Emission of Photon Multiplets by a dc-Biased Superconducting Circuit

[PHYSICAL REVIEW X 12, 021006 (2022)]

G.C. Ménard, A. Peugeot, C. Padurariu, C. Rolland, B. Kubala,
Y. Mukharsky, Z. Iftikhar, C. Altimiras, P. Roche, H. le Sueur, P. Joyez,
D. Vion, D. Esteve, J. Ankerhold, and F. Portier

Presented by: Rubek Poudel, TU Munich

January 10, 2023

Outline

Quantum concept

- Max Planck: light emission by hot matter
  - Recognition of the granular character of light
  - Concept of photons as particles
  - Energy of a photon : $E = \hbar\omega$

Focus: Emission of bunches of photons (in a single event)

- Model of the experiment
- Performing the experiment
- Amplitude of photon emission
- K-granularity?

Light-matter coupling

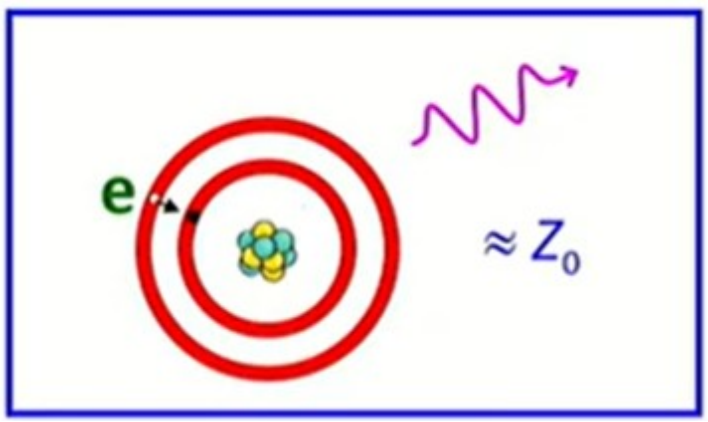


Figure: Excited atom in a box

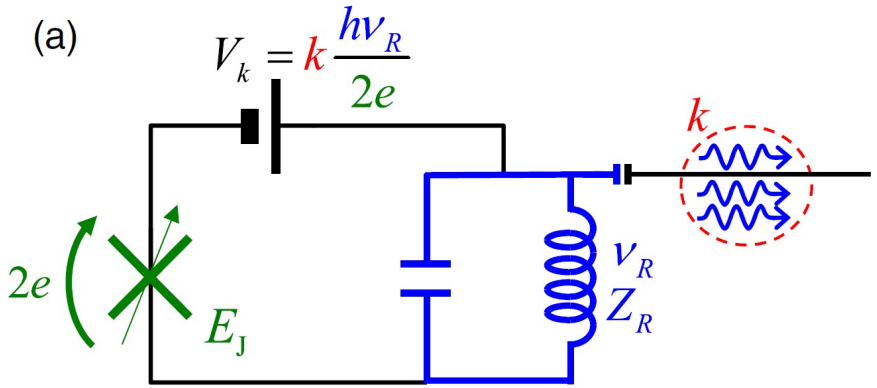
For matter light coupling:

$$\alpha_{\mathrm{QED}} = \frac{1}{2}\frac{\mathrm{Z}_0}{\mathrm{R}_\mathrm{K}} = \frac{1}{137}$$

$$\mathrm{R}_\mathrm{K} = \frac{\mathrm{h}}{\mathrm{e}^2},\ \mathrm{Z}_0 = \sqrt{\frac{\mu_0}{\epsilon_0}}$$

- 'α' is nature given

Analogy to the experiment :



$$\alpha = \pi \frac{Z_R}{R_Q}$$

$$Z_R = \sqrt{\frac{L}{C}},\ R_Q = \frac{h}{(2e)^2}$$

- 'α' can be engineered

Josephson Junction

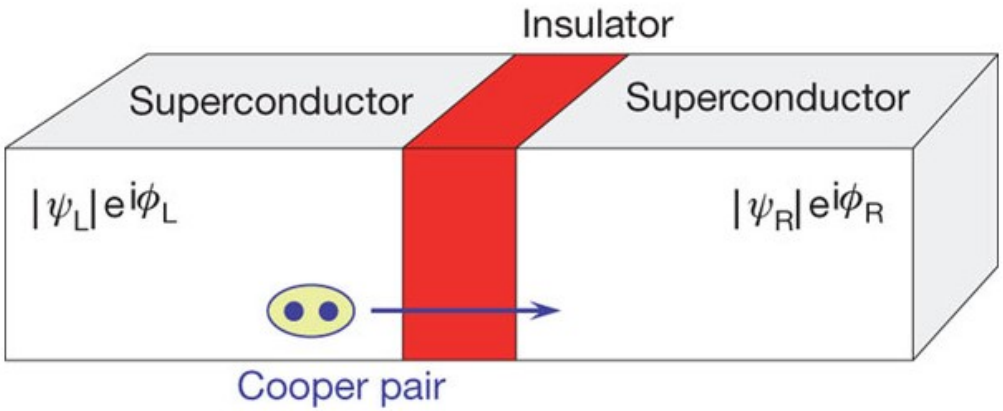


Figure: A Josephson's Junction, where Φ represents the phase

$$I(t) = I_c \sin(\Phi_R - \Phi_L)$$

$$\frac{\partial \Phi}{\partial t} = \frac{2eV(t)}{\hbar}$$

Voltage-biased Josephson Junction

For: $2eV_k = k \cdot h\nu_R$

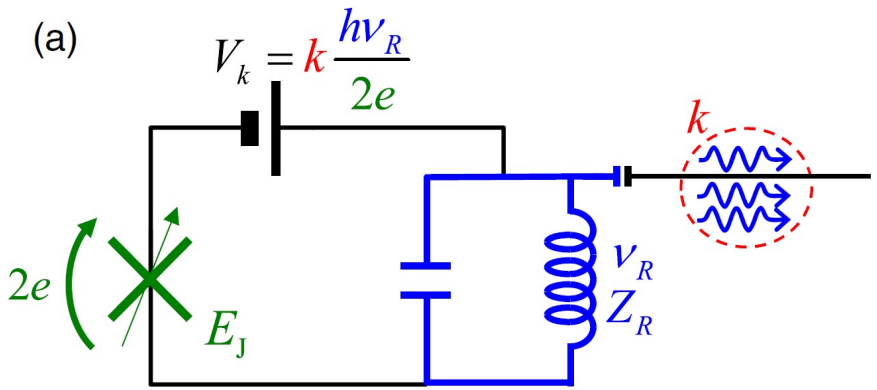
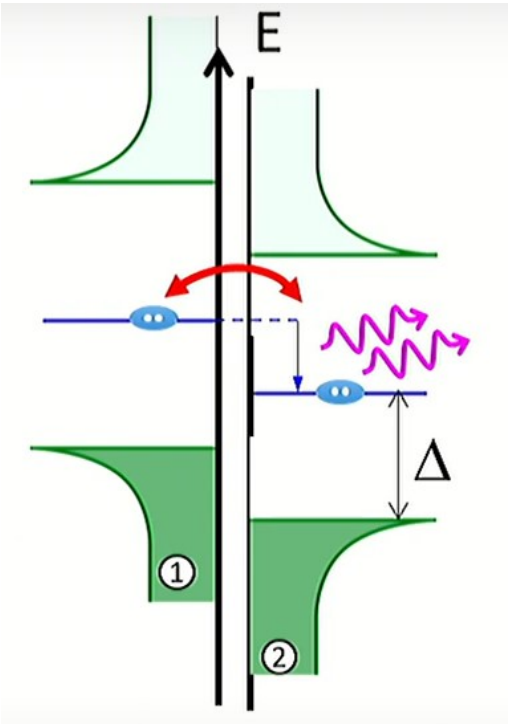


Figure: Voltage-biased SIS Junction



Hamiltonian

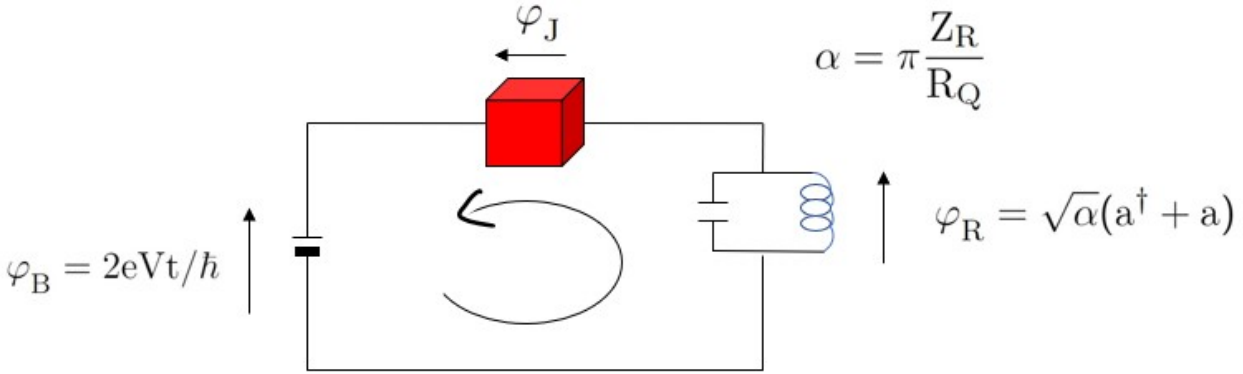
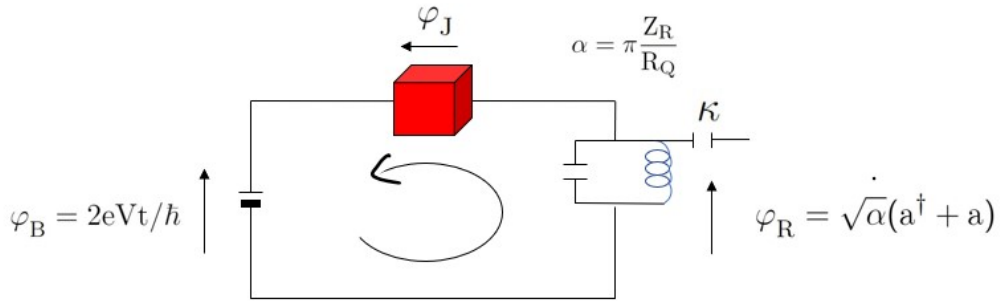


Figure: Schematic of the voltage biased Josephson Junction

$$\hat{H} = \hbar\omega_R \hat{a}^\dagger \hat{a} - E_J \cos[\omega_J t - \sqrt{\alpha}(\hat{a}^\dagger + \hat{a})]$$

Hamiltonian: Rotating Wave Approximation (RWA)



$$2eV_k = k \cdot h\nu_R + \delta/2\pi \qquad \kappa = \frac{2\pi\nu_R}{Q}$$

$$\hat{H}_k = -\frac{E_J e^{-\alpha/2}}{2} \alpha^{k/2} [e^{-i\delta_k t} (i\hat{a}^\dagger)^k \hat{B}_k + \text{H.c.}],$$

- Amplitude of production of photon favored by high α
- Lindblad master equation simulation and Quantum regression theorem for photon statistics.

Fabrication

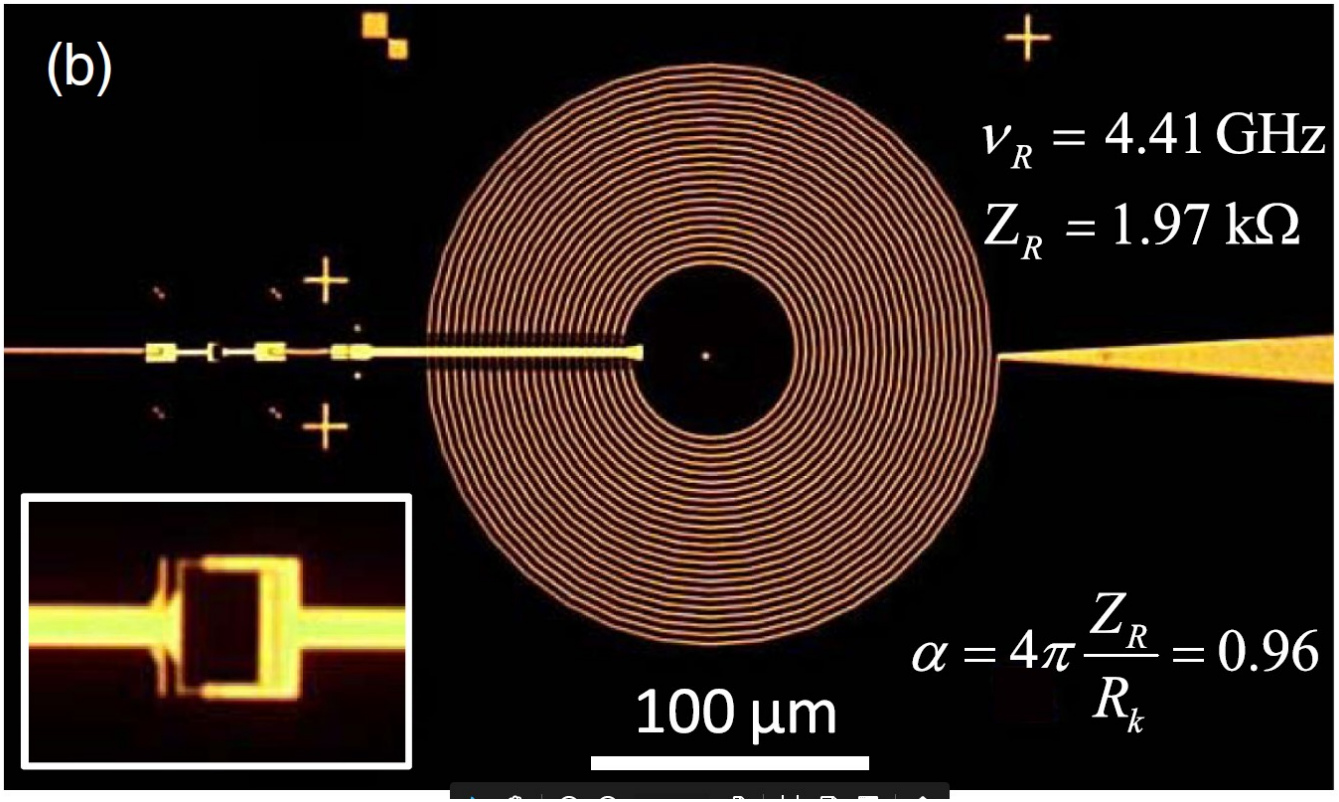


Figure: Optical micrograph of the sample

Experimental Setup

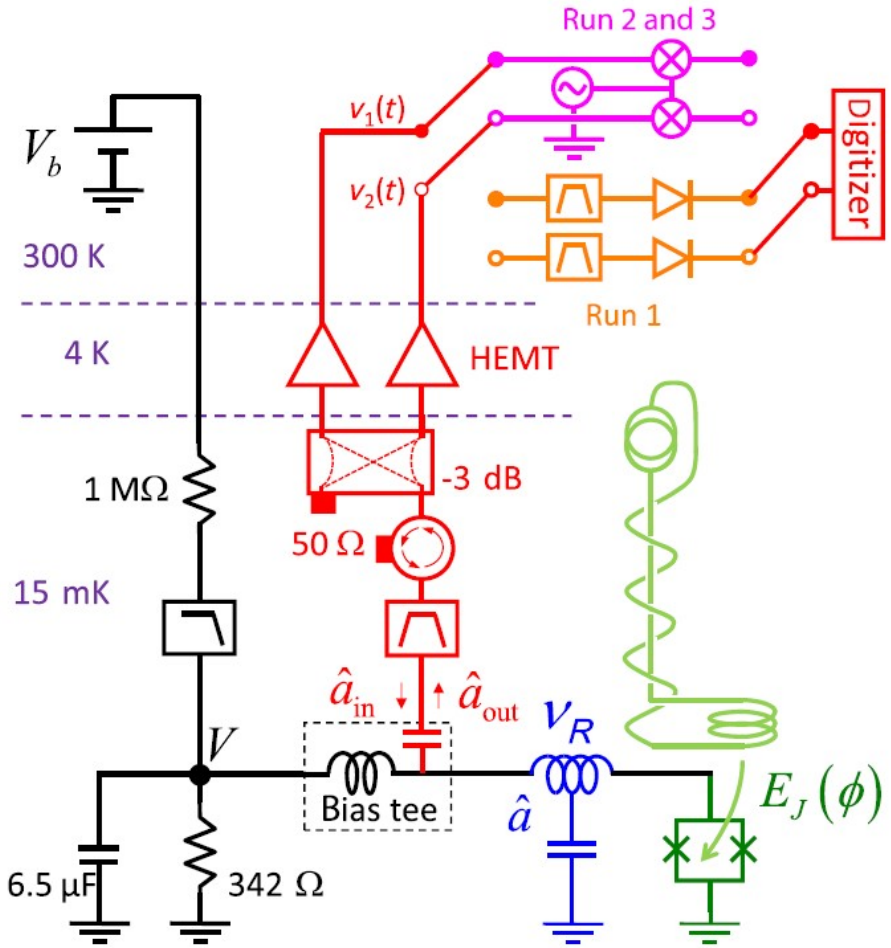
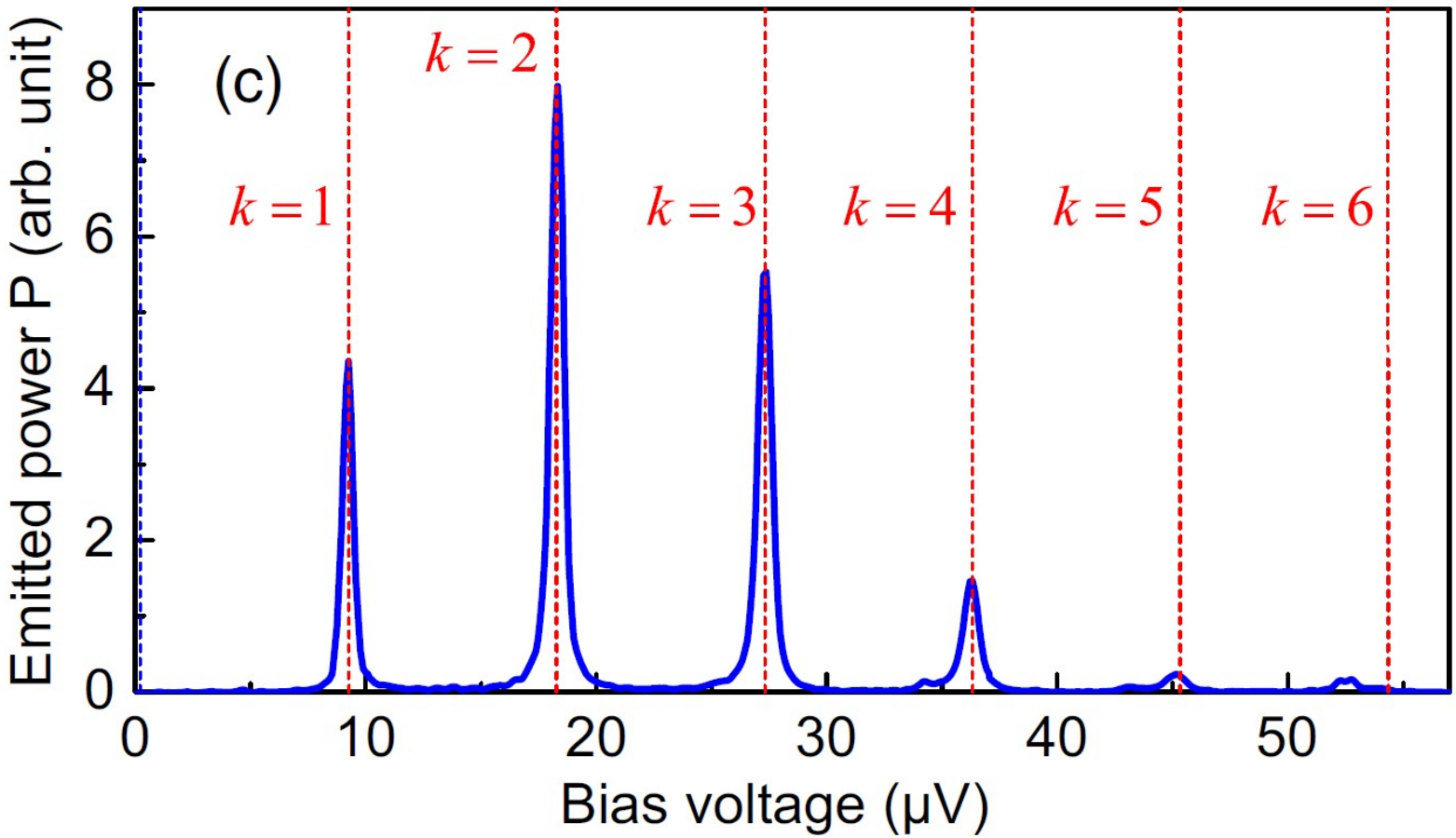


Figure: Schematic of the experimental setup

Emission spectrum



Multiphoton emission spectra and emitted power

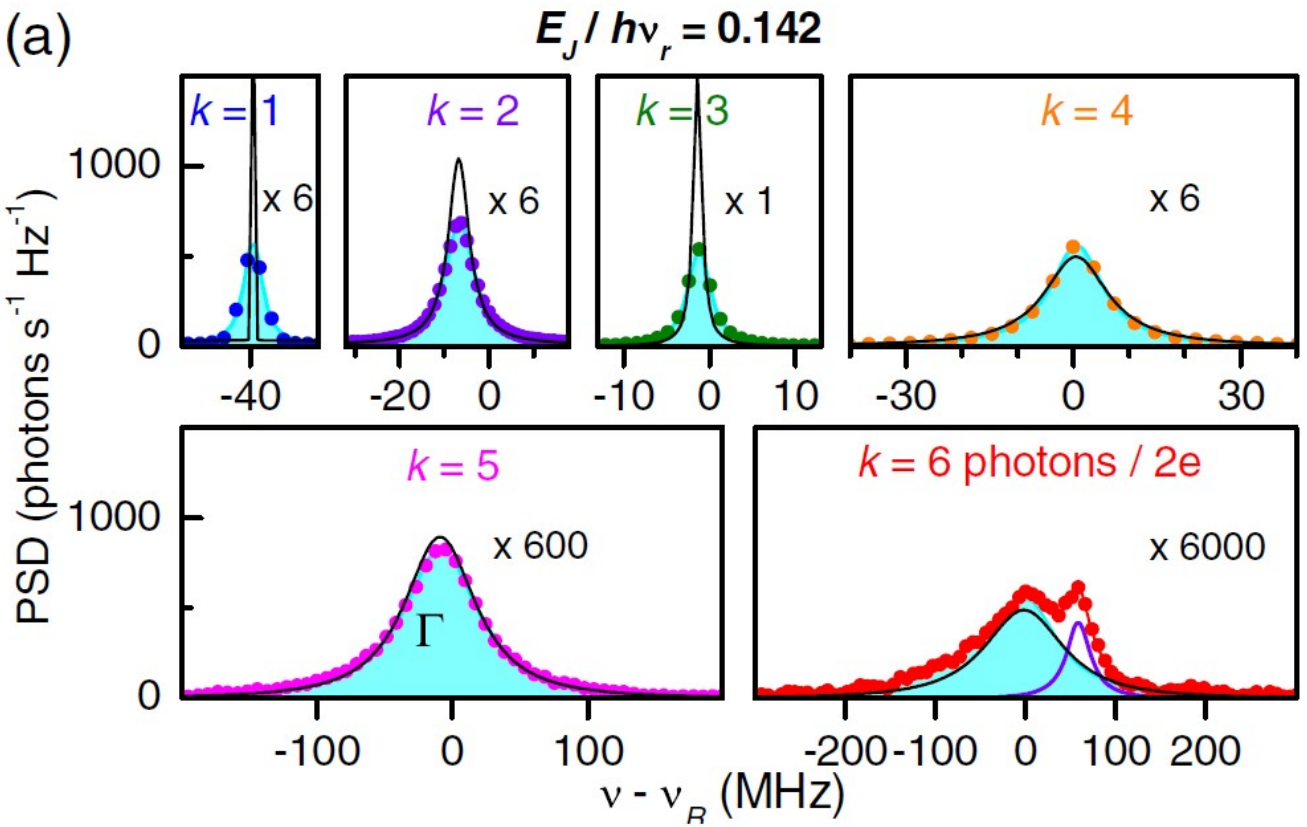
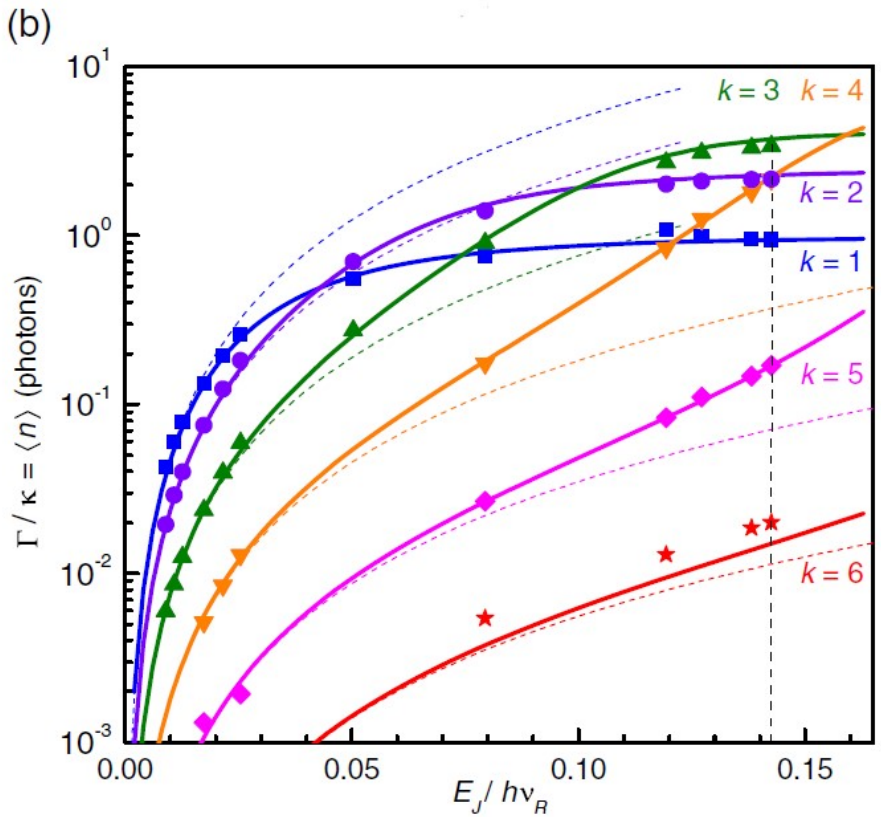


Figure: Multiphoton emission spectra and emitted power for k = 1-6

Photons Rate: Results of simulations



Purcell relaxation rate:

$$\gamma_k = \frac{\Gamma_k}{k} = -\left(\frac{E_J}{\hbar\omega_R}\right)^2 \frac{\alpha^k e^{-\alpha}}{kk!} \frac{Q\omega_R}{1 + (\frac{2Q\delta_k}{k\omega_R})^2}$$

Granularity of Photon Emission

Fano Factor:

$$F_{-2e} = \frac{\mathrm{Var}(N)}{\overline{N}} \qquad F_{ph} = \frac{\mathrm{Var}(kN)}{k\overline{N}} = k \cdot F_{-2e}$$

$$F_k = 1 + 2\Gamma_k \int_0^{+\infty} [g^{(2)}(\tau) - 1] d\tau$$

$$g^{(2)}(\tau) = \frac{\langle \hat{a}^\dagger_{out}(0)\hat{a}^\dagger_{out}(\tau)\hat{a}_{out}(\tau)\hat{a}_{out}(0)\rangle}{\langle \hat{a}^\dagger_{out}\hat{a}_{out}\rangle^2}$$

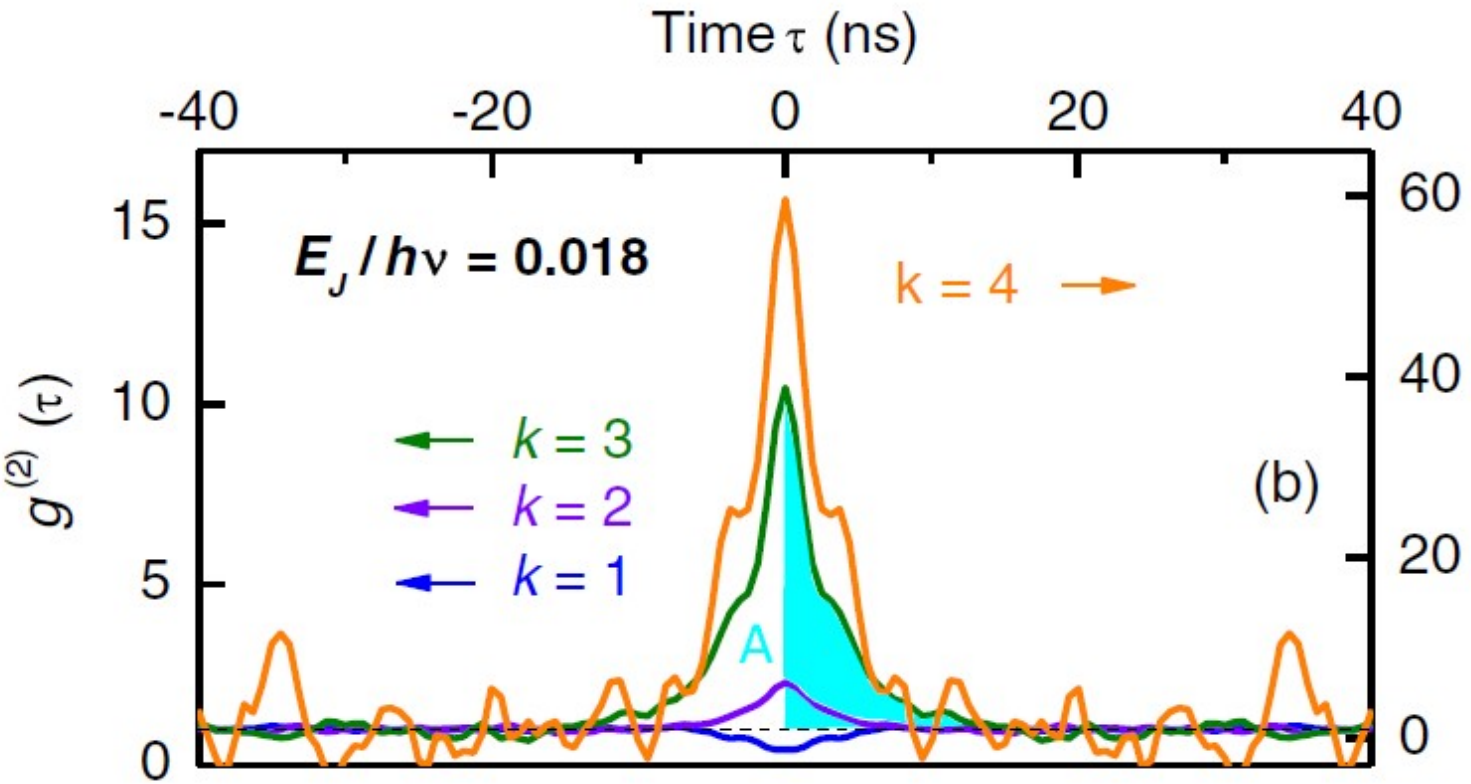


Figure: g^2 functions as a function of time

$$F_k = 1 + 2\Gamma_k \int_0^{+\infty} [g^{(2)}(\tau) - 1] d\tau$$

K-photon bunching

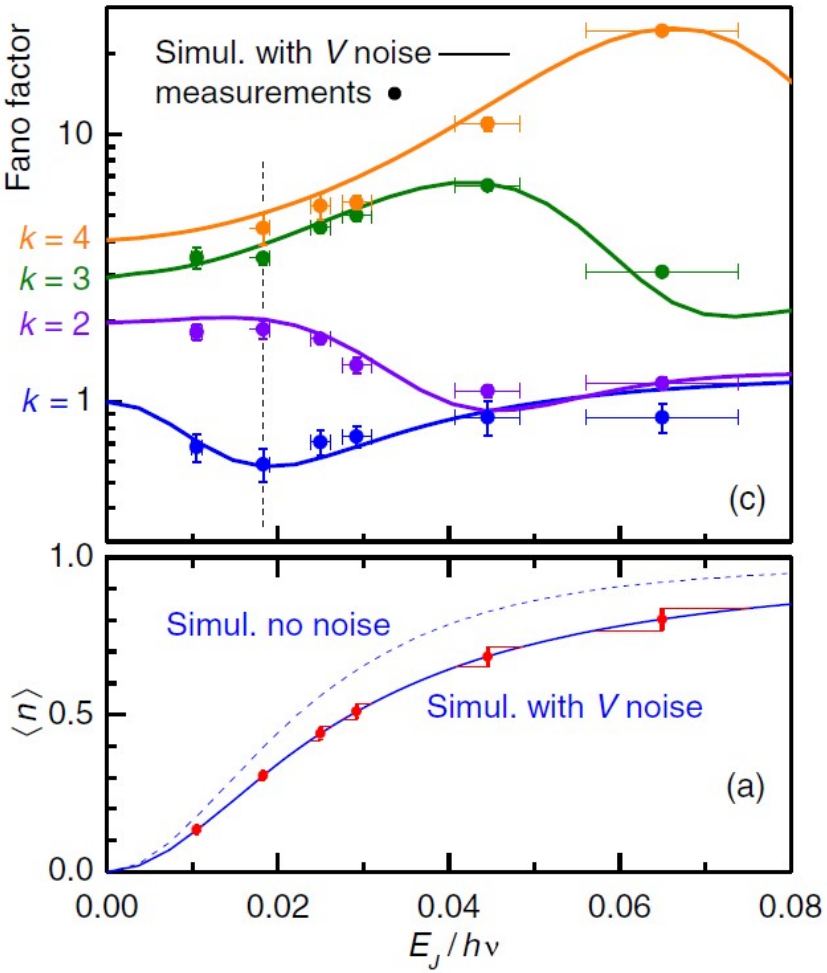
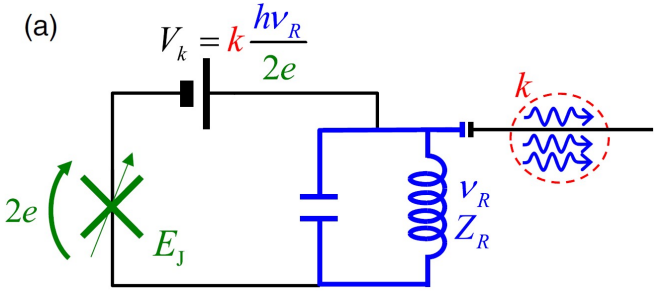
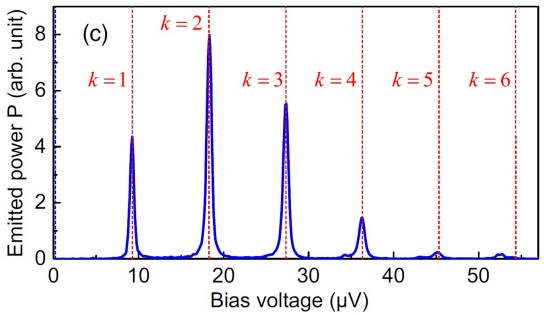


Figure: Granularity of photon emission vs E_J

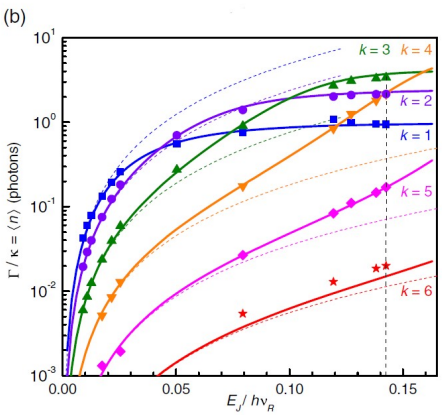
Summary



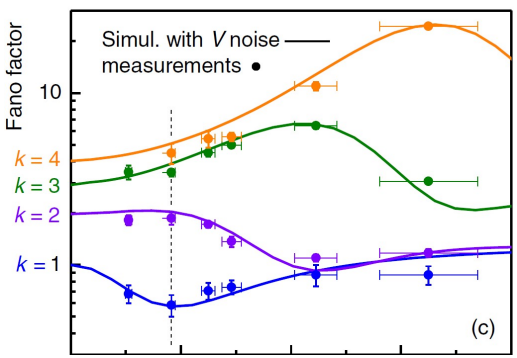
- A simple dc-biased JJ



- k-photon emission



- Photon rates



- k-granularity

Thank you for your attention ☺

References I

- C. Cohen-Tannoudji, J. Dupont-Roc, and G.W. Grynberg, Introduction to Quantum Electrodynamics (Wiley-Interscience, New York, 1989).

- M. Corona, K. Garay-Palmett, and A. B. U'Ren, Third-Order Spontaneous Parametric Down-Conversion in Thin Optical Fibers as a Photon-Triplet Source, Phys. Rev. A 84, 033823 (2011).

- C. Altimiras, F. Portier, and P. Joyez, Interacting Electrodynamics of Short Coherent Conductors in Quantum Circuits, Phys. Rev. X 6, 031002 (2016).

- Simon Dambach, Bjorn Kubala, Vera Gramich, and Joachim Ankerhold, Time-Resolved Statistics of Nonclassical Light in Josephson Photonics, Phys. Rev. B 92, 054508 (2015).

References II

- A. Peugeot, G. M´enard, S. Dambach, M.Westig, B. Kubala, Y. Mukharsky, C. Altimiras, P. Joyez, D. Vion, P. Roche, D. Esteve, P. Milman, J. Leppäkangas, G. Johansson, M. Hofheinz, J. Ankerhold, and F. Portier, Generating Two Continuous Entangled Microwave Beams Using a dc- Biased Josephson Junction, Phys. Rev. X 11, 031008 (2021).

- I. C. Fulga, F. Hassler, and C.W. J. Beenakker, Nonzero Temperature Effects on Antibunched Photons Emitted by a Quantum Point Contact Out of Equilibrium, Phys. Rev. B 81, 115331 (2010).