Les Houches, France, 07/12/11

Probing "inside" quantum collapse with solid-state qubits

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Outline:

- State collapse in Copenhagen Q.M.
 - What is "inside" collapse? Bayesian framework.
 - broadband meas. (double-dot qubit & QPC)
 - narrowband meas. (circuit QED setup)
 - Experiments and experimental proposals
 - partial collapse and uncollapse
 - persistent Rabi oscillations (spectrum, quantum feedback)



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Copenhagen quantum mechanics = Schrödinger equation + collapse postulate

- 1) Fundamentally random measurement result *r* (out of allowed set of eigenvalues). Probability: $p_r = |\langle \psi | \psi_r \rangle|^2$
- 2) State after measurement corresponds to result: ψ_r
- Contradicts Schr.Eq. (spooky), but follows from common sense
- Needs "observer": 1) ask a question, 2) get information

Why so strange (unobjective)?

- "Shut up and calculate"
- Actually, use proper philosophy



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Werner Heisenberg

Books:

Physics and Philosophy: The Revolution in Modern Science
Philosophical Problems of Quantum Physics
The Physicist's Conception of Nature Across the Frontiers



Niels Bohr



Immanuel Kant (1724-1804), German philosopher

Critique of pure reason (materialism, but not naive materialism) Nature - "Thing-in-itself" (noumenon, not phenomenon) Humans use "concepts (categories) of understanding"; make sense of phenomena, but never know noumena directly A priori: space, time, causality

A naïve philosophy should not be a roadblock for good physics, quantum mechanics requires a non-naïve philosophy Wavefunction is not a reality, it is only our description of reality



Triumph of Copenhagen Q.Mech. (my subjective opinion)

- Theoretical attempts of "improved" Q.M. failed
- Bell inequality experiments proved impossibility of "objective" (local) Q.M.
- Ensembles (way to exclude collapse) vs. single systems Quantum computing (D. Mermin, "Copenhagen computation")
- Other "interpretations"??? Textbooks? ("many-worlds" – a different story)
- Continuous, partial or weak quantum measurement (what is "inside" collapse)

optical experiments (quantum trajectory theory) superconducting experiments:

partial collapse (UCSB'06), uncollapsing (UCSB'08), non-decaying Rabi oscillations & L-G ineq. (Saclay'10)



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"Inside" collapse: <u>state evolution</u> due to continuous or partial measurement

- When: information comes gradually in time (because of weak coupling with a noisy detector)
 - information is inconclusive

Quantum Bayesian framework (slight technical extension of the collapse postulate)

- Quantum back-action (spooky, physically unexplainable) simple: update the state using information from measurement and probability concept (Bayes rule)
- 2) Add "classical" back-action if any (anything with a physical mechanism)
- 3) Add noise/decoherence if any
- 4) Add Hamiltonian (unitary) evolution if any

(Practically equivalent to many other approaches: POVM, quantum trajectory, quantum filtering, etc.) – Alexander Korotkov — University of California, Riverside



"Typical" broadband setup: double-quantum-dot qubit + quantum point contact (QPC) detector

 $|1\rangle \circ |1\rangle \circ |1\rangle \circ |2\rangle \circ |2\rangle \circ |2\rangle \circ |1\rangle \circ |1\rangle \circ |2\rangle \circ |2\rangle \circ |1\rangle = I(t)$

Gurvitz, 1997

$$H = H_{QB} + H_{DET} + H_{INT}$$
$$H_{QB} = \frac{\varepsilon}{2}\sigma_z + H\sigma_x$$
$$I(t) = I_0 + \frac{\Delta I}{2}z(t) + \xi(t)$$
$$const + signal + noise$$

Two levels of average detector current: I_1 for qubit state $|1\rangle$, I_2 for $|2\rangle$ Response: $\Delta I = I_1 - I_2$ Detector noise: white, spectral density S_I

For low-transparency QPC

$$\begin{split} H_{DET} &= \sum_{l} E_{l} a_{l}^{\dagger} a_{l} + \sum_{r} E_{r} a_{r}^{\dagger} a_{r} + \sum_{l,r} T(a_{r}^{\dagger} a_{l} + a_{l}^{\dagger} a_{r}) \\ H_{INT} &= \sum_{l,r} \Delta T \left(c_{1}^{\dagger} c_{1} - c_{2}^{\dagger} c_{2} \right) \left(a_{r}^{\dagger} a_{l} + a_{l}^{\dagger} a_{r} \right) \\ S_{I} &= 2eI \end{split}$$

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Bayesian formalism for DQD-QPC system

 $H_{QB} = 0$ $|1\rangle \circ$ $H_{QB} \circ e$ $|2\rangle \circ e$ \bigcup I(t)

Qubit evolution due to measurement (quantum back-action): $\psi(t) = \alpha(t) |1\rangle + \beta(t) |2\rangle$ or $\rho_{ij}(t)$

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 dephasing!), $\rho_{ij}/(\rho_{ii}\rho_{jj})^{1/2} = \text{const}$

(A.K., 1998)

Bayes rule (1763, Laplace-1812):

$$\frac{1}{\tau} \int_0^{\tau} I(t) dt$$

$$I_1$$
measured

So simple because:

- 1) no entaglement at large QPC voltage (classical detector; Markovian)
- 2) QPC happens to be an ideal detector
- 3) no Hamiltonian evolution of the qubit

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Now add classical back-action and decoherence

$$|1\rangle \circ$$

$$|2\rangle \circ |2\rangle$$

$$|1\rangle$$

$$I(t)$$

$$\Delta I = I_1 - I_2$$
noise S_I

$$I_m = \frac{1}{\tau} \int_0^{\tau} I(t) dt$$

$$H_{qb} = 0$$

$$\begin{cases}
 quantum backaction (non-unitary, "spooky", "unphysical") \\
 \frac{\rho_{11}(\tau)}{\rho_{22}(\tau)} = \frac{\rho_{11}(0)}{\rho_{22}(0)} \frac{\exp[-(I_m - I_1)^2/2D]}{\exp[-(I_m - I_2)^2/2D]} \\
 no self-evolution of qubit assumed \\
 \rho_{12}(\tau) = \rho_{12}(0) \sqrt{\frac{\rho_{11}(\tau) \rho_{22}(\tau)}{\rho_{11}(0) \rho_{22}(0)}} \exp(iKI_m \tau) \exp(-\gamma\tau) \\
 \ decoherence$$

classical backaction (unitary)

 $D = S_I / 2\tau$



Example of "classical" ("physical") backaction: Each electron passed through QPC rotates qubit (sensitivity of tunneling phase for an asymmetric barrier) $\arg(T^*\Delta T) \neq 0$

$$H_{DET} = \sum_{l} E_{l} a_{l}^{\dagger} a_{l} + \sum_{r} E_{r} a_{r}^{\dagger} a_{r} + \sum_{l,r} T a_{r}^{\dagger} a_{l} + h.c.$$
$$H_{INT} = \sum_{l,r} \Delta T (c_{1}^{\dagger} c_{1} - c_{2}^{\dagger} c_{2}) a_{r}^{\dagger} a_{l} + h.c.$$

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Another example of classical back-action

$$H_{qb} = 0$$
quantum backaction (non-unitary, "spooky", "unphysical")
$$I(t) \begin{cases} \rho_{11}(\tau) \\ \rho_{22}(\tau) \end{cases} = \frac{\rho_{11}(0)}{\rho_{22}(0)} \exp[-(I_m - I_1)^2/2D] \\ \exp[-(I_m - I_2)^2/2D] \\ \exp[-(I_m - I_2)^2/2D] \\ \exp[-(I_m \tau) \exp(-\gamma \tau) \\ exp(-\gamma \tau) \\ exp$$

Now add Hamiltonian evolution



- Time derivative of the quantum Bayes rule
- Add unitary evolution of the qubit

Evolution of qubit *wavefunction* can be monitored if $\gamma=0$ (quantum-limited)

noise $S_{\xi} = S_I$

Relation to "conventional" master equation

$$\dot{\rho}_{11} = -\dot{\rho}_{22} = -2H \operatorname{Im} \rho_{12} + \rho_{11}\rho_{22}\frac{2\Delta I}{S_I}[I(t) - I_0]$$

$$\dot{\rho}_{12} = i\varepsilon\rho_{12} + iH(\rho_{11} - \rho_{22}) + \rho_{12}(\rho_{11} - \rho_{22})\frac{\Delta I}{S_I}[I(t) - I_0]$$

$$+ iK[I(t) - I_0]\rho_{12} - \gamma\rho_{12}$$

 $\hbar = 1$

response ΔI noise S_I

Averaging over measurement result I(t) leads to usual master equation:

$$\dot{\rho}_{11} = -\dot{\rho}_{22} / dt = -2 H \operatorname{Im} \rho_{12}$$

$$\dot{\rho}_{12} = i \varepsilon \rho_{12} + i H (\rho_{11} - \rho_{22}) - \Gamma \rho_{12}$$

 Γ – ensemble decoherence, $\Gamma = (\Delta I)^2 / 4S_I + K^2S_I / 4 + \gamma$ spooky physical dephasing

Quantum efficiency:
$$\eta = \frac{(\Delta I)^2 / 4S_I}{\Gamma}$$
 or $\tilde{\eta} = 1 - \frac{\gamma}{\Gamma}$

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Two ways to think about a non-ideal detector ($\eta < 1$)



These ways are equivalent (same results for any expt.) ⇒ matter of convenience



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Stratonovich and Ito forms for nonlinear stochastic differential equations

Definitions of the derivative:

$$\frac{df(t)}{dt} = \lim_{\Delta t \to 0} \frac{f(t + \Delta t/2) - f(t - \Delta t/2)}{\Delta t} \quad \text{(Stratonovich)}$$
$$\frac{df(t)}{dt} = \lim_{\Delta t \to 0} \frac{f(t + \Delta t) - f(t)}{\Delta t} \quad \text{(Ito)}$$

Why matters? Usually $(f + df)^2 \approx f^2 + 2f df$, $(df)^2 << df$ But if $df = \xi dt$ (white noise ξ), then $(df)^2 = \xi^2 dt^2 \approx \frac{S_{\xi}}{2} dt$ Simple translation rule:

$$\frac{d}{dt}x_{i}(t) = G_{i}(\vec{x},t) + F_{i}(\vec{x},t)\xi(t) \qquad \text{(Stratonovich)}$$
$$\frac{d}{dt}x_{i}(t) = G_{i}(\vec{x},t) + F_{i}(\vec{x},t)\xi(t) + \frac{S_{\xi}}{4}\sum_{k}\frac{\partial F_{i}(\vec{x},t)}{dx_{k}}F_{k}(\vec{x},t) \quad \text{(Ito)}$$

Advantage of Stratonovich: usual calculus rules (intuition) Advantage of Ito: simple averaging

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Methods for calculations

Monte Carlo

- "Ideologically" simplest
- In many cases most efficient
- Idea: use finite time step Δt
 - find probability distribution for $I_m(\Delta t)$
 - pick a random number for $I_m(\Delta t)$
 - do quantum Bayesian update

Analytics (or non-random numerics)

- Be very careful about Ito-Stratonovich issue
- Use Stratonovich form for derivations (derivatives, etc.)
- Convert into Ito for averaging over noise
- Very good idea to compare with Monte Carlo and/or check second order terms in *dt*



Many similar approaches to non-projective (continuous, partial, weak, generalized, etc.) quantum measurements

Names: Davies, Kraus, Holevo, Mensky, Caves, Knight, Plenio, Walls, Carmichael, Milburn, Wiseman, Gisin, Percival, Belavkin, etc. (very incomplete list)

Key words: POVM, restricted path integral, <u>quantum trajectories</u>, quantum filtering, quantum jumps, stochastic master equation, etc.

Matter of taste, convenience, and studied system

Bayesian approach is quite close to quantum trajectories (just a different language, Ito/Stratonovich, etc.)



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Quantum measurement in POVM formalism

Davies, Kraus, Holevo, etc. system < > ancilla projective measurement (Nielsen-Chuang, pp. 85, 100) $\psi \rightarrow \frac{M_r \psi}{\|M_r \psi\|} \text{ or } \rho \rightarrow \frac{M_r \rho M_r^{\dagger}}{\operatorname{Tr}(M_r \rho M_r^{\dagger})}$ Measurement (Kraus) operator M_r (any linear operator in H.S.): Probability: $P_r = ||M_r \psi||^2$ or $P_r = \operatorname{Tr}(M_r \rho M_r^{\dagger})$ Completeness: $\sum_{r} M_{r}^{\dagger} M_{r} = 1$ (People often prefer linear evolution and non-normalized states) decomposition $M_r = U_r \sqrt{M_r^{\dagger} M_r}$ Relation between POVM and quantum Bayesian formalism: unitary Bayes (almost equivalent)

Simple derivation of Lindblad equation: process happens or null-result



Relation with weak values



Narrowband linear measurement



Paramp traditionally discussed in terms of noise temperature

 $\begin{array}{l} \theta \geq 0 \\ \theta \geq \frac{\hbar \omega}{2} \end{array} \begin{array}{l} \mbox{for phase-sensitive (degenerate, homodyne) paramp} \\ \mbox{Haus, preserving (non-degenerate, heterodyne) paramp} \\ \mbox{Haus, Mullen, 1962} \\ \mbox{Giffard, 1976} \end{array} \end{array}$

We will discuss it in terms of qubit evolution due to measurement



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Phase-sensitive (degenerate) paramp

pumps $\omega_a + \omega_b = 2\omega_d$ quadrature $\cos(\omega_d t + \varphi)$ is amplified, quadrature $\sin(\omega_d t + \varphi)$ is suppressed

Assume *I*(*t*) measures $\cos(\omega_d t + \varphi)$, then *Q*(*t*) not needed get some information ($\sim \cos^2 \varphi$) about qubit state and some information ($\sim \sin^2 \varphi$) about photon fluctuations

$$\begin{cases} \frac{\rho_{gg}(\tau)}{\rho_{ee}(\tau)} = \frac{\rho_{gg}(0)}{\rho_{ee}(0)} \frac{\exp[-(\overline{I} - I_g)^2/2D]}{\exp[-(\overline{I} - I_e)^2/2D]} & \overline{I} = \frac{1}{\tau} \int_0^{\tau} I(t) \, dt & D = S_I/2\tau \\ I_g - I_e = \Delta I \cos\varphi & K = \frac{\Delta I}{S_I} \sin\varphi \\ \rho_{ge}(\tau) = \rho_{ge}(0) \sqrt{\frac{\rho_{gg}(\tau) \rho_{ee}(\tau)}{\rho_{gg}(0) \rho_{ee}(0)}} \exp(iK\overline{I}\tau) & \Gamma = \frac{(\Delta I \cos\varphi)^2}{4S_I} + K^2 \frac{S_I}{4} = \frac{\Delta I^2}{4S_I} = \frac{8\chi^2 \overline{n}}{\kappa} \\ \text{(rotating frame)} & \text{Same as for QPC/SET, but trade-off } (\phi) \\ \text{between quantum \& classical back-actions} \\ \text{Minimize of California, Riverside} & \text{Constant of California, Riverside} \\ \end{cases}$$



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for quantum feedback

Equal contributions to ensemble dephasing from quantum & classical back-actions





Impossible in principle!

Technical reason: Outgoing information makes it an open system

Philosophical reason: Random measurement result, but deterministic Schrödinger equation

Einstein: God does not play dice (actually plays!) Heisenberg: unavoidable quantum-classical boundary

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Superconducting experiments "inside" quantum collapse

- UCSB-2006 Partial collapse
- UCSB-2008 Reversal of partial collapse (uncollapse)
- Saclay-2010 Continuous measurement of Rabi oscillations (+violation of Leggett-Garg inequality)



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Partial collapse of a Josephson phase qubit

N. Katz, M. Ansmann, R. Bialczak, E. Lucero, R. McDermott, M. Neeley, M. Steffen, E. Weig, A. Cleland, J. Martinis, A. Korotkov, Science-06

What happens if no tunneling?

Ma

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

Non-trivial: • amplitude of state $|0\rangle$ grows without physical interaction

finite linewidth only after tunneling

continuous null-result collapse

(idea similar to Dalibard-Castin-Molmer, PRL-1992)

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Partial collapse: experimental results



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N. Katz et al., Science-06

- In case of no tunneling phase qubit evolves
- Evolution is described by the Bayesian theory without fitting parameters
- Phase qubit remains coherent in the process of continuous collapse (expt. ~80% raw data, ~96% corrected for T₁, T₂)

quantum efficiency $\eta_0 > 0.8$

Good agreement with the theory

Uncollapsing for qubit-QPC system (theory)

A.K. & Jordan, 2006



Simple strategy: continue measuring until *r*(*t*) becomes zero! Then any unknown initial state is fully restored.

(same for an entangled qubit)

It may happen though that r=0 never happens; then undoing procedure is unsuccessful.

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Experiment on wavefunction uncollapse



If no tunneling for both measurements, then initial state is fully restored <u>N. Katz</u>, M. Neeley, M. Ansmann, R. Bialzak, E. Lucero, A. O'Connell, H. Wang, A. Cleland, <u>J. Martinis</u>, and A. Korotkov, PRL-2008

Uncollapse protocol:

- partial collapse
- π -pulse
- partial collapse (same strength)

١

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

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

phase is also restored ("spin echo")

Experimental results on the Bloch sphere



Both spin echo (azimuth) and uncollapsing (polar angle) Difference: spin echo – undoing of an <u>unknown unitary</u> evolution, uncollapsing – undoing of a <u>known</u>, <u>but non-unitary</u> evolution

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Suppression of T_1 -decoherence by uncollapse



Ideal case (T_1 during storage only) for initial state $|\psi_{in}\rangle = \alpha |0\rangle + \beta |1\rangle$ $|\psi_f\rangle = |\psi_{in}\rangle$ with probability (1-*p*) e^{-t/T_1}

 $|\psi_{f}\rangle = |0\rangle$ with $(1-\rho)^{2}|\beta|^{2}e^{-t/T_{1}}(1-e^{-t/T_{1}})$

procedure preferentially selects events without energy decay

Uncollapse seems to be **the only** way to protect against T_1 -decoherence without encoding in a larger Hilbert space (QEC, DFS)



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Non-decaying (persistent) Rabi oscillations



Indirect experiment: spectrum of persistent Rabi oscillations



peak-to-pedestal ratio = $4\eta \le 4$

$$S_{I}(\omega) = S_{0} + \frac{\Omega^{2} (\Delta I)^{2} \Gamma}{(\omega^{2} - \Omega^{2})^{2} + \Gamma^{2} \omega^{2}}$$

$$I(t) = I_0 + \frac{\Delta I}{2}z(t) + \xi(t)$$

(const + signal + noise

A.K., LT'1999 A.K.-Averin, 2000

z is Bloch coordinate

amplifier noise ⇒ higher pedestal, poor quantum efficiency, but the peak is the same!!! $\begin{array}{c}
S_{I}(\omega) \\
\eta \ll 1 \\
0 \quad 1 \, \omega/\Omega^{2}
\end{array}$

integral under the peak \Leftrightarrow variance $\langle z^2 \rangle$

How to distinguish experimentally persistent from non-persistent? Easy!

perfect Rabi oscillations: $\langle z^2 \rangle = \langle \cos^2 \rangle = 1/2$ imperfect (non-persistent): $\langle z^2 \rangle \ll 1/2$ quantum (Bayesian) result: $\langle z^2 \rangle = 1$ (!!!)

(demonstrated in Saclay expt.)

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How to understand $\langle z^2 \rangle = 1$?

$$I(t) = I_0 + \frac{\Delta I}{2}z(t) + \xi(t)$$



First way (mathematical)

We actually measure operator: $z \rightarrow \sigma_z$

$$z^2 \rightarrow \sigma_z^2 = 1$$

Second way (Bayesian)

$$S_{I}(\omega) = S_{\xi\xi} + \frac{\Delta I^{2}}{4}S_{zz}(\omega) + \frac{\Delta I}{2}S_{\xi z}(\omega)$$

W

quantum back-action changes zin accordance with the noise ξ (what you see becomes reality)

Equal contributions (for weak coupling and η=1)

Can we explain it in a more reasonable way (without spooks/ghosts)?



or some other z(t)?

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No (under assumptions of macrorealism; Leggett-Garg, 1985)



Leggett-Garg-type inequalities for continuous measurement of a qubit

qubit
$$\leftarrow$$
 detector \downarrow *I*(*t*)

Ruskov-A.K.-Mizel, PRL-2006 Jordan-A.K.-Büttiker, PRL-2006

Assumptions of macrorealism Leggett-Garg, 1985 (similar to Leggett-Garg'85): $K_{ii} = \langle Q_i Q_i \rangle$ if $Q = \pm 1$, then $I(t) = I_0 + (\Delta I / 2)z(t) + \xi(t)$ $1+K_{12}+K_{23}+K_{13}\geq 0$ $|z(t)| \leq 1, \quad \langle \xi(t) \ z(t+\tau) \rangle = 0$ $K_{12}+K_{23}+K_{34}-K_{14} \leq 2$ Then for correlation function quantum result $K(\tau) = \langle I(t) I(t+\tau) \rangle$ $\frac{3}{2}\left(\Delta I/2\right)^2$ $K(\tau_1) + K(\tau_2) - K(\tau_1 + \tau_2) \le (\Delta I / 2)^2$ and for area under narrow spectral peak $\int [S_{I}(f) - S_{0}] df \leq (8/\pi^{2}) (\Delta I/2)^{2}$ $(\Delta I/2)^2$ η is not important!

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t violation

 $\times \frac{3}{2}$

 $\times \frac{\pi}{8}$

tant! Experimentally measurable violation (Saclay experiment) University of California, Riverside

Saclay experiment



A.Palacios-Laloy, F.Mallet, F.Nguyen, P. Bertet, D. Vion, D. Esteve, A.K., Nature Phys., 2010

- superconducting charge qubit (transmon) in circuit QED setup
- microwave reflection from cavity: full collection, only phase modulation
- driven Rabi oscillations (z-basis is |g>&|e>)

Standard (not continuous) measurement here: ensemble-averaged Rabi starting from ground state



Now continuous measurement

Palacios-Laloy et al., 2010



Theory by dashed lines, very good agreement

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Violation of Leggett-Garg inequalities

Palacios-Laloy et al., 2010

In time domain

Rescaled to qubit *z*-coordinate $K(\tau) \equiv \langle z(t) z(t+\tau) \rangle$



Standard deviation $\sigma = 0.065 \Rightarrow$ violation by 5σ

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Natural next step: quantum feedback control of persistent Rabi oscillations

In simple monitoring the phase of persistent Rabi oscillations fluctuates randomly:

 $z(t) = \cos[\Omega t + \varphi(t)]$ for $\eta=1$

phase noise \Rightarrow finite linewidth of the spectrum

Goal: produce persistent Rabi oscillations without phase noise by synchronizing with a classical signal $z_{\text{desired}}(t) = \cos(\Omega t)$



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Several types of quantum feedback (broadband monitoring with no classical back-action) **Bayesian** Direct "Simple" Best but very difficult Similar to Wiseman Imperfect but simple & Milburn (1993) (monitor quantum state (do as in usual classical and control deviation) (apply measurement signal to feedback) control with minimal processing) $\frac{\Delta H_{\rm fb}}{F} = F \times \phi_m$ desired evolution feedback Η control stage signal comparison circuit barrier height $\Delta H_{\rm fb} / H = F \sin(\Omega t)$ control $\rho_{ij}(t)$ $\times \left(\frac{I(t) - I_0}{\Delta I / 2} - \cos \Omega t\right)$ aubit C<<1 detector I(t)**Bayesian** ^C qubit $\cos{(\Omega t)}, \tau$ -average equations $\phi_{\rm m}$ oha: **I**(t detector local osci (feedback fidelity) × sin (Ω t), τ-averag environment $\Delta H_{\rm fb} / H = F \times \Delta \varphi$ 0.8 0.6 -(feedback fidelity) $\eta_{eff} =$ C = 0.1**D** (feedback fidelity) 0.80 0.82 0.80 0.80 averaging time $\tau_{2} = (2\pi/\Omega)/10$ $\tau \left[(\Delta \mathbf{I})^2 / \mathbf{S}_{\mathbf{I}} \right] = 1$ 0.4 C=1n=10.2 $C_{env}/C_{det} = 0 / 0.1 / 0.5$ 0.0 C=C_{det}=1 _ 0.2 0.4 0.8 0.0 0.6 $\tau_a=0$ F (feedback strength) Ω Ruskov & A.K., 2002 0.0 4 5 6 0.0 0.2 0.6 0.8 0.4 F (feedback strength) F/C (feedback strength) Ruskov & A.K., 2002 A.K., 2005

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Quantum feedback in cQED setup

We have to undo both effects: disturbance of qubit phase ("classical") and disturbance of Rabi phase ("spooky")

 \Rightarrow have to control both qubit parameters (except for phase-sens., φ =0)

Phase-preserving case

$$\begin{cases} \frac{\rho_{gg}(\tau)}{\rho_{ee}(\tau)} = \frac{\rho_{gg}(0)}{\rho_{ee}(0)} \frac{\exp[-(\bar{I} - I_g)^2 / 2D]}{\exp[-(\bar{I} - I_e)^2 / 2D]} \\ \rho_{ge}(\tau) = \rho_{ge}(0) \sqrt{\frac{\rho_{gg}(\tau) \rho_{ee}(\tau)}{\rho_{gg}(0) \rho_{ee}(0)}} \exp(iK\bar{Q}\tau) \end{cases}$$

Use different quadratures for two feedback channels

Use direct feedback for qubit energy +some feedback for µwave amplitude

Phase-sensitive case

$$\int \frac{\rho_{gg}(\tau)}{\rho_{ee}(\tau)} = \frac{\rho_{gg}(0)}{\rho_{ee}(0)} \frac{\exp[-(\overline{I} - I_g)^2 / 2D]}{\exp[-(\overline{I} - I_e)^2 / 2D]}$$
$$\rho_{ge}(\tau) = \rho_{ge}(0) \sqrt{\frac{\rho_{gg}(\tau) \rho_{ee}(\tau)}{\rho_{gg}(0) \rho_{ee}(0)}} \exp(iK\overline{I}\tau)$$

Use the same signal for both

If $\phi=0$ (*K*=0), then only feedback for μ wave amplitude



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Conclusions

- Nothing is wrong with collapse postulate: just use proper philosophy
- It is easy to see what is "inside" collapse: simple Bayesian framework works for many solid-state setups
- Measurement backaction necessarily has a "spooky" part (informational, without a physical mechanism); it may also have a "classical" part (with a physically understandable mechanism)
- Three superconducting experiments so far: partial collapse, uncollapse, monitoring of non-decaying Rabi oscillations
- Many other proposals. Hopefully other experiments are coming soon. Quantum feedback is one of most interesting.

