Emission of Microwave Photon Pairs by a Tunnel Junction

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We report the observation of photon pairs in the photoassisted shot noise of a tunnel junction in the quantum regime at very high frequency and very low temperature. We have measured the fluctuations of the noise power generated by the junction at two different frequencies, $f_1 = 4.4$ and $f_2 = 7.2$ GHz, while driving the junction with a microwave excitation of frequency $f_0 = f_1 + f_2$. We observe clear correlations between the fluctuations of the two noise powers even when the mean photon number per measurement is much smaller than one. This is strong evidence for photons being emitted in pairs. We also demonstrate that the electromagnetic field generated by the junction exhibits two-mode amplitude squeezing, a proof of its nonclassicality. The data agree very well with predictions based on the fourth cumulant of the current fluctuations generated by the junction.

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Generation and control of nonclassical electromagnetic fields is of great importance when it comes to deepening the understanding of quantum electrodynamics. While usual methods for the production of such fields rely on a nonlinearity (of a crystal, a Josephson junction, etc.), a recent experiment performed on a normal conductor, a tunnel junction under microwave irradiation, has unveiled an alternative: the use of electron shot noise in a quantum conductor [1]. While a classical current generates a classical field [2], also known as a coherent state of light, it appears that when electron transport requires a quantum mechanical description, the random electromagnetic field that corresponds to current noise is nonclassical. This was shown in [1] by the observation of vacuum noise squeezing. Squeezed electromagnetic fields are usually the result of nonlinearities which appear in the Hamiltonian describing the electromagnetic field by terms such as a^2 and $a^{\dagger 2}$, with a and $a^\dagger$ the photon annihilation and creation operators, i.e., by emission or absorption of pairs of photons [3]. Since a tunnel junction under appropriate dc and ac bias can emit a squeezed electromagnetic field despite its linearity, it is natural to consider whether the field it generates contains pairs of photons. It is precisely the goal of the present Letter to address this question experimentally.

Another recent experiment has demonstrated that photoassisted noise may exhibit correlations between the power fluctuations measured at two different frequencies for an adequate choice of the excitation frequency [4]. Since this experiment was performed at a relatively high temperature $T = 3$ K with regard to the frequency range, 4–8 GHz, i.e., $k_B T \gg hf$, the power fluctuations were classical, meaning that the measured correlations corresponded to fluctuations of photon fluxes with many (~40) photons emitted within an experimental detection window. Here we report the observation of similar correlations at very low temperature $T = 20$ mK and under weak excitation. We demonstrate that there still are correlations between power fluctuations measured at two frequencies, f_1 and f_2, even when in the quantum regime $k_B T \ll hf_{1,2}$ and when the average number of photons observed within a detection window is much smaller than one. This is strong evidence for photons of frequencies f_1 and f_2 being emitted as a pair when the junction is irradiated at frequency $f_1 + f_2$. Moreover, we show that the fluctuations of the electromagnetic powers at frequencies f_1 and f_2 are correlated below the photon shot noise, a proof of the existence of two-mode amplitude squeezing. Our data are in very good agreement with the theoretical predictions based on the fourth cumulant of current fluctuations [4] when analyzed in the quantum regime.

The present Letter is organized as follows: we first present the principle of the experiment, its implementation and calibration. Then we show our results and the theoretical predictions. We interpret our data in usual terms of quantum optics by introducing first a photon-photon correlator, the analysis of which demonstrates the existence of photon pairs, and second the so-called noise reduction factor, which shows evidence of the existence of two-mode amplitude squeezing in the electromagnetic field generated by the junction.

Principle of the experiment.— The power $P(t)$ of the electromagnetic field radiated by a conductor in a given frequency band centered on frequency f fluctuates in time following $P(t) = \langle P \rangle + \delta P(t)$. The average power $\langle P \rangle$ is related to the spectral density $S(f)$ of the current fluctuations in the sample at frequency f by $\langle P \rangle = G(f)[S(f) + S_a(f)]\Delta f$, where Δf is the detection bandwidth, and $G(f)$ and $S_a(f)$ the gain and noise spectral density of the setup. We measure the correlation $G_2 = \langle \delta P_1 \delta P_2 \rangle$ between the power fluctuations $\delta P_{1,2}$ in two separate, nonoverlapping frequency bands centered on f_1 and f_2 as a function of the dc and ac bias of the junction.

The detection frequencies are chosen such that $hf_{1,2} \gg k_B T$, i.e., where quantum properties of the radiated field are prominent.

Experimental setup (see Fig. 1).—The sample is a 23.6 Ω $Al/Al_2O_3/Al$ tunnel junction in the presence of a magnetic field to insure that the aluminum remains a normal metal at all temperatures. It is cooled to a very low temperature 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 (> 8 GHz), and the detection (4–8 GHz). The noise generated by the junction in the 4–8 GHz range is amplified by a high electron mobility transistor amplifier placed at 3 K, then separated in two frequency bands centered on frequencies $f_1 = 4.4$ GHz and $f_2 = 7.2$ GHz with bandwidths $\Delta f_1 = 0.65$ GHz and $\Delta f_2 = 0.38$ GHz. The powers $P_{1,2}$ are measured with fast power detectors (diode symbols) with a 1 ns response time and digitized at a rate of 400 MS/s to compute $G_2 = \langle P_1 P_2\rangle - \langle P_1\rangle\langle P_2\rangle$ in real time.

Calibration.—$G(f)$, $S_a(f)$, the electron temperature T, and the attenuation of the excitation line were all ascertained by measuring and fitting the photoassisted noise at relatively high ac excitations. This yields $T = 20$ mK and a setup noise temperature of 5 K. Since the signal measured here is 1000 times weaker than that measured in [4], the experiment was first performed by replacing the sample with a macroscopic 50 Ω resistor heated with a dc current. For such a sample one expects $G_2 = 0$. The observed signal thus allowed us to calibrate out the spurious signal of the detection, mainly due to the cross talk between the digitizer channels.

Results.—As in [4], we observe $G_2 \neq 0$ only for excitation frequencies f_0 which respect $f_0 = (f_1 \pm f_2)/p$ with p, an integer. In the following we will focus only on $f_0 = f_1 + f_2 = 11.6$ GHz, which best corresponds to the quantum regime.

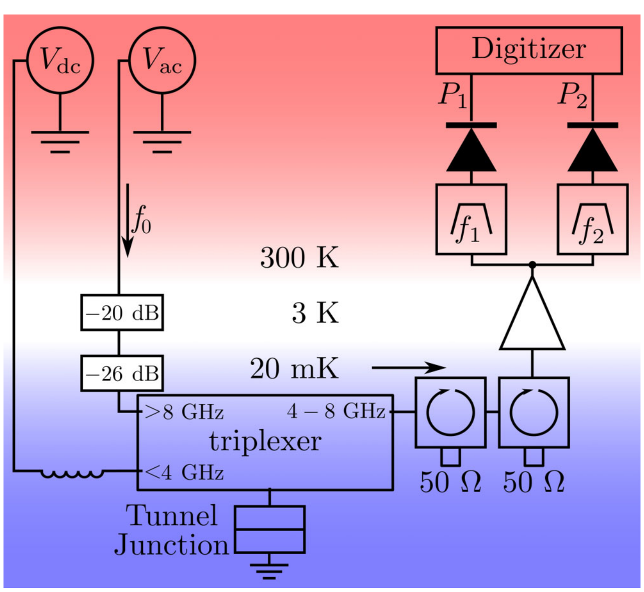

FIG. 1 (color online). Experimental setup.

We show on Fig. 2 the result for G_2, expressed in units of K^2, as a function of the dc bias voltage V_{dc} (colored symbols), for various ac voltages V_{ac}. The data exhibit kinks at integer multiples of $V_{dc} = hf_2/e \approx 30\ \mu V$, which are characteristic of quantum effects related to emission or absorption of photons [5]. Solid lines are the theoretical predictions for G_2 in terms of the fourth cumulant of current fluctuations C_4 given by [4]:

$$C_4 = |\langle i(f_1) i(f_2)\rangle|^2. \tag{1}$$

The two-frequency current-current correlator, which describes the noise dynamics under ac excitation, is given by [6–8]:

$$\langle i(f) i(f_0 - f)\rangle = \sum_n \frac{\alpha_n}{2}[S_0(f_{n+}) - S_0(f_{n-})], \tag{2}$$

with $S_0(f) = (hf/R)\coth(hf/2k_B T)$, the equilibrium noise spectral density at frequency f in a tunnel junction of resistance R, $f_{n\pm} = f + nf_0 \pm eV_{dc}/h$, and $\alpha_n = J_n(eV_{ac}/hf_0)J_{n+1}(eV_{ac}/hf_0)$, where J_n are the Bessel functions of the first kind.

As evidenced by Fig. 2, our data match very well with the theoretical expectation, thereby validating the proportionality between G_2 and C_4 in the quantum regime. The only difference between theory and experiment is that we observe a small extra contribution to G_2, which is most

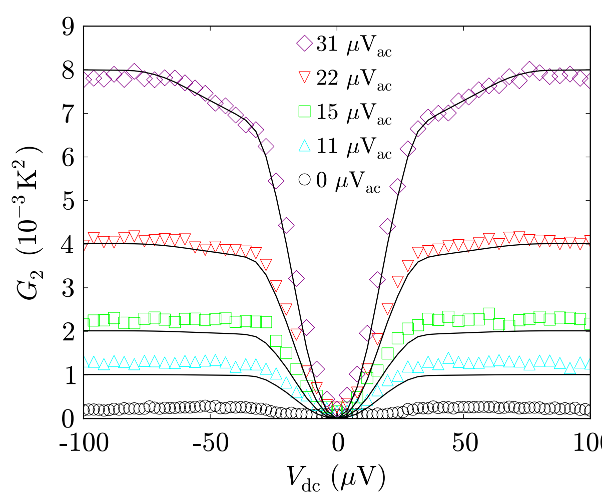

FIG. 2 (color online). Reduced power-power correlator G_2 vs dc bias voltage for various ac excitation amplitudes at frequency $f_0 = f_1 + f_2 = 11.6$ GHz. Symbols are experimental data and solid lines theoretical expectations of Eqs. (1) and (2). Symbol sizes represent experimental uncertainty and each point was averaged over 773 s (3.1×10^{11} samples) for curves $V_{ac} = 15\ \mu V_{ac}$ and above, 1546 s (6.2×10^{11} samples) at $V_{ac} = 11\ \mu V_{ac}$ and 1.5×10^4 s (6.3×10^{12} samples) at $V_{ac} = 0\ \mu V_{ac}$.

noticeable at very low ac bias. In particular, the photo-assisted G_2 should be zero in the absence of ac excitation while we measure a tiny contribution of magnitude $\sim 2 \times 10^{-4}$ K^2. While experimental uncertainty, represented by symbol size on Fig. 2, can partly explain this observation, the difference is non-negligible. This might be due to an imperfect calibration of the setup, but could also correspond to a real signal. Indeed, the current fluctuations generated by the junction are not Gaussian, which causes the existence of an intrinsic fourth cumulant, given by $e^3 V \Delta f/(k_B^2 G) \sim 1.5 \times 10^{-5}$ K^2 at $V_{\mathrm{dc}} = 100\ \mu$V, i.e., smaller than the observed signal by more than an order of magnitude.

As is the case for the third moment [9–11], environmental effects can contribute to the fourth cumulant. In particular, a contribution $\sim (dS/dV)^2 \langle \delta V^2 \rangle$ is expected. Here, (dS/dV) stands for the noise susceptibility [6–8] and $\langle \delta V^2 \rangle$ the voltage noise experienced by the sample within the relevant bandwidth. Considering low-frequency (≤ 400 MHz) fluctuations of a 50 Ω environment, a noise temperature of 5 K would be required to explain the observed signal. Further experimental study is required in order to fully explore this phenomenon.

*Photon-photon correlations.—*The power detectors used in our experiment are not photodetectors, but are sensitive to the total electric field generated by the sample. The detected power thus contains the contributions of photons emitted and absorbed by the junction as well as vacuum fluctuations. The amplifier noise adds a large contribution to this, which contributes to the average power but not to G_2. We will now evaluate G_2 in terms of photons emitted by the junction.

The total noise spectral density we detect can be decomposed into $S = S_{\mathrm{em}} + Ghf$ where $S_{\mathrm{em}} = 2Ghf\langle n(f) \rangle$ is the emission noise [12–14] and $\langle n(f) \rangle$ is the average number of photons emitted at frequency f per unit time per unit bandwidth. At equilibrium, one obtains the average number of photons emitted from $S_0(f)$: $n_0(f) = [\exp(hf/k_B T) - 1]^{-1}$, here $\sim 10^{-8}$, which corresponds to the Bose-Einstein distribution, as expected for thermal radiation.

Similarly, we can express the power-power correlator G_2 in terms of a photon-photon correlator. Using $\langle \delta P_1 \delta P_2 \rangle \propto \langle \delta n_1 \delta n_2 \rangle = \langle n_1 n_2 \rangle - \langle n_1 \rangle \langle n_2 \rangle$ with $n_{1,2} = n(f_{1,2})$, we define the normalized correlator [3,15,16]:

$$g_2 = \frac{\langle n_1 n_2 \rangle}{\langle n_1 \rangle \langle n_2 \rangle} = 1 + \frac{G_2}{S_{\mathrm{em}}(f_1) S_{\mathrm{em}}(f_2)}, \qquad (3)$$

which is shown by the red circles in Fig. 3, left scale.

While $g_2 = 1$ corresponds to photons at frequencies f_1 and f_2 being emitted independently, as for chaotic light, a value above 1 like the one observed here indicates the existence of correlations in the emission of photons [3]. When the number of emitted photons is large, correlations can be of classical origin, as in [4]. However, $g_2 > 1$ for $\langle n_{1,2} \rangle \ll 1$, which can be seen in the large peak we observe on Fig. 3, implies the existence of correlations at the single photon level, i.e., photon pairs. The average photon numbers $\langle n_{1,2} \rangle$ are plotted on the right scale of Fig. 3. These are calculated from the noise spectral density under ac excitation using $S(f) = \frac{1}{2} \Sigma_n J_n^2 (eV_{\mathrm{ac}}/hf_0)[S_0(f_{n+}) + S_0(f_{n-})]$.

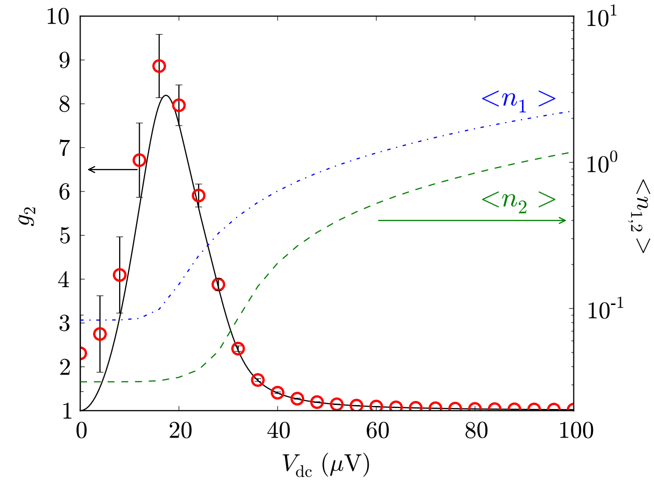

FIG. 3 (color online). Left scale: Normalized photon-photon correlator g_2 vs dc bias voltage for a fixed ac bias $V_{\mathrm{ac}} = 22\ \mu$V. Red circles are experimental data, where each point was averaged over 773 s (3.1×10^{11} samples), and the full line represents theoretical expectations from Eq. (3). Right scale (dashed lines): Number of emitted photons per unit bandwidth per unit time $\langle n_{1,2} \rangle$ in branches 1 and 2.

The shape of g_2 on Fig. 3 can be understood using Eq. (3). For $V_{\mathrm{dc}} = 0$, one expects $G_2 = 0$; therefore, $g_2 = 1$. However, since we observe $G_2(V_{\mathrm{dc}} = 0) > 0$, we obtain $g_2 > 1$. When V_{dc} increases and $V_{\mathrm{dc}} \leq V_{\mathrm{ac}}$, G_2 increases rapidly (see Fig. 2) while the number of emitted photons remains constant, as can be seen on Fig. 3, right axis. This leads to a sharp rise in g_2. At higher dc bias, G_2 remains constant while $\langle n_{1,2} \rangle$ rise quickly with dc bias. This results in a decrease of g_2, which decays down to 1 at large dc bias. In Ref. [4] was demonstrated the existence of correlated power fluctuations in photoassisted shot noise. Here, we show that the underlying mechanism, the modulation of noise by a time-dependent voltage, still applies down to the single photon level, i.e., results in correlated emission of single photons. Consequently, since noise modulation saturates at high V_{dc}, so does the emission rate of photon pairs.

The number of photons detected in each measurement of duration $\tau = 2.5$ ns, $\langle n \rangle = \Delta f \tau$, is close to $\langle n \rangle$ since $\Delta f_1 \tau = 1.65$ and $\Delta f_2 \tau = 0.95$. Thus, the peak in g_2 coincides with small photon numbers $\langle n_1 \rangle \simeq 0.11$ and $\langle n_2 \rangle \simeq 0.03$. If photons of frequency f_2 were always part of a pair, one would have $\langle n_1 n_2 \rangle = \langle n_2 \rangle$ and $g_2 = 1/\langle n_1 \rangle = 9.1$. As we discuss below, this is almost the case.

In order to quantify the probability that a photon detected by our setup was emitted as part of a pair, we adopt a simple model valid in the $\langle n_{1,2}\rangle \ll 1$ limit: we neglect the possibility of two photons reaching the same detector within a detection window. In that case, probabilities of detecting one photon at frequencies f_1 and f_2 within a detection window are, respectively, $P(1) = \langle n_1\rangle$ and $P(2) = \langle n_2\rangle$, while that of detecting a pair of photons is given by $P(1,2) = \langle n_1 n_2\rangle$. The probability of detecting a pair of photons when a photon is detected at frequency f_2 is therefore $P(1|2) = \langle n_1 n_2\rangle/\langle n_2\rangle$. The data in Fig. 3 yield a probability of 94% at $V_{\mathrm{dc}} = 16\ \mu\mathrm{V}$, $V_{\mathrm{ac}} = 22\ \mu\mathrm{V}$ that a photon detected at f_2 was emitted as part of a pair. Both $\langle n_{1,2}\rangle$ and $\langle n_1 n_2\rangle$ can be controlled using V_{ac}. Specifically, $\langle n(V_{\mathrm{dc}} = 0)\rangle \propto V_{\mathrm{ac}}^2$ and $\langle n_1 n_2\rangle \propto V_{\mathrm{ac}}^2$ at large dc bias. As a result, the peak in g_2 decreases as V_{ac} increases. Indeed, we observe $g_2^{\mathrm{max}}(V_{\mathrm{ac}} = 31\,\mu\mathrm{V}) = 5$ and $g_2^{\mathrm{max}}(V_{\mathrm{ac}} = 15\,\mu\mathrm{V}) = 19$.

The creation of photon pairs of different frequencies in the microwave domain has been achieved recently with the help of superconducting circuits [17–19]. Specifically, [17] reported a yield of 6×10^6 pairs per second, while our junction generates the same amount of pairs for a bandwidth of 200 MHz. Since the two photons have different frequencies, a (purely dispersive) diplexer can be used to separate them spatially without loss.

Noise reduction factor.—The previous description corresponds to coincidence measurements in optics. Our observations can also be viewed as evidence for two-mode amplitude squeezing, i.e., the ability for two light beams to have relative intensity fluctuations below the classical limit [15]. Classically, the variance of $n_1 - n_2$ is limited by the photon shot noise of the two beams, given by $\langle n_1\rangle + \langle n_2\rangle$. Thus, one usually defines the noise reduction factor NRF as [16,20,21]:

$$\mathrm{NRF} = \frac{\langle(\delta n_1 - \delta n_2)^2\rangle}{\langle n_1\rangle + \langle n_2\rangle}, \tag{4}$$

which is greater than 1 for classical light. To calculate the NRF for our experiment, one needs to know the variance of the photon number fluctuations at each frequency $\langle \delta n_{1,2}^2\rangle$.

This quantity is difficult to ascertain experimentally given the large contribution of the amplifier. However, the voltage noise measured in each frequency band is almost Gaussian, i.e., identical to that of the thermal noise of a macroscopic resistor, whose photon statistics is that of chaotic light. Thus it obeys $\langle \delta n^2\rangle = \langle n\rangle(\langle n\rangle + 1)$ [22,23]. More precisely, the current measured at frequency f can be described using $i(t) \propto a e^{-i2\pi f t} + a^\dagger e^{i2\pi f t}$. This leads to $\langle i(t)^2\rangle \propto \langle n\rangle + 1/2$, as discussed before, and to a fourth cumulant $\langle\langle i(t)^4\rangle\rangle \propto (\langle \delta n^2\rangle - \langle n\rangle(\langle n\rangle + 1))$. Since current fluctuations at a given frequency are almost Gaussian, $\langle\langle i(t)^4\rangle\rangle \approx 0$, yielding $\langle \delta n^2\rangle = \langle n\rangle(\langle n\rangle + 1)$. Using this result, we can calculate the NRF, which clearly goes below 1, as represented on Fig. 4 where we observe a minimum value of 0.71. This proves the existence of two-mode vacuum amplitude squeezing in the noise emitted by the junction, a direct consequence of the presence of photon pairs. In terms of the current-current correlator, our result is another example of violation by electronic quantum noise of a Cauchy-Schwartz inequality [24].

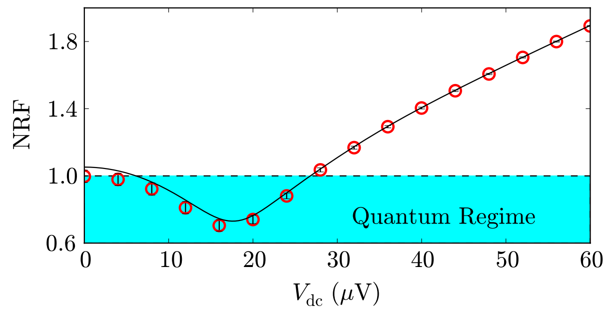

FIG. 4 (color online). Noise reduction factor vs dc bias voltage for a fixed ac bias $V_{\mathrm{ac}} = 22\ \mu\mathrm{V}$. Red circles are experimental data, where each point was averaged over 773 s (3.1×10^{11} samples), and the full line represents theoretical expectations. The shaded region NRF< 1 corresponds to nonclassical electromagnetic field.

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