k}{\sqrt{2hf_k/R}},$$

$$\hat{p}_k = \frac{\hat{P}_k}{\sqrt{2hf_k/R}},$$

chosen so that $\langle [\hat{x}_k, \hat{p}_{k'}] \rangle = \delta_{k,k'}$ with $k, k' = 1, 2$. At equilibrium ($V_{dc} = V_{ac} = 0$) and very low temperature ($k_B T \ll hf_{1,2}$), the noise generated by the junction corresponds to vacuum fluctuations and $\langle \hat{x}_k^2 \rangle = \langle \hat{p}_k^2 \rangle = 1/2$. Experimentally, this can be seen in Fig. 4 as a plateau in $\langle \hat{x}_k^2 \rangle$ vs V_{dc} at $V_{ac} = 0$ (black circles) and low V_{dc} , which is outlined by a dashed line.

Single-mode squeezing refers to the possibility of going below $1/2$ for either $\langle \hat{x}_k^2 \rangle$ or $\langle \hat{p}_k^2 \rangle$. This has been observed when the excitation frequency f_0 corresponds to $f_0 = f_k$ or $f_0 = 2f_k$ [16]. As can be seen in Fig. 4, there is no single-mode squeezing for $f_0 = f_1 + f_2$ and $\langle \hat{x}_1^2 \rangle > 1/2$ (as well as $\langle \hat{x}_2^2 \rangle = \langle \hat{p}_1^2 \rangle = \langle \hat{p}_2^2 \rangle > 1/2$, data not shown). Using the operators $\hat{u} = (\hat{x}_1 - \hat{x}_2)/\sqrt{2}$ and $\hat{v} = (\hat{p}_1 + \hat{p}_2)/\sqrt{2}$, two-mode squeezing refers to the possibility of either $\langle \hat{u}^2 \rangle$ or

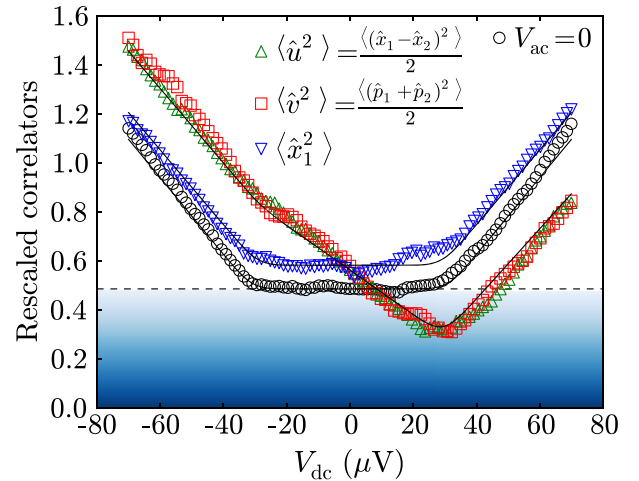


FIG. 4 (color online). Rescaled (unitless) variances of the electro-magnetic field generated by a 70Ω tunnel junction at 18 mK under 14.5 GHz, $V_{ac} = 37 \mu\text{V}$ microwave excitation and without excitation using signal quadratures at frequencies $f_1 = 7$ GHz, $f_2 = 7.5$ GHz. Symbols represent experimental data and lines are theoretical expectations. Symbol sizes represent experimental uncertainty. The shaded area showcases the less-than-vacuum noise levels.

$\langle \hat{v}^2 \rangle$ going below 1/2, which corresponds to their value for vacuum fluctuations. As evidenced by Fig. 4, $\langle \hat{u}^2 \rangle \approx \langle \hat{v}^2 \rangle$ goes below 1/2 for a certain range of dc bias, a clear proof of the existence of two-mode squeezing for electronic shot noise.

The optimal squeezing observed corresponds to $\langle \hat{u}^2 \rangle = 0.32 \pm 0.05$, $\langle \hat{v}^2 \rangle = 0.31 \pm 0.05$, i.e., 2.1 dB below vacuum, versus the theoretical expectation of $\langle \hat{u}^2 \rangle = \langle \hat{v}^2 \rangle = 0.33$. This minimum is observed at $V_{\text{dc}} \approx 30 \mu\text{V} \approx hf_{1,2}/e$. All data are in good agreement with theoretical predictions, plotted as full black lines in Fig. 4 with $\langle \hat{x}_k^2 \rangle = \langle \hat{p}_k^2 \rangle = S(f_k)$, with the photoassisted shot noise given by $S(f) = \frac{1}{2} \sum_n J_n^2(eV_{\text{ac}}/hf_0)[S_0(f_{n+}) + S_0(f_{n-})]$ [25]. Curves for $\langle (\hat{x}_1 + \hat{x}_2)^2 \rangle / 2$ and $\langle (\hat{p}_1 - \hat{p}_2)^2 \rangle / 2$ follow the same behavior with reversed dc bias, showing minima of 0.35 ± 0.05 and 0.41 ± 0.05 or 1.6 dB at $V_{\text{dc}} \approx -30 \mu\text{V} \approx -hf_{1,2}/e$. The latter data were omitted from Fig. 4 in order to simplify it.

Entanglement.—While the presence of two-mode squeezing shows the existence of strong correlations between quadratures of the electromagnetic field at different frequencies, this is not enough to prove the existence of entanglement. A criterion certifying the inseparability of the two modes, and thus entanglement between them, is given in terms of the quantity $\delta = \langle \hat{u}^2 \rangle + \langle \hat{v}^2 \rangle$. In the case of a classical field, this must obey $\delta > 1$ [26]. This is equivalent to a Bell-like inequality for continuous variables. As we reported in Fig. 4, we observe $\delta = 0.6 \pm 0.1$. Thus, photons emitted at frequencies f_1 and f_2 are not only correlated but also form EPR pairs suitable for quantum information processing with continuous variables [27].

Two-mode quadrature-squeezed states are usually characterized by their covariance matrix. Following the notations of Ref. [28], our experiment corresponds to $n = 2\langle x_{1,2}^2 \rangle \approx 2\langle p_{1,2}^2 \rangle$, $k = 2\langle x_1 x_2 \rangle \approx -2\langle p_1 p_2 \rangle$ so that $\delta = n - k$. Equilibrium at $T = 0$ corresponds to $n = 1$ and $k = 0$. Our observed optimal squeezing corresponds to $n = 1.3 \pm 0.1$ and $k = 0.52 \pm 0.05$. From these numbers, one can calculate all the statistical properties that characterize the electromagnetic field generated by the junction. In particular, we find a formation entanglement of $E_F \approx 0.2$ (as defined in Ref. [28]) and a purity of $\mu = 0.82$ (as defined in Ref. [29]). While in our experiment, the entangled photons are not spatially separated, this could easily be achieved using a diplexer, which can separate frequency bands without dissipation.

A cursory analysis of the data in terms of EPR steering shows that according to the definitions presented in Ref. [30], we obtain $\mu' = 0.62$ (not to be confused with μ from Ref. [29]), $\bar{n} = 0.15$. According to Eqs. (71) and (77) from that work, we clearly respect the criteria for entanglement but fall shy of being able to observe steering. Numerical calculations using Eq. (1) show that the condition for steerability could be fulfilled at lower temperature ($T < 16.8$ mK with the present setup) or higher

frequency, while we should observe $\mu' = 0.85$ and $\bar{n} = 0.06$ at $T = 0$ K. Although a temperature of $T < 16.8$ mK seems experimentally accessible, the physical meaning of steerability in terms of electron quantum shot noise still needs to be understood.

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*jean-charles.forgues@usherbrooke.ca

†christian.lupien@usherbrooke.ca

‡bertrand.reulet@usherbrooke.ca

- [1] J. B. Johnson, Thermal agitation of electricity in conductors, *Phys. Rev.* **32**, 97 (1928).
- [2] H. Nyquist, Thermal agitation of electric charge in conductors, *Phys. Rev.* **32**, 110 (1928).
- [3] B. M. Oliver, Thermal and quantum noise, *Proc. IEEE* **53**, 436 (1965).
- [4] H. B. Callen and T. A. Welton, Irreversibility and generalized noise, *Phys. Rev.* **83**, 34 (1951).
- [5] C. W. J. Beenakker and H. Schomerus, Counting Statistics of Photons Produced by Electronic Shot Noise, *Phys. Rev. Lett.* **86**, 700 (2001).
- [6] C. W. J. Beenakker and H. Schomerus, Antibunched Photons Emitted by a Quantum Point Contact out of Equilibrium, *Phys. Rev. Lett.* **93**, 096801 (2004).
- [7] A. V. Lebedev, G. B. Lesovik, and G. Blatter, Statistics of radiation emitted from a quantum point contact, *Phys. Rev. B* **81**, 155421 (2010).
- [8] F. Qassemi, B. Reulet, and A. Blais, Quantum optics theory of electronic noise in coherent conductors (unpublished).
- [9] J. Gabelli and B. Reulet, Shaping a time-dependent excitation to minimize the shot noise in a tunnel junction, *Phys. Rev. B* **87**, 075403 (2013).
- [10] J. Gabelli and B. Reulet, Dynamics of Quantum Noise in a Tunnel Junction under ac Excitation, *Phys. Rev. Lett.* **100**, 026601 (2008).
- [11] J. Gabelli and B. Reulet, “The noise susceptibility of a photo-excited coherent conductor,” [arXiv:0801.1432](https://arxiv.org/abs/0801.1432).
- [12] J. Gabelli and B. Reulet, The noise susceptibility of a coherent conductor, *Proc. SPIE, Fluctuations and Noise in Materials* **25**, 66000T (2007).
- [13] J.-C. Forgues, F. B. Sane, S. Blanchard, L. Spietz, C. Lupien, and B. Reulet, Noise intensity-intensity correlations and the fourth cumulant of photo-assisted shot noise, *Sci. Rep.* **3**, 2869 (2013).
- [14] J.-C. Forgues, C. Lupien, and B. Reulet, Emission of Microwave Photon Pairs by a Tunnel Junction, *Phys. Rev. Lett.* **113**, 043602 (2014).

- [15] A. Bednorz, C. Bruder, B. Reulet, and W. Belzig, Nonsymmetrized Correlations in Quantum Noninvasive Measurements, *Phys. Rev. Lett.* **110**, 250404 (2013).
- [16] G. Gasse, C. Lupien, and B. Reulet, Observation of Squeezing in the Electron Quantum Shot Noise of a Tunnel Junction, *Phys. Rev. Lett.* **111**, 136601 (2013).
- [17] C. Eichler, D. Bozyigit, C. Lang, M. Baur, L. Steffen, J. M. Fink, S. Filipp, and A. Wallraff, Observation of Two-Mode Squeezing in the Microwave Frequency Domain, *Phys. Rev. Lett.* **107**, 113601 (2011).
- [18] E. Flurin, N. Roch, F. Mallet, M. H. Devoret, and B. Huard, Generating Entangled Microwave Radiation Over Two Transmission Lines, *Phys. Rev. Lett.* **109**, 183901 (2012).
- [19] F. Nguyen, E. Zakka-Bajjani, R. W. Simmonds, and J. Aumentado, Quantum Interference between Two Single Photons of Different Microwave Frequencies, *Phys. Rev. Lett.* **108**, 163602 (2012).
- [20] E. P. Menzel, F. Deppe, M. Mariani, M. A. Araque Caballero, A. Baust, T. Niemczyk, E. Hoffmann, A. Marx, E. Solano, and R. Gross, Dual-Path State Reconstruction Scheme for Propagating Quantum Microwaves and Detector Noise Tomography, *Phys. Rev. Lett.* **105**, 100401 (2010).
- [21] M. Mariani, E. P. Menzel, F. Deppe, M. A. Araque Caballero, A. Baust, T. Niemczyk, E. Hoffmann, E. Solano, A. Marx, and R. Gross, Planck Spectroscopy and Quantum Noise of Microwave Beam Splitters, *Phys. Rev. Lett.* **105**, 133601 (2010).
- [22] E. P. Menzel, R. Di Candia, F. Deppe, P. Eder, L. Zhong, M. Ihmig, M. Haerberlein, A. Baust, E. Hoffmann, D. Ballester, K. Inomata, T. Yamamoto, Y. Nakamura, E. Solano, A. Marx, and R. Gross, Path Entanglement of Continuous-Variable Quantum Microwaves, *Phys. Rev. Lett.* **109**, 250502 (2012).
- [23] D. Bozyigit, C. Lang, L. Steffen, J. M. Fink, C. Eichler, M. Baur, R. Bianchetti, P. J. Leek, S. Filipp, M. P. da Silva, A. Blais, and A. Wallraff, Antibunching of microwave-frequency photons observed in correlation measurements using linear detectors, *Nat. Phys.* **7**, 154 (2011).
- [24] C. Eichler, D. Bozyigit, C. Lang, L. Steffen, J. Fink, and A. Wallraff, Experimental State Tomography of Itinerant Single Microwave Photons, *Phys. Rev. Lett.* **106**, 220503 (2011).
- [25] G. B. Lesovik and L. S. Levitov, Noise in an ac biased junction: Nonstationary Aharonov-Bohm effect, *Phys. Rev. Lett.* **72**, 538 (1994).
- [26] L.-M. Duan, G. Giedke, J. I. Cirac, and P. Zoller, Inseparability Criterion for Continuous Variable Systems, *Phys. Rev. Lett.* **84**, 2722 (2000).
- [27] S. L. Braunstein and P. van Loock, Quantum information with continuous variables, *Rev. Mod. Phys.* **77**, 513 (2005).
- [28] G. Giedke, M. M. Wolf, O. Krüger, R. F. Werner, and J. I. Cirac, Entanglement of Formation for Symmetric Gaussian States, *Phys. Rev. Lett.* **91**, 107901 (2003).
- [29] J. DiGuglielmo, B. Hage, A. Franzen, J. Fiurášek, and R. Schnabel, Experimental characterization of Gaussian quantum-communication channels, *Phys. Rev. A* **76**, 012323 (2007).
- [30] E. G. Cavalcanti, S. J. Jones, H. M. Wiseman, and M. D. Reid, Experimental criteria for steering and the Einstein-Podolsky-Rosen paradox, *Phys. Rev. A* **80**, 032112 (2009).