Measurement theory for phase qubits

Co-P.I.: Alexander Korotkov, UC Riverside

(Lead P.I.: John Martinis, UCSB)

The team: 1) Qin Zhang, *graduate student* (just graduated)
2) Dr. Abraham Kofman, *researcher*
3) Alexander Korotkov, *professor*

Since last review (June 2006)

Published: 6 journal papers (incl. 2 PRLs)

Submitted: 2 journal papers

Total since beginning of the grant (June 2004)

15 journal papers published + 2 submitted

Research accomplishments since last review

- Developed theory of the Bell (CHSH) inequality violation for phase qubits, taking into account finite measurement fidelity, decoherence, and crosstalk; computed thresholds for the inequality violation; proposed a version of the inequality insensitive to the crosstalk.

- Developed theory of quantum undemolition (QUD) (measurement undoing); proposed a QUD experiment for a phase qubit (recently realized in John Martinis' group).

- Analyzed in detail partial collapse process for a phase qubit, taking into account level discreteness and decoherence; analyzed crossover behavior in presence of both null-result measurement and Rabi oscillations.

Research topics for the next year

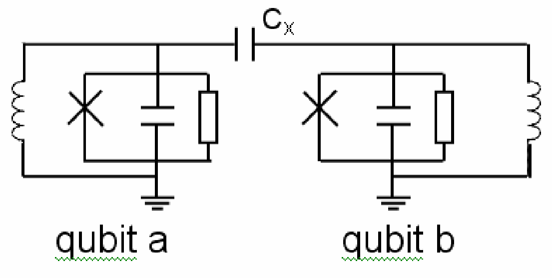
- Gate fidelities for coupled phase qubits
- Process tomography characterization for quantum gates based on phase qubits
- Quantum efficiency of binary-outcome detectors (as for phase qubits)
- QUD analysis and related problems of quantum measurement

Theory of Bell inequality (BI) violation in phase qubits

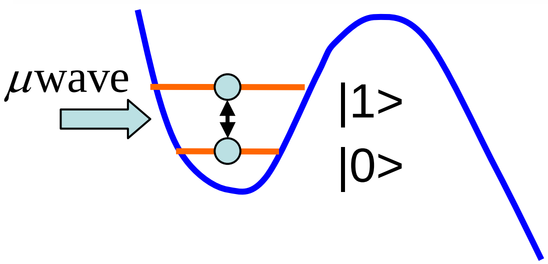
A. Kofman and A. Korotkov

BI in CHSH form: $-2 \le S \le 2$ Quantum max/min: $S_{\pm} = \pm 2\sqrt{2}$

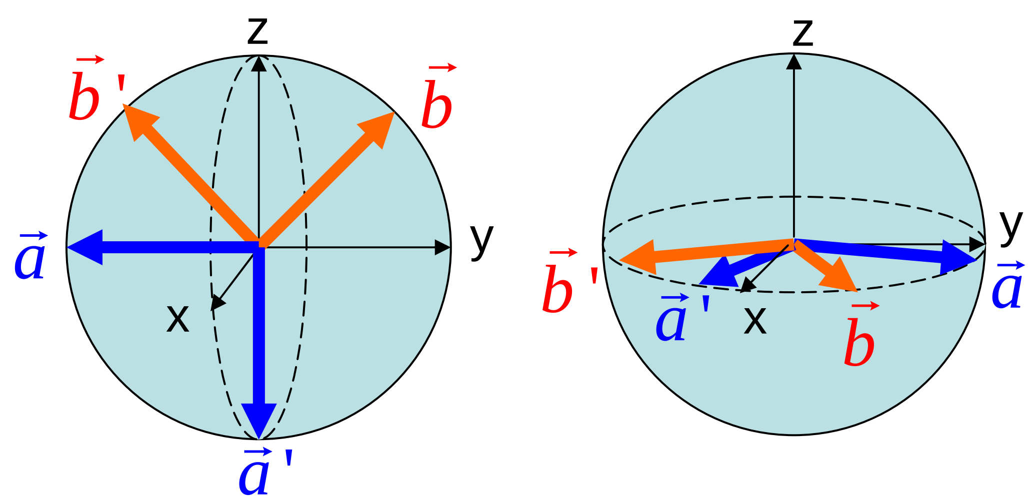
$$S = E(\vec{a},\vec{b}) - E(\vec{a},\vec{b}\,') + E(\vec{a}\,',\vec{b}) + E(\vec{a}\,',\vec{b}\,'), \quad E(\vec{a},\vec{b}) = p_{11}(\vec{a},\vec{b}) + p_{00}(\vec{a},\vec{b}) - p_{10}(\vec{a},\vec{b}) - p_{10}(\vec{a},\vec{b})$$



Pseudospin measurement along arbitrary axis $(\vec{a},\vec{a}\,',\vec{b},\vec{b}\,')$ is realized by rotation (microwave) + measurement along z-axis.



Two configuration types for max violation:



Effects considered:

- **measurement errors**
- **decoherence**
- **crosstalk**

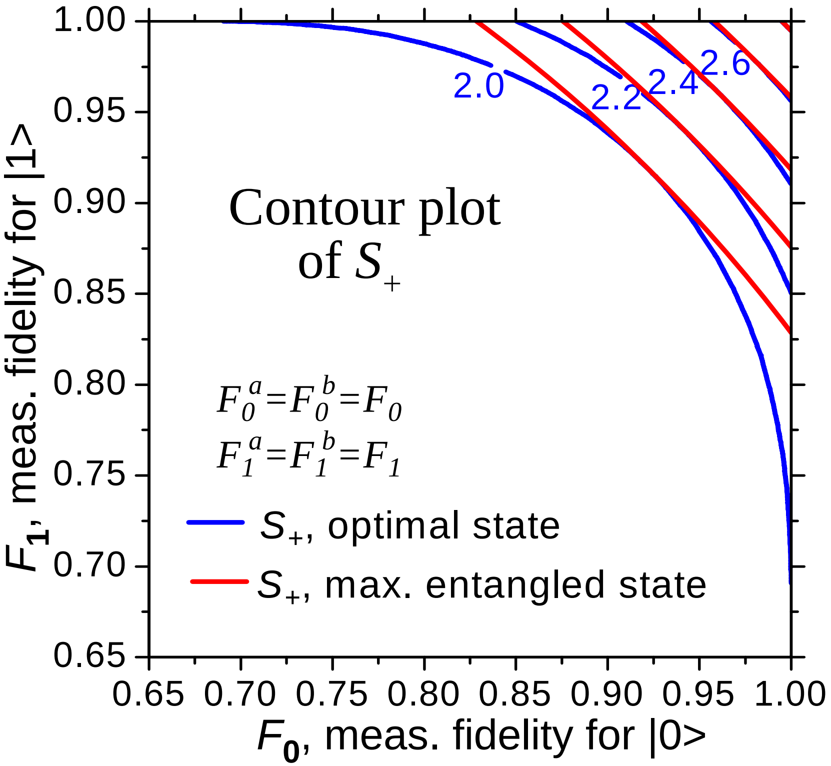
Effect of measurement errors

For max-entangled state $(|10\rangle + |01\rangle)/\sqrt{2}$

$$S_\pm = 2(F_1^a - F_0^a)(F_1^b - F_0^b) \pm 2\sqrt{2}(F_1^a + F_0^a - 1)(F_1^b + F_0^b - 1)$$

$F_i^{a,b}$ is measurement fidelity for state $|i\rangle$

Actually, optimal state is entangled **non-maximally:** $\cos\beta\,|10\rangle + \sin\beta\,|01\rangle$, but not much improvement for strong violation



Effect of measurement crosstalk

$(|10\rangle \to |11\rangle$ with probability p_c^a, $|01\rangle \to |11\rangle$ with probability $p_c^b)$

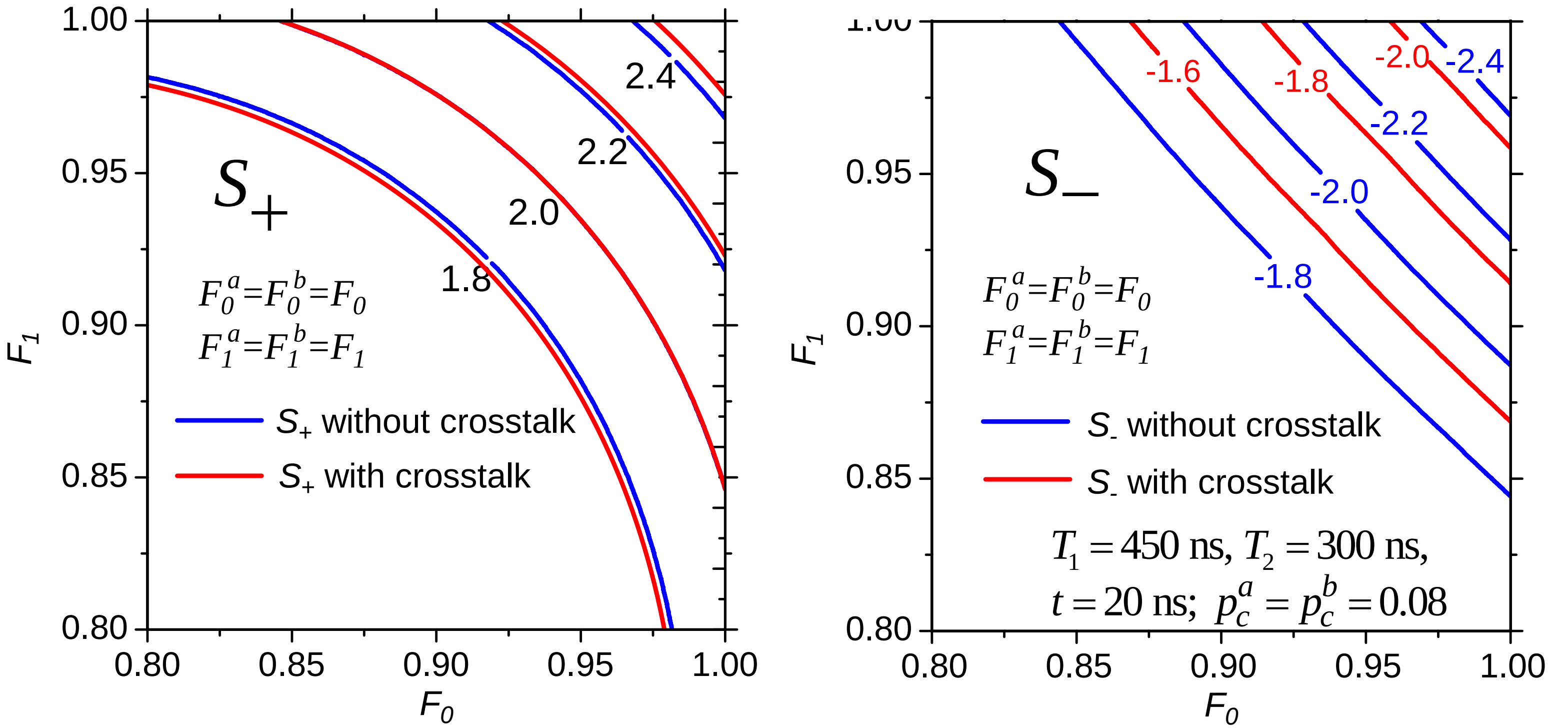
Crosstalk is a **nonlocal** effect ➔ modified CHSH inequality:

$$-2 + 4\min\{p_c^a, p_c^b\} \le S \le 2 + 2\,|\,p_c^a - p_c^b\,|$$

Quantum max/min: $S_\pm^C = 2p_c + (1-p_c)S_\pm$ (for $p_c^a = p_c^b = p_c$)

Crosstalk decreases both gaps between classical and quantum results

Combined effects of errors, decoherence, and crosstalk



Equal errors and crosstalk make preferable measurement of *positive* S

Version of Bell (CHSH) inequality **insensitive to crosstalk**:

Idea: use only “null-result” measurements (opposite to optics!)

$$\boxed{-1 \le T \le 0} \quad T = p_{00}(\vec{a},\vec{b}) - p_{00}(\vec{a},\vec{b}\,') + p_{00}(\vec{a}\,',\vec{b}) + p_{00}(\vec{a}\,',\vec{b}\,') - p_0(\vec{a}\,') - p_0(\vec{b})$$

$p_0(\vec{a}\,')$ $[p_0(\vec{b})]$ is non-switching probability for measuring qubit a (b) only

Quantum undemolition for phase qubits (uncollapsing wavefunction)

Theory: A. Korotkov and A. Jordan *Recent experiment*: N. Katz et al.

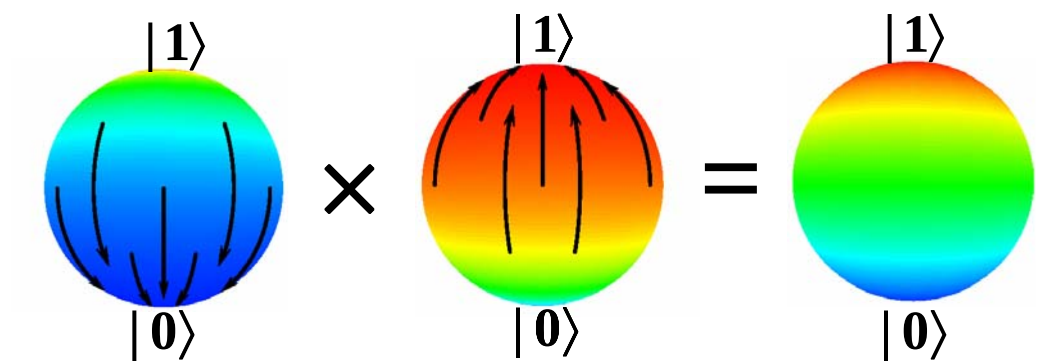
ψ_0 (unknown) —weak (partial) measurement→ ψ_1 (partially collapsed)
- successful → ψ_0 (still unknown)
- unsuccessful → ψ_2

undemolition

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

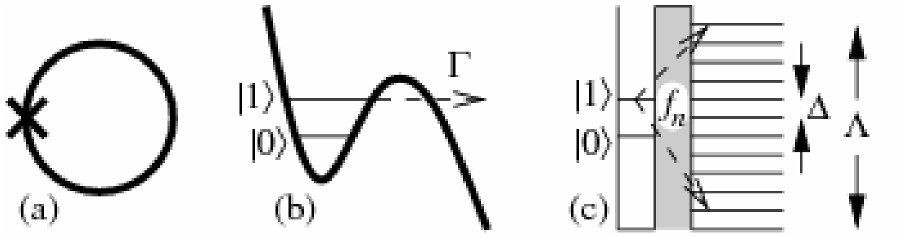
$$\frac{e^{i\phi}\alpha e^{-\Gamma t/2}|0\rangle+e^{i\phi}\beta e^{-\Gamma t/2}|1\rangle}{\text{Norm}} = e^{i\phi}(\alpha|0\rangle+\beta|1\rangle)$$

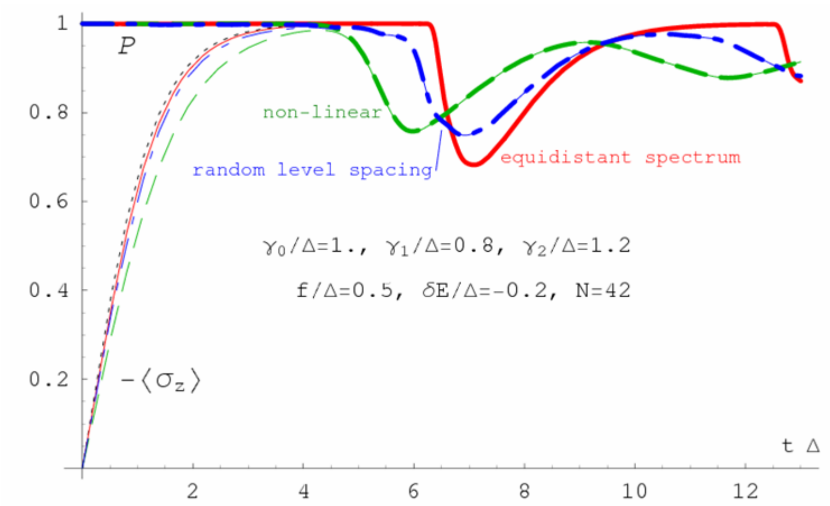
Expt. protocol:
1) partial collapse
2) π-pulse
3) partial collapse
4) π-pulse



Partial-collapse theory for phase qubits

L. Pryadko and A. Korotkov





Simple model for **null-result** evolution:

$$\psi(t) = \frac{\alpha|0\rangle + \beta e^{-\Gamma t/2}|1\rangle}{\sqrt{|\alpha|^2 + |\beta|^2 e^{-\Gamma t}}}$$

Expt: N. Katz et al., Science-06

Better model: tunneling into discrete levels + decoherence (in the second well and inter-well)

$$\dot{\rho} = -i[H,\rho] + \sum_k \frac{\gamma_k}{2}([\Lambda_k\rho,\Lambda_k^\dagger]+[\Lambda_k,\rho\Lambda_k^\dagger])$$

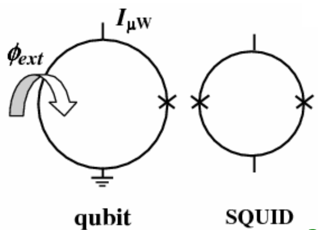
Result: qubit remains practically pure despite extra decoherence processes

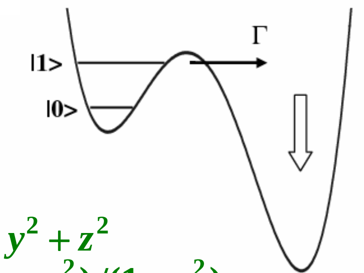
cond-mat/0704.3806

Crossover of phase qubit dynamics in presence of weak collapse and μwaves

PRB 75, 220501(R) (2007)

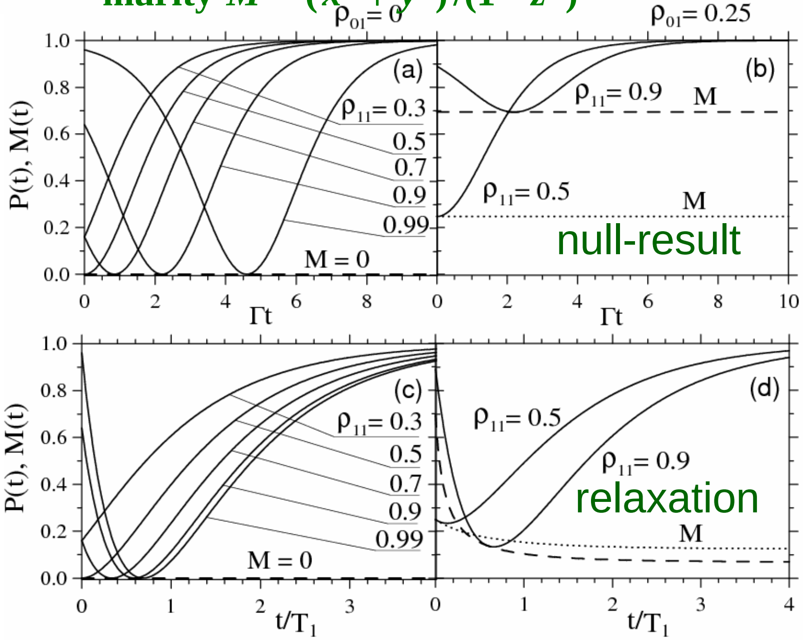
R. Ruskov, A. Mizel, and A. Korotkov



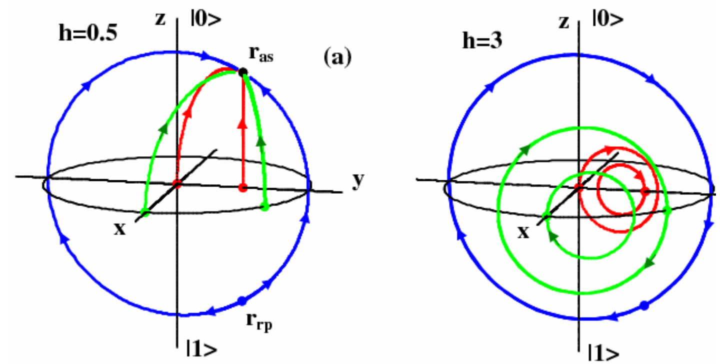


purity $P = x^2 + y^2 + z^2$

murity $M = (x^2 + y^2)/(1 - z^2)$

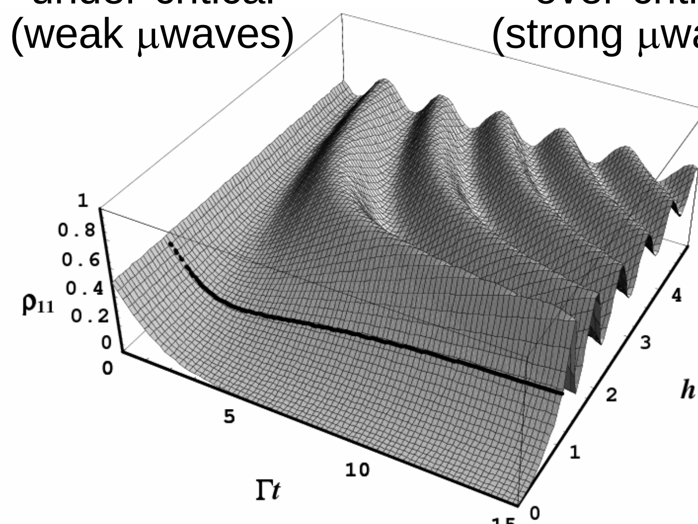


Null-result measurement + Rabi oscillations (μwaves)



under-critical (weak μwaves)

over-critical (strong μwaves)



$$h = \frac{2\Omega_R}{\Gamma}$$

Evolutions due to null-result measurement and relaxation are clearly distinguishable

Crossover between asymptotic stability and non-decaying oscillations