Measurement theory for phase qubits

Co-P.I. Alexander Korotkov, UC Riverside

The team: 1) Qin Zhang, *graduate student*
2) Dr. Abraham Kofman, *researcher* (started in June 2005)
3) Alexander Korotkov, *associate prof.*

Since last review

Published: 5 journal papers and 1 proceeding

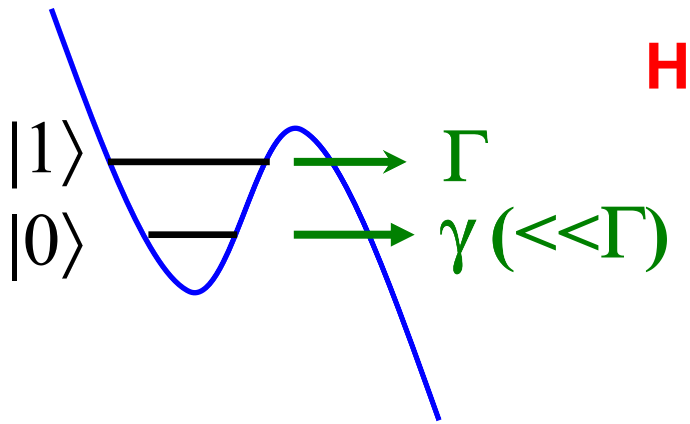
Submitted (not published): 3 journal papers

Full-scale funding is starting in Year 2 (since June 2005) (60% of that in Year 1)

Research accomplishments since last review

- Finished research supported by previous NSA/ARDA/ARO project (quantum feedback, etc.)
- Developed basic theoretical approach to quantum back-action during "fast" measurement of one phase qubit
- Developed improved semiclassical theory for measurement cross-talk for measurement of two phase qubits
- Derived Bell-like inequalities in time (similar to Leggett-Garg inequalities) for continuous measurement of a qubit

Quantum back-action during "fast" measurement of a phase qubit



How quantum state changes in time?

(what happens if measured for too short time?)

Main idea (for simplicity γ=0):

$$\psi = \alpha\,|0\rangle + \beta\,|1\rangle \;\rightarrow\; \psi(t) = \begin{cases} |\,out\rangle, \text{ if switched} \\ \dfrac{\alpha\,|0\rangle + \beta\, e^{-\Gamma t/2}\,|1\rangle}{Norm}, \text{ if not switched} \end{cases}$$

(similar to "quantum-jump" approach in optics)

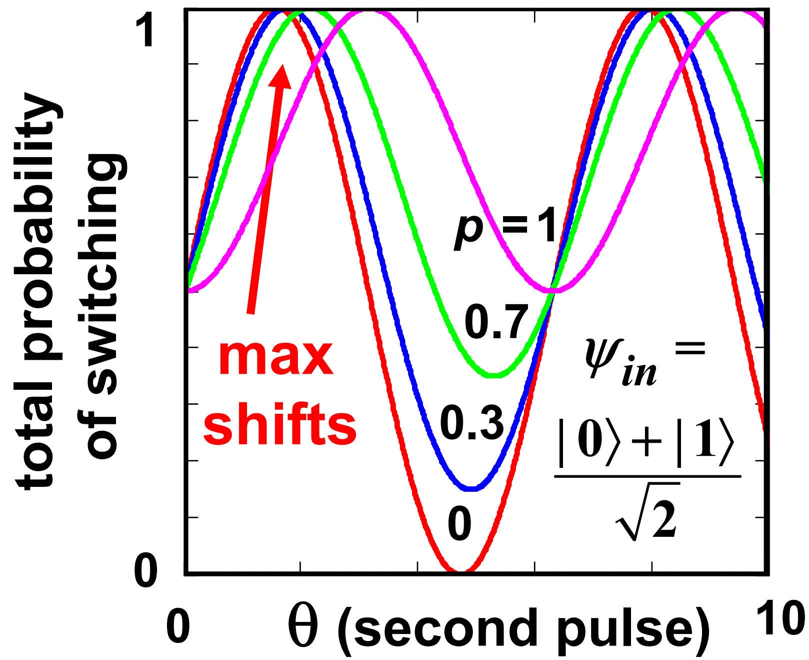
Effect of remaining coherence after incomplete (too short) measurement

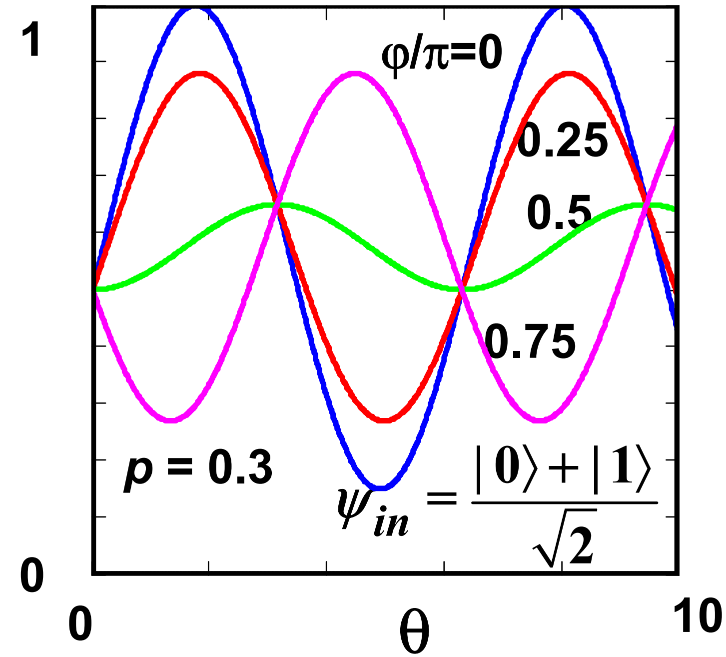
Protocol:

0) state preparation by rf pulse
1) incomplete measurement
2) additional rf pulse (θ-pulse)
3) measurement again (complete)

p = 1-exp(-Γt) – probability of state |1⟩ switching after incomplete measurement

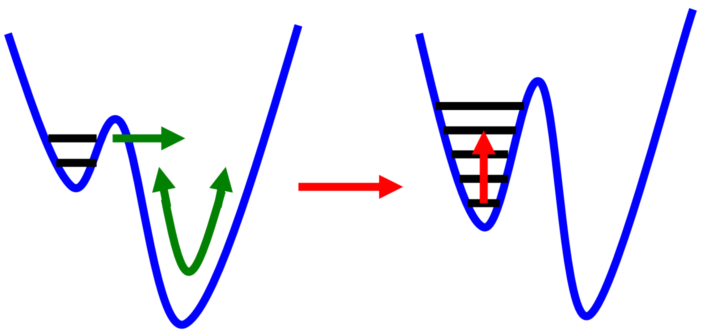
φ – extra phase (z-rotation)





Alexander Korotkov
University of California, Riverside

Measurement cross-talk for measurement of two phase qubits



Origin of the cross-talk:

Measurement of the first qubit and its tunneling into the deep well leads to damped oscillations, which produce microwave voltage perturbing the second qubit

Detrimental effect of the cross-talk: For initial state $|10\rangle$ the cross-talk may excite second qubit resulting in a wrong measurement result $|11\rangle$

Theoretical approaches for study of the cross-talk:

(a) Both qubits are modeled “classically”

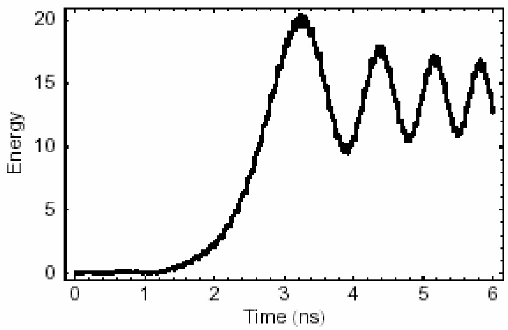
(b) Second qubit is modeled quantum-mechanically, while first qubit evolution is still “classical” (reasonable since for the first qubit the quantum number is large, $n \sim 150$)

(c) Both qubits are modeled quantum-mechanically

So far we use and compare approaches (a) and (b)

Both qubits considered “classically”

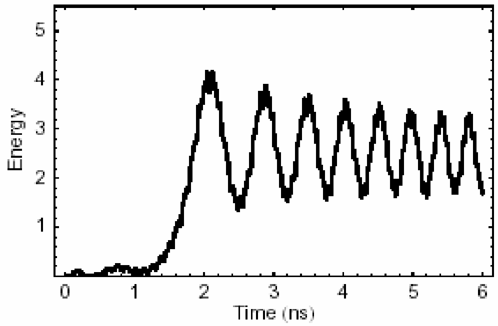
Excitation of the II qubit after measurement of state $|10\rangle$:



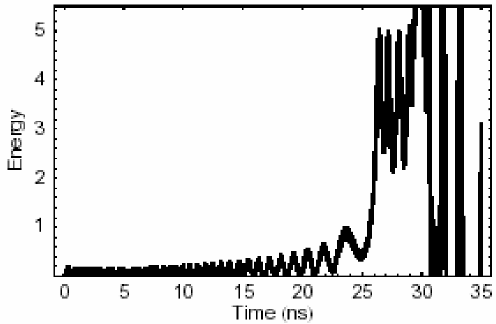
Oscillator model, $T_1 = 25$ ns

(J. Martinis' group, Science, 2005)

Real qubit potential, $N \equiv \frac{\Delta U}{\omega_p} = 5$:



$T_1 = 25$ ns.



$T_1 = 500$ ns.

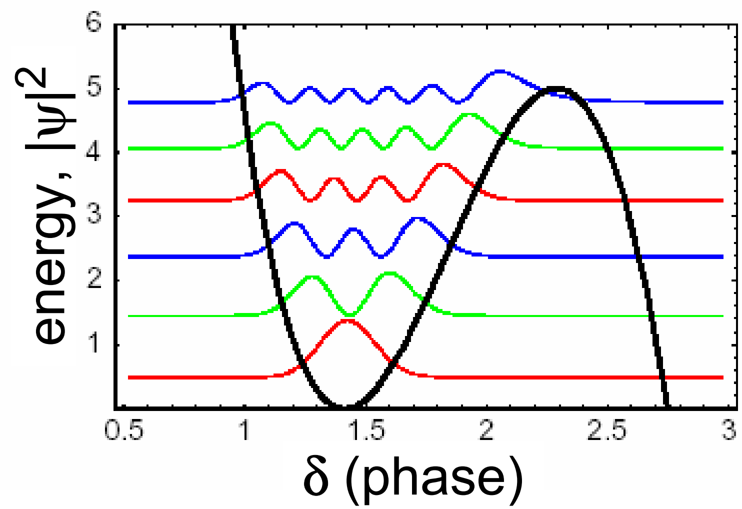
Qubit anharmonicity makes energy transfer less efficient (good news)

Eventual classical escape from well for T_1>400 ns

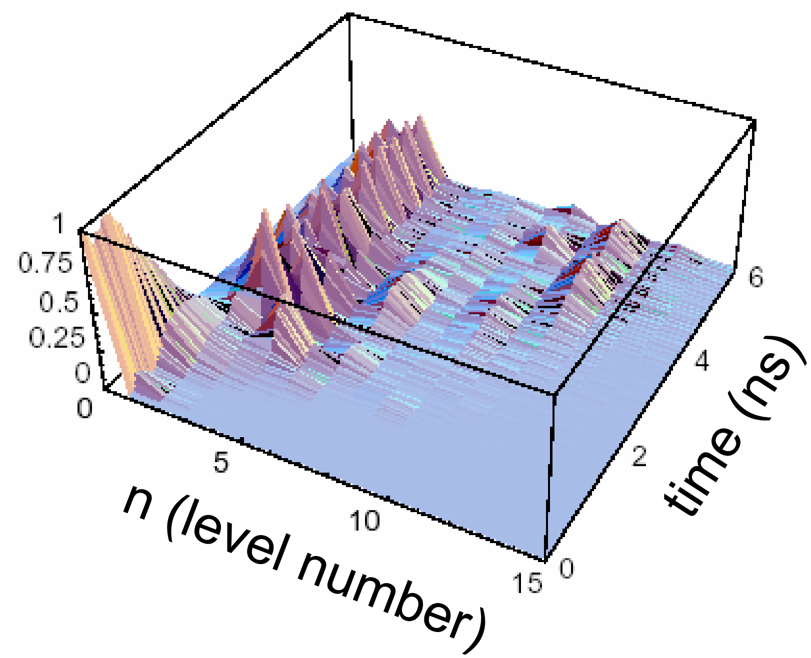
Numerical solution of Schroedinger equation for the second qubit

Now second qubit is considered fully quantum-mechanically (still "classical" approach for the first qubit)

Energy levels (in units of the plasma frequency ω_p) and wave functions



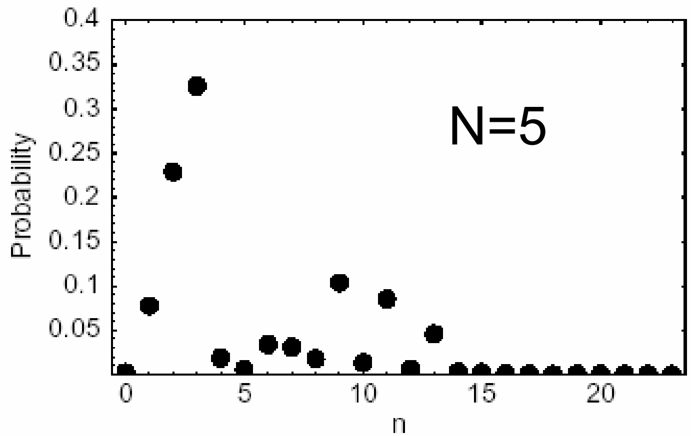
Level populations vs. time



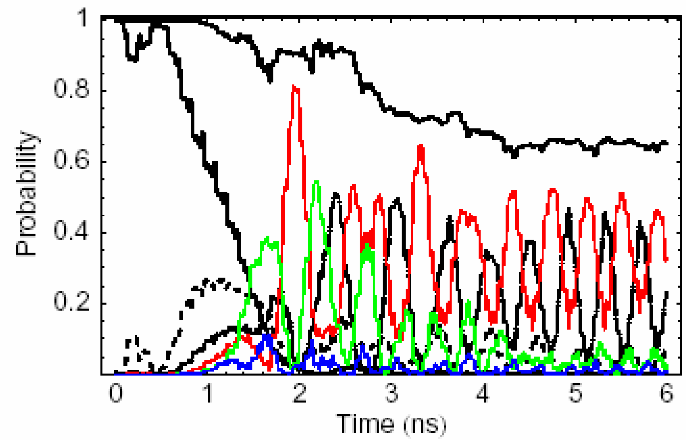
Qubit potential barrier is $5\times Ñ\omega_p$ (N=5)

Measurement cross-talk in hybrid (classical-quantum) approach

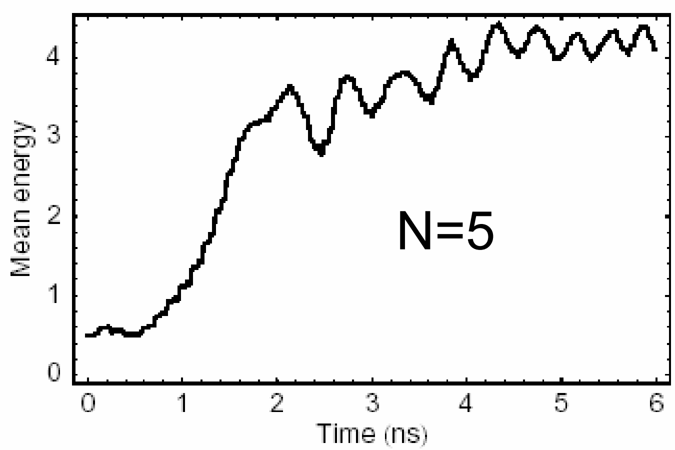
Level populations at $t = 6$ ns



Populations of the bound states vs. t



Mean energy $\bar{E}$



Upper solid line – probability $P(t)$ to remain in the well. $n = 0$ - solid, 1 - dashed, 2 - dotted, 3 - red, 4 - green, 5 - blue.

Mean energy is less than the barrier height, but still finite escape probability (significant difference from classical consideration)

Bell-like inequalities in time for continuous measurement of a qubit

(R. Ruskov, A. Korotkov, A. Mizel, cond-mat/0505094)

qubit ⟷ detector → $I(t)$

Continuous monitoring of a qubit (charge, flux, or phase)

$$I(t) = I_0 + z(t)\frac{\Delta I}{2} + \xi(t), \quad \xi(t) - \text{noise}, \quad \Delta I = I_1 - I_2$$

Since |z|≤1, and assuming non-invasive measurability in case of macro-realism (Leggett-Garg, 1985), we derive:

$$K_I(\tau_1) + K_I(\tau_2) - K_I(\tau_1 + \tau_2) \le (\Delta I / 2)^2$$

for detector signal correlation function $K_I(\tau) = \langle I(t) I(t+\tau)\rangle - \langle I\rangle^2$

Quantum calculation shows that $K_I(\tau) + K_I(\tau) - K_I(2\tau)$

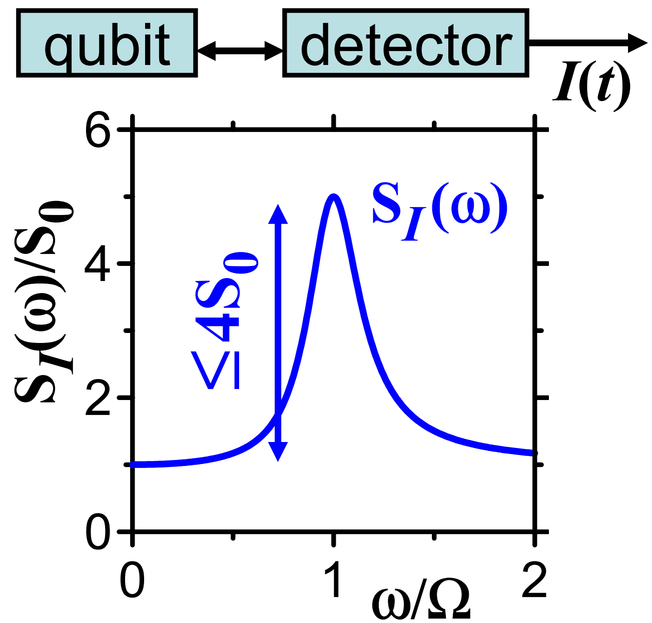
can reach $\frac{3}{2}(\Delta I / 2)^2$ for weak continuous monitoring

Violation by factor up to 3/2

Consequences for measured detector signal spectral density

(Ruskov-Korotkov-Mizel, 2005)

Quantum case (earlier result, 1999)



$$S_I(\omega) = S_0 + \frac{\Omega^2(\Delta I)^2\Gamma}{(\omega^2 - \Omega^2)^2 + \Gamma^2\omega^2}$$

Area under the spectral peak is $(\Delta I/2)^2$

(independent of detector efficiency)

Macro-realistic bounds (this work)

If single spectral peak of the same (Lorentzian) shape, then

area $\leq$ $(2/3)\,(\Delta I/2)^2$

For any peak at non-zero frequency a weaker bound

(still violated): area $\leq$ $(8/\pi^2)\,(\Delta I/2)^2$

Experimentally measurable violation of classical bound

Research topics for the next year

- Quantum-rigorous theory of the classical measurement cross-talk of phase qubits
- Theoretical fidelity of one-shot measurements of phase qubits
- Quantum back-action for measurement of phase qubits
- Related problems of quantum measurement