Persistent Rabi oscillations revealed in low-frequency noise

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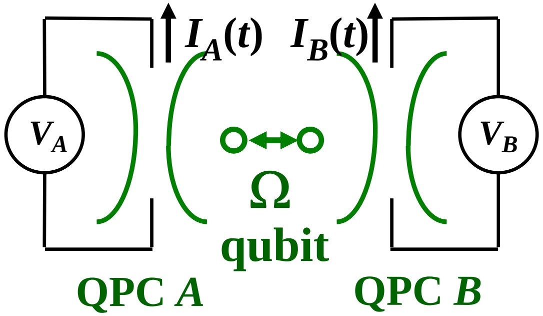
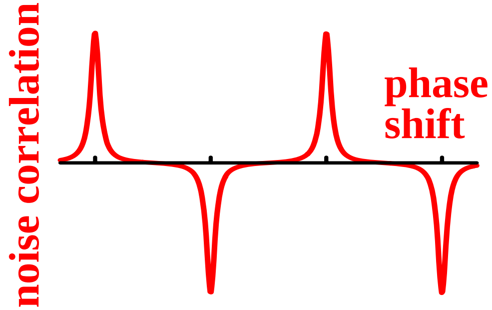
Outline:

- Introduction (recent experiments on weak collapse of solid-state qubits)
- Idea of the new experimental proposal
- Calculation results and estimates

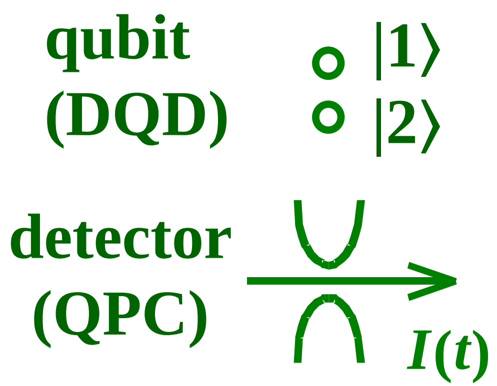




Support:

Non-projective (weak, continuous) measurement of a charge qubit

Korotkov, 1998



Evolution due to measurement
("spooky" quantum back-action)

$$\psi(t) = \alpha(t)\,|1\rangle + \beta(t)\,|2\rangle \quad \text{or} \quad \rho_{ij}(t)$$

1) $|\alpha(t)|^2$ and $|\beta(t)|^2$ evolve as probabilities,
i.e. according to the **Bayes rule** (same for ρ_{ii})

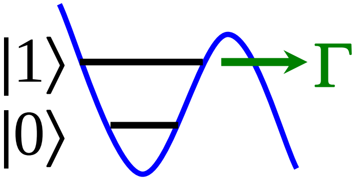
2) phases of $\alpha(t)$ and $\beta(t)$ do not change
(**no decoherence!**), $\rho_{ij}/(\rho_{ii}\,\rho_{jj})^{1/2} = \text{const}$

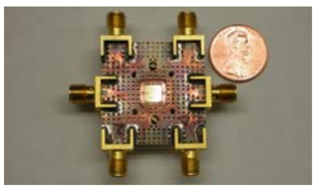
Similar to POVM, general quantum meas., quantum trajectories, etc.

Existing solid-state experiments (3 expts.)

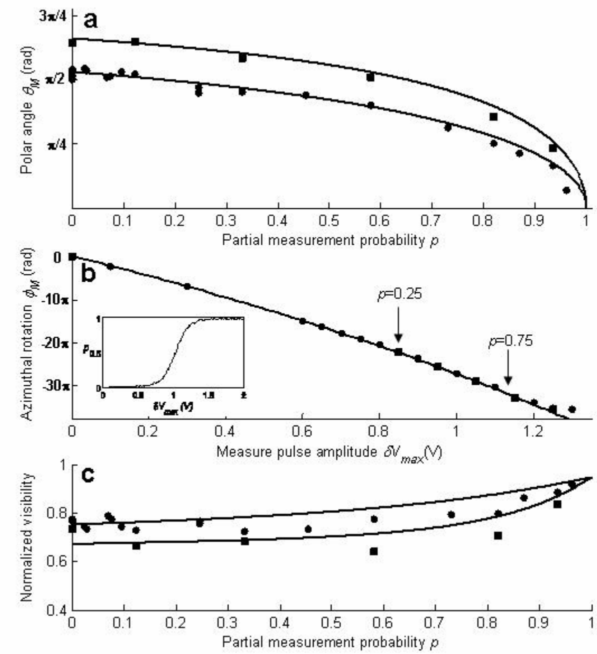
1. Partial collapse of a phase qubit

N. Katz et al., Science-06 (Martinis group, UCSB)





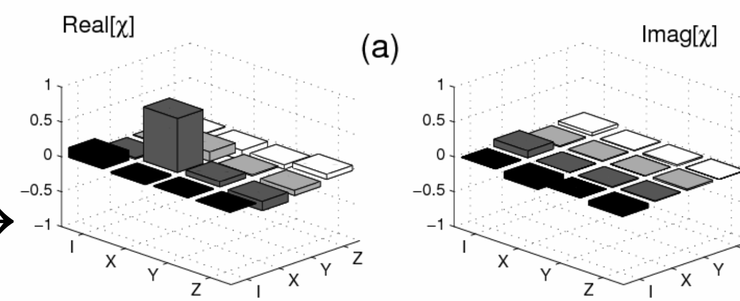
$$\psi(t) = \begin{cases} |out\rangle, \text{ if tunneled} \\ \dfrac{\alpha|0\rangle + \beta e^{-\Gamma t/2} e^{i\varphi}|1\rangle}{\sqrt{|\alpha|^2 + |\beta|^2 e^{-\Gamma t}}}, \text{ if not tunneled} \end{cases}$$

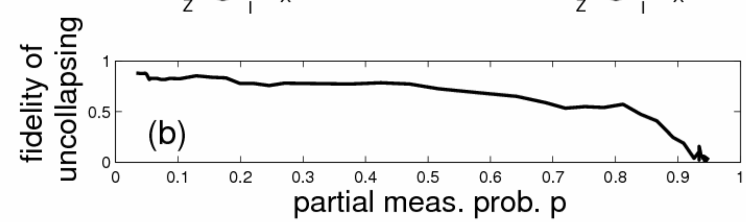


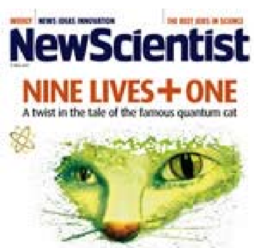
2. Uncollapse of a phase qubit
(by erasing classical information)

N. Katz et al., PRL-08 (Martinis group, UCSB)

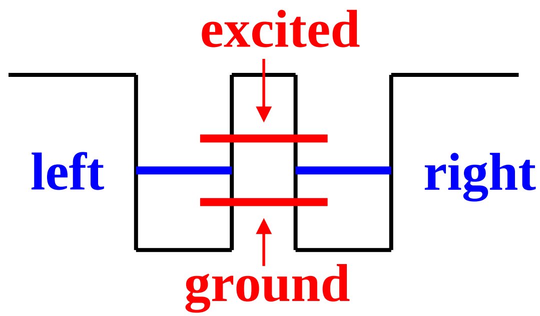
$$\alpha|0\rangle + \beta|1\rangle \rightarrow (\alpha|0\rangle + e^{i\phi}\beta e^{-\Gamma t/2}|1\rangle)/\text{Norm} \rightarrow$$
$$\rightarrow e^{i\phi}(\alpha|0\rangle + \beta|1\rangle)$$



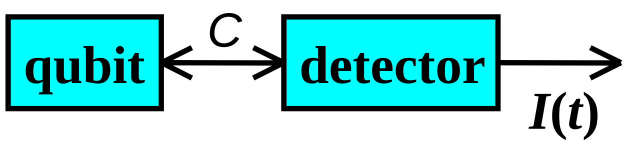


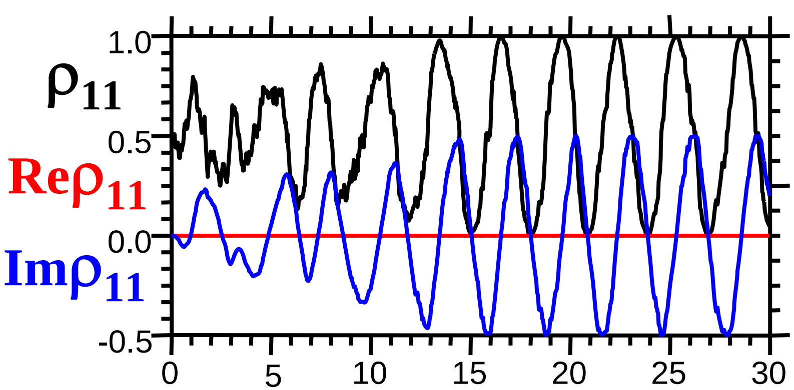


Persistent Rabi oscillations

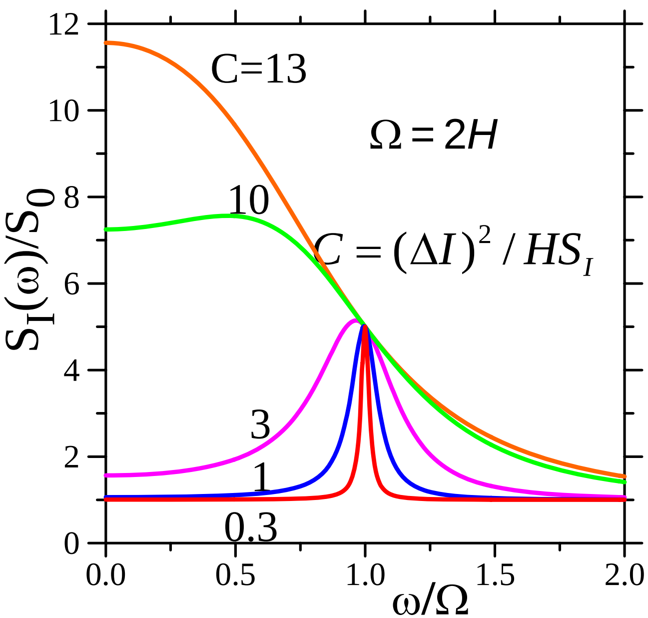


- Relaxes to the ground state if left alone (low-T)
- Becomes fully mixed if coupled to a high-T (non-equilibrium) environment
- Oscillates persistently between left and right if (weakly) measured continuously





Korotkov, 1998



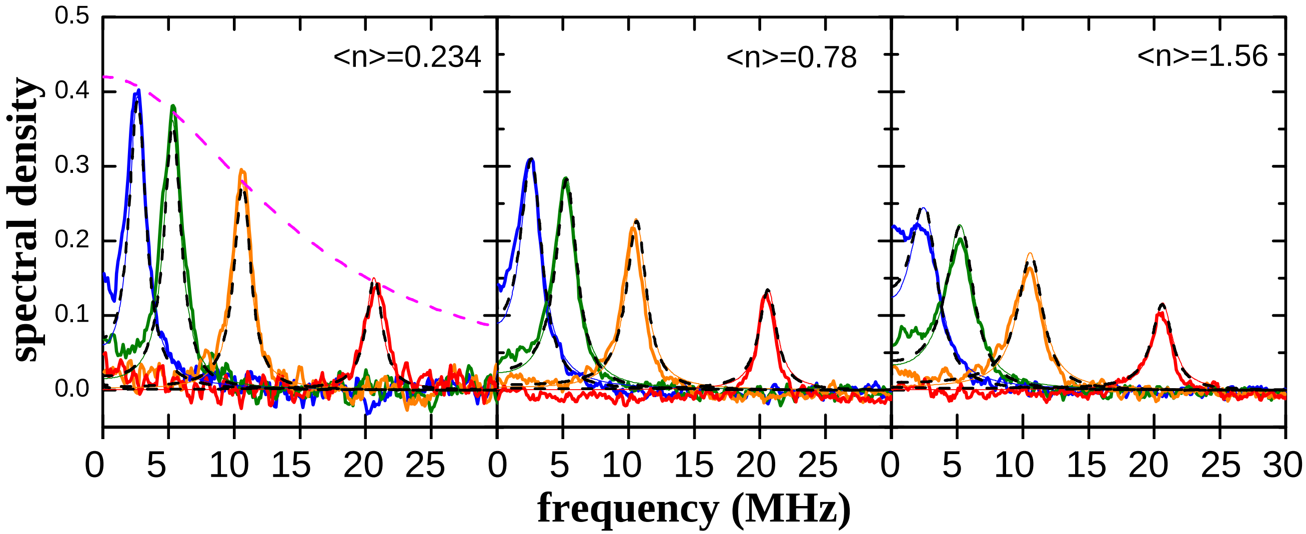
Korotkov, 1999
Korotkov-Averin, 2000

Existing solid-state experiments (cont.)

3. Persistent Rabi oscillations

A. Palacios-Laloy et al. (Saclay group, unpublished)

courtesy of Patrice Bertet

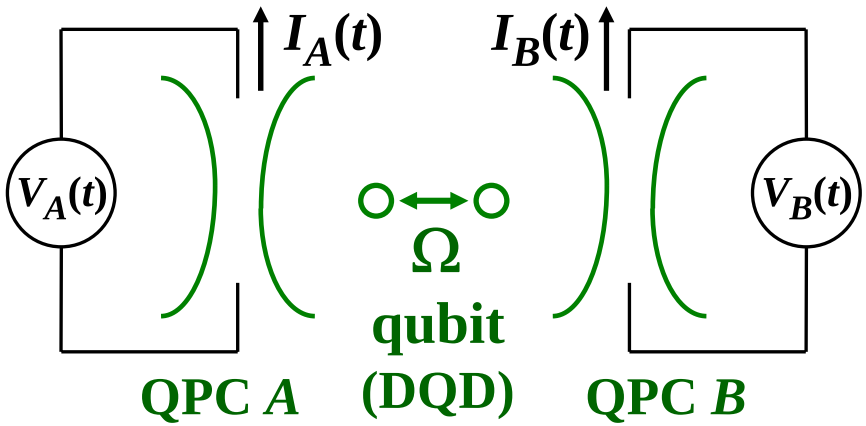


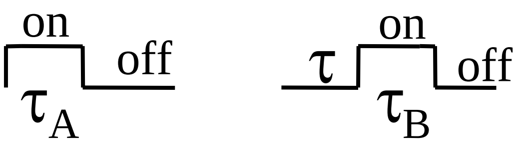
- superconducting charge qubit (transmon)
- circuit QED setup
- driven Rabi oscillations

All experiments so far are with superconducting qubits.
Can we do something with semiconductor qubits?

Technology is still not very good ⇒ need a non-demanding (but non-trivial) experiment

Setup: one qubit & two detectors





For single-shot measurements partial collapse revealed via **correlations** of $\int I_A$ and $\int I_B$.

(Korotkov, PRB-2001)

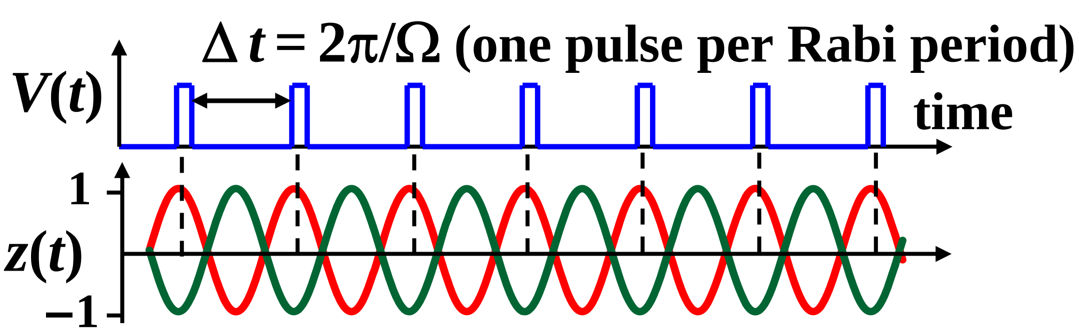
Same idea with another averaging → weak values

(Romito et al., PRL-2008)

Single-shot measurements are not yet available

⇒ use train (comb) of meas. pulses in QND regime

One-detector stroboscopic QND measurement



Stroboscopic QND:

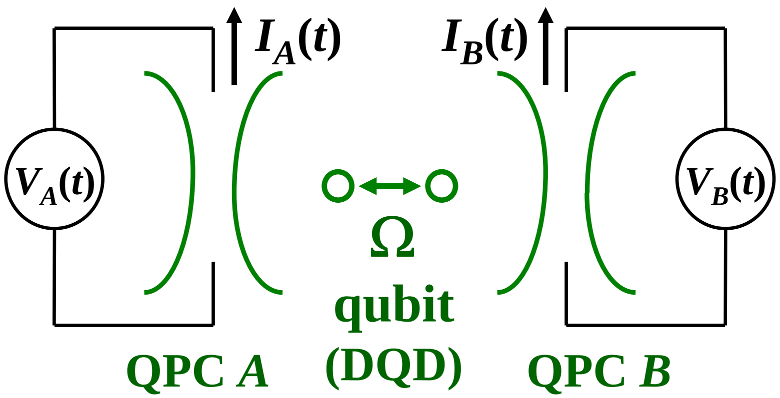
Braginsky et al., 1978

Jordan-Buttiker, 2005

Jordan-Korotkov, 2006

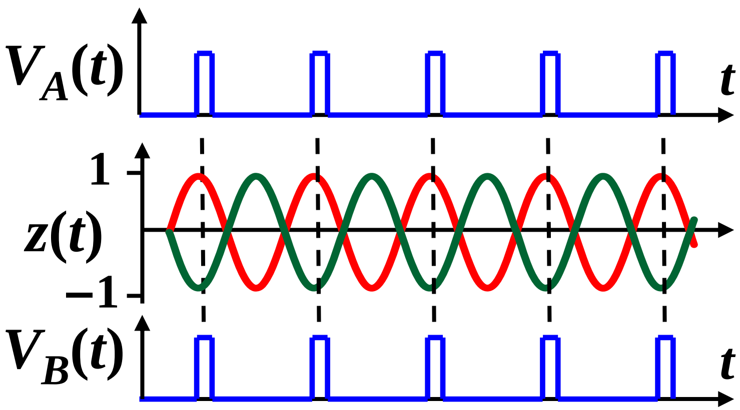
Stroboscopic QND measurement synchronizes (!) phase of persistent Rabi oscillations (attracts to either 0 or π)

Idea of the experiment



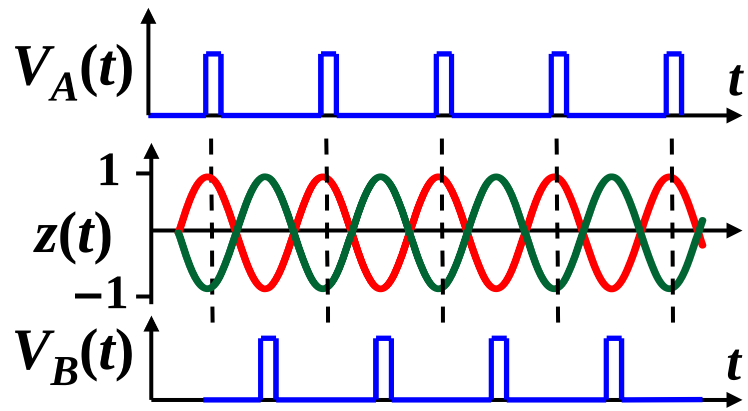
Imperfect QND ⇒ random switching between two Rabi phases (0 and π)
⇒ low-frequency telegraph noise

same combs on V_A and V_B



anticorrelation between I_A and I_B

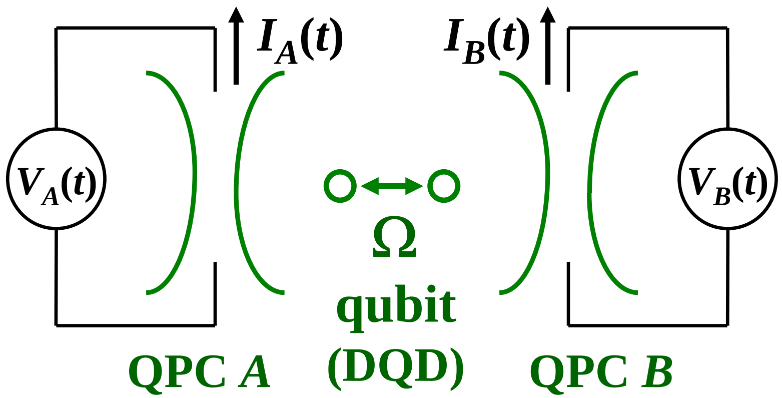
π-shifted combs on V_A and V_B

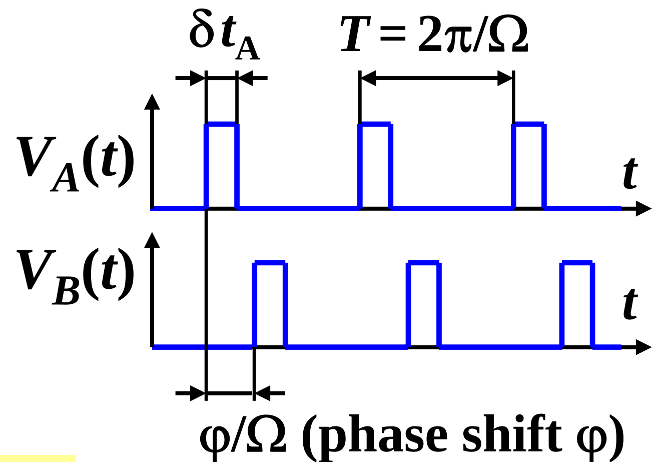


correlation (still QND!)

correlation/anticorrelation between low-frequency (telegraph) noises indicates presence of persistent Rabi oscillations

Analytical results for current noise





$$S_{IA}(\omega) \simeq S_A \frac{\delta t_A}{T} + \left(\frac{\delta t_A}{T}\right)^2 (\Delta I_A)^2 \frac{1/2\Gamma_S}{1+(\omega/2\Gamma_S)^2}$$

shot noise — telegraph noise

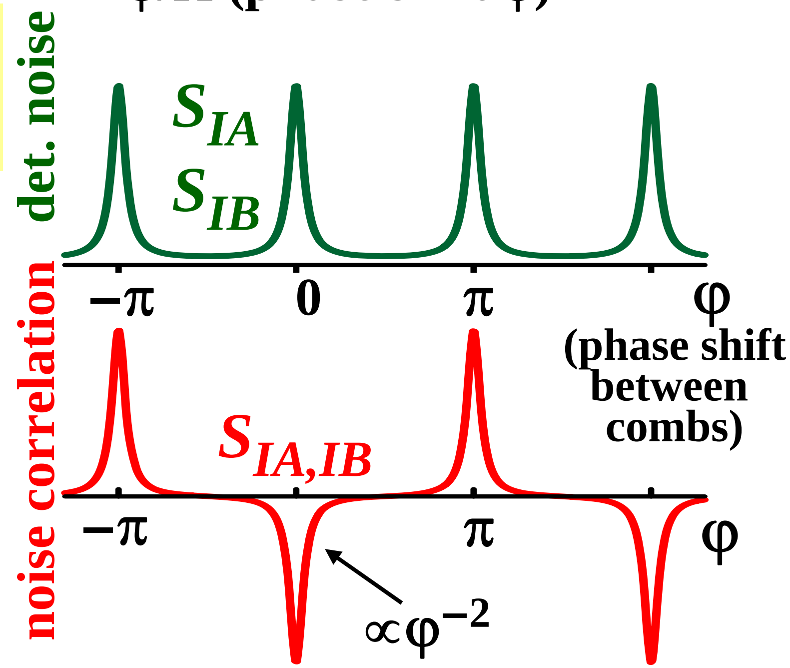
$$S_{IA,IB}(\omega) \simeq \pm \frac{\delta t_A}{T} \frac{\delta t_B}{T} \Delta I_A \, \Delta I_B \frac{1/2\Gamma_S}{1+(\omega/2\Gamma_S)^2}$$

(fully correlated/anticorrelated in first approx.)

$$\Gamma_S \simeq \frac{1}{4T_2} + \frac{\Omega}{4\pi}\left[\varphi^2 \frac{M_A M_B}{M_A+M_B} + \frac{\delta t_A^2 M_A + \delta t_B^2 M_B}{12\, T^2}\right]$$

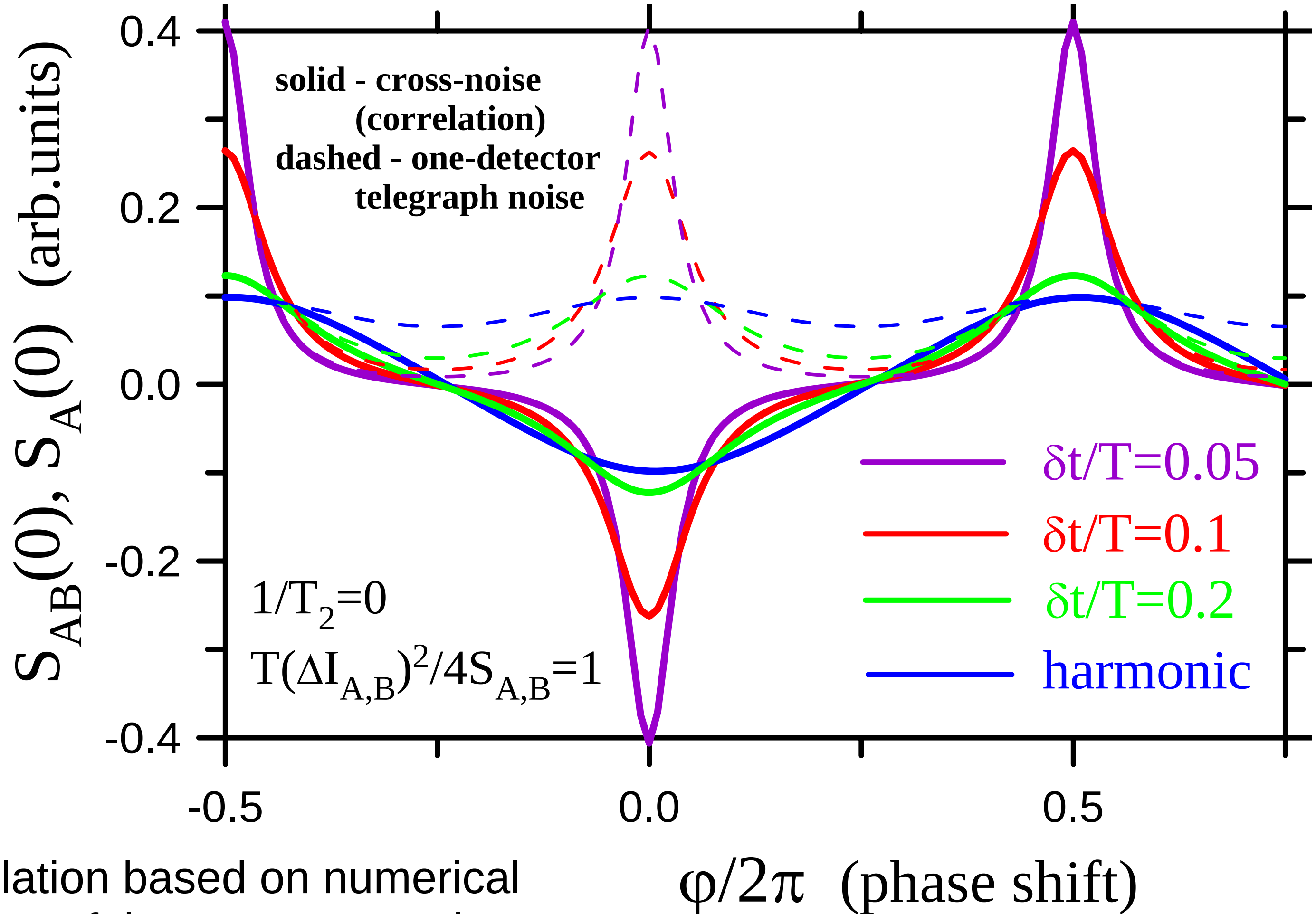
$$M_{A,B} = \delta t_{A,B} (\Delta I_{A,B})^2 / 4S_{A,B}, \;\; S_{A,B} = 2eI_{A,B}(1-T_{A,B})$$

Assumed: $\varphi \ll 1, \;\; \delta t \ll T, \;\; \delta t \ll 4S/(\Delta I)^2, \;\; T_2 \gg T$



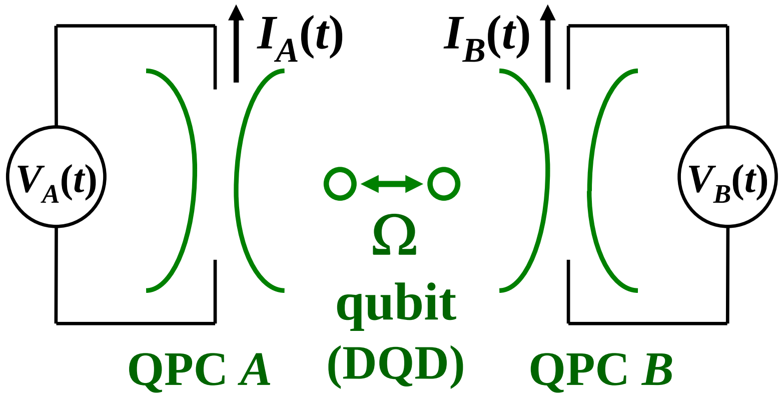
Numerical results

Low-frequency telegraph noise
(dashed) and cross-noise (solid)



Calculation based on numerical
solution of the master equation

Estimates



Assume:

QPC current $I = 100$ nA

response $\Delta I/I = 0.1$

duty cycle δt/T=0.2 (symmetric)

Rabi frequency ~ 2 GHz

Then:

"attraction" (collapse) time 1.5 ns (few Rabi periods)

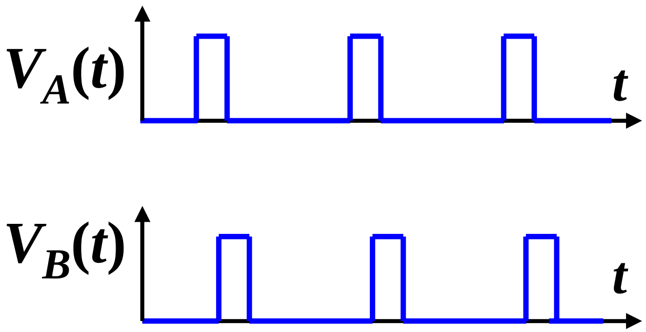
switching rate $\Gamma_s \simeq \frac{1}{4T_2} + \frac{1}{1\,\mu\text{s}} + \frac{\varphi^2}{13\,\text{ns}}$ (many Rabi periods)

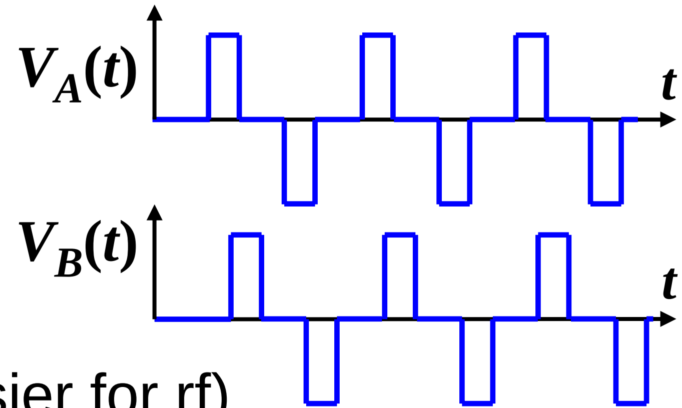
need $T_2 > 10$ ns

$$\frac{S_{\text{telegraph}}}{S_{\text{shot}}} \simeq 600 \times \min\left(\frac{T_2}{250\,\text{ns}}, 1\right)$$ (relatively large noise signal)

seems to be reasonable and doable

Useful modification

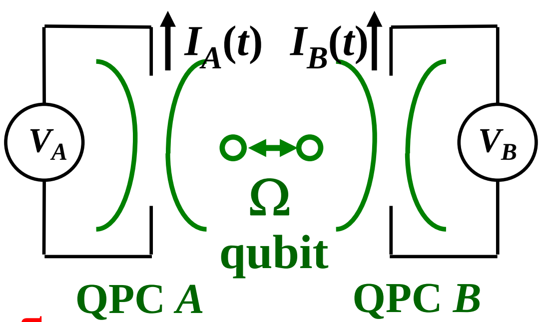


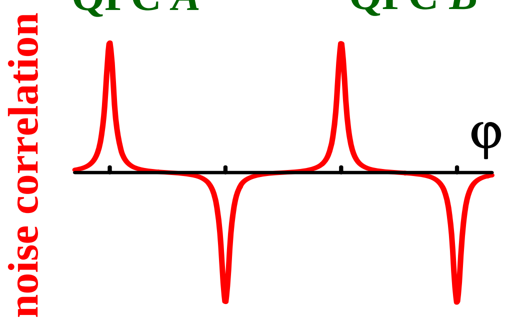


(zero average, easier for rf)

(harmonic rf is also OK)

Any alternative explanation?





1) no oscillations – then no corr./anticorr.

2) unsynchronized Rabi oscillations – then different dependence on φ (cos φ instead of φ^{-2}); also $\int S_{telegr}(f)\,df$ at least twice smaller

3) resonant frequency - driven Rabi? Then oscillations between |g⟩ and |e⟩ (both do not give a signal) with different frequency. Driven Rabi <u>decreases</u> corr./anticorr. (not an alternative explanation, but should be avoided)

Good news: both phases insensitive to driven Rabi

Summary

- Proposed experiment: persistent Rabi oscillations may be revealed in one-qubit-two-detectors setup (new features compared to Saclay experiment: synchronization and non-driven Rabi)

- Mechanism: stroboscopic QND measurement attracts to one of two Rabi phases $\Rightarrow$ strong telegraph noise;
  correlation/anticorrelation in two detector noises reveals persistent Rabi oscillations

- Experiment may be realized with semiconductor or superconducting qubits