Probing “inside” quantum collapse with solid-state qubits

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Outline:

- What is “inside” collapse? Bayesian framework.
  - broadband meas. (double-dot qubit & QPC)
  - narrowband meas. (circuit QED setup)
- Realized experiments
  - partial collapse (null-result & continuous)
  - uncollapse (+ entanglement preservation)
  - persistent Rabi oscillations, quantum feedback
Quantum mechanics =
Schrödinger equation (evolution) +
collapse postulate (measurement)

1) Probability of measurement result
\[ p_r = |\langle \psi | \psi_r \rangle|^2 \]

2) Wavefunction after measurement
\[ = \psi_r \]

- State collapse follows from common sense
- Does not follow from Schrödinger Eq. (contradicts)

What is “inside” collapse?
What if collapse is stopped half-way?
What is the evolution due to measurement? (What is “inside” collapse?)

- controversial for last 80 years, many wrong answers, many correct answers
- solid-state systems are more natural to answer this question

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

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

**Key words:** POVM, restricted path integral, quantum trajectories, quantum filtering, quantum jumps, stochastic master equation, etc.

**Our limited scope:**
(simplest system, experimental setups)

- solid-state qubit
- detector
- classical output
Quantum Bayesian framework
(slight technical extension of the collapse postulate)

1) **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.)
“Typical” setup: double-quantum-dot qubit + quantum point contact (QPC) detector

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

$$H_{DET} = \sum_l E_l a_l^\dagger a_l + \sum_r E_r a_r^\dagger a_r + \sum_{l,r} T (a_r^\dagger a_l + a_l^\dagger a_r)$$

$$S_I = 2eI$$

(“broadband”)
Bayesian formalism for DQD-QPC system

\[ H_{QB} = 0 \]

Qubit evolution due to measurement (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 \( \rho_{ii} \))

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):

\[
P(A_i | \text{res}) = \frac{P(A_i) P(\text{res} | A_i)}{\sum_k P(A_k) P(\text{res} | A_k)}
\]

So simple because:

1) no entanglement at large QPC voltage
2) QPC is ideal detector
3) zero qubit Hamiltonian
Now add classical back-action and decoherence

\[ H_{\text{qb}} = 0 \]

\[ \Delta I = I_1 - I_2 \]

\[ I_m \equiv \frac{1}{\tau} \int_0^\tau I(t) \, dt \]

\[ D = S_I / 2\tau \]

Example of classical (“physical”) backaction:

Each electron passed through QPC rotates qubit

\[ \text{arg}(T^* \Delta T) \neq 0 \]

\[ H_{\text{DET}} = \sum_l E_l a_l^\dagger a_l + \sum_r E_r a_r^\dagger a_r + \sum_{l,r} T(a_r^\dagger a_l + a_l^\dagger a_r) \]

\[ H_{\text{INT}} = \sum_{l,r} \Delta T (c_1^\dagger c_1 - c_2^\dagger c_2) a_r^\dagger a_l + \text{h.c.} \]
Now add Hamiltonian evolution

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

\[
\rho_{11} = -\rho_{22} = -2 \frac{H}{\hbar} \text{Im} \rho_{12} + \rho_{11}\rho_{22} \frac{2\Delta I}{S_I} [I(t) - I_0]
\]

\[
\rho_{12} = i \epsilon \rho_{12} + i \frac{H}{\hbar} (\rho_{11} - \rho_{22}) + \rho_{12}(\rho_{11} - \rho_{22}) \frac{\Delta I}{S_I} [I(t) - I_0] - \gamma \rho_{12}
\]

\[\Delta I = I_1 - I_2, \quad I_0 = (I_1 + I_2)/2, \quad S_I \text{ – detector noise}\]

\[\gamma = 0 \text{ for QPC}\]

For simulations: \[I = I_0 + \frac{\Delta I}{2} (\rho_{11} - \rho_{22}) + \xi\]

Evolution of qubit \textit{wavefunction} can be monitored if $\gamma=0$ (quantum-limited)
Relation to “conventional” master equation

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

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

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

\[ \dot{\rho}_{11} = -\rho_{22} / dt = -2H \text{Im} \rho_{12} \]

\[ \dot{\rho}_{12} = i \varepsilon \rho_{12} + iH (\rho_{11} - \rho_{22}) - \Gamma \rho_{12} \]

\( \Gamma \) – ensemble decoherence, \( \Gamma = (\Delta I)^2 / 4S_I + K^2 S_I / 4 + \gamma \)

Quantum efficiency: \( \eta = \frac{(\Delta I)^2}{4S_I} \Gamma \) or \( \tilde{\eta} = 1 - \frac{\gamma}{\Gamma} \)
Quantum measurement in POVM formalism

Davies, Kraus, Holevo, etc.
(Nielsen-Chuang, pp. 85, 100)

Measurement (Kraus) operator $M_r$ (any linear operator in H.S.):

Probability: $P_r = \frac{M_r \psi}{\|M_r \psi\|}$ or $P_r = \text{Tr}(M_r \rho M^\dagger_r)$

Completeness: $\sum_r M^\dagger_r M_r = 1$ (People often prefer linear evolution and non-normalized states)

Relation between POVM and quantum Bayesian formalism:

decomposition $M_r = U_r \sqrt{M^\dagger_r M_r}$ (almost equivalent)
Narrowband linear measurement
(circuit QED setup)

Difference from broadband: **two quadratures**
(two signals: $A(t) \cos \omega t + B(t) \sin \omega t$)

$H = \frac{1}{2} \omega_{qb} \sigma_z + \omega_r a^\dagger a + \chi a^\dagger a \sigma_z$

- qubit state changes resonator freq.,
- number of photons affects qubit freq.

Blais et al., 2004
Gambetta et al., 2006, 2008

Schoelkopf et al.
Phase-sensitive (degenerate) paramp

get some information ($\sim \cos^2 \varphi$) about qubit state and some information ($\sim \sin^2 \varphi$) about photon fluctuations

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

$$\rho_{ge}(\tau) = \rho_{ge}(0) \frac{\rho_{gg}(\tau) \rho_{ee}(\tau)}{\rho_{gg}(0) \rho_{ee}(0)} \exp(i\bar{I}\tau)$$

Bayes

$$\bar{I} = \frac{1}{\tau} \int_0^\tau I(t) \, dt \quad D = S_I / 2\tau$$

$$I_g - I_e = \Delta I \cos \varphi$$

$$K = \frac{\Delta I}{S_I} \sin \varphi$$

$$\Gamma = \frac{(\Delta I \cos \varphi)^2}{4S_I} + \frac{K^2 S_I}{4} = \frac{\Delta I^2}{4S_I} = \frac{8\chi^2 \bar{n}}{\kappa}$$

Same as for QPC, but $\varphi$ controls trade-off between quantum & classical back-actions (we choose if photon number fluctuates or not)

A.K., arXiv:1111.4016
Phase-preserving (nondegenerate) paramp

Now information in both \( I(t) \) and \( Q(t) \).

Choose

\[
I(t) \leftrightarrow \cos(\omega_d t) \quad \text{(qubit information)} \\
Q(t) \leftrightarrow \sin(\omega_d t) \quad \text{(photon fluct. info)}
\]

Small \( \delta\omega \Rightarrow \) can follow \( \varphi(t) \)

Large \( \delta\omega \ (>> \Gamma) \Rightarrow \) averaging over \( \varphi \) (phase-preserving)

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

\[
\begin{align*}
\bar{I} &= \frac{1}{\tau} \int_0^\tau I(t) \, dt \\
\bar{Q} &= \frac{1}{\tau} \int_0^\tau Q(t) \, dt \\
D &= \frac{S_I}{2\tau} \\
I_g - I_e &= \frac{\Delta I}{\sqrt{2}} \\
K &= \frac{\Delta I}{\sqrt{2S_I}} \\
\Gamma &= \frac{\Delta I^2}{8S_I} + \frac{\Delta I^2}{8S_I} = 8\chi^2n
\end{align*}
\]

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

A.K., arXiv:1111.4016

Understanding important for quantum feedback
Why not just use Schrödinger equation for the whole system?

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
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)
- Berkeley-2012  Quantum feedback of persistent Rabi osc. (phase-sensitive paramp)
- Yale-2012  Partial (continuous) measurement (phase-preserving paramp)
Partial collapse of a Josephson phase qubit

Main idea:

What happens if no tunneling?

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

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)
Partial collapse: experimental results

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 $T_1, T_2$)

quantum efficiency $\eta_0 > 0.8$

Good confirmation of the theory
Uncollapsing for qubit-QPC system (theory)


First “accidental” measurement
Uncollapsing measurement

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 uncollapsing is unsuccessful.

Somewhat similar to quantum eraser of Scully and Druhl (1982)
Experiment on wavefunction uncollapse


**Uncollapse protocol:**
- partial collapse
- $\pi$-pulse
- partial collapse (same strength)

If no tunneling for both measurements, then initial state is fully restored

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

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

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 unknown unitary evolution, uncollapsing – undoing of a known, but non-unitary evolution

N. Katz et al.
Suppression of $T_1$-decoherence by uncollapse

A.K. & Keane, PRA-2010

Protocol:

$\rho_{11}$ storage period $t$

| $\psi_f$ ⟩ = $\psi_{\text{in}}$ ⟩ with probability $(1-p) e^{-t/T_1}$

| $\psi_f$ ⟩ = |0⟩ with $(1-p)^2 |\beta|^2 e^{-t/T_1} (1-e^{-t/T_1})$

Ideal case ($T_1$ during storage only)

for initial state $|\psi_{\text{in}}⟩ = \alpha |0⟩ + \beta |1⟩$

$F_{\text{av}}$, $F_\chi$ fidelity

Realistic case ($T_1$ and $T_\phi$ at all stages)

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

Trade-off: fidelity vs. probability
Realization with photons


- Works perfectly (optics, not solid state!)
- Amplitude damping (“energy relaxation”) decoherence is imitated in a clever way

\[ p = 0.9 \]
\[ \gamma \text{ is purity} \]

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Uncollapsing preserves entanglement


- Extension of 1-qubit experiment
- Revives entanglement even from “sudden death”


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Recent experiment in Michel Devoret’s group

Courtesy of Michel Devoret (Yale Univ., manuscript in preparation)

MEASUREMENT PROTOCOL

State preparation

\( R_x(\pi/2) \)

Variable strength measurement

\( \bar{n} \) varies

(\( X_f, Y_f, Z_f \))

Tomography

\( R_x(\pi/2), R_y(\pi/2), \) or \( Id \)

\( \bar{n} = 5 \)

outcome (\( I_m, Q_m \))

\( \bar{n} = 5 \)

z

y

x

(phase-preserving paramp)

Repeat 10,000,000 times

\( x_f = \pm 1 \) or \( y_f = \pm 1 \) or \( z_f = \pm 1 \)

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MEASUREMENT WITH $\bar{n} = 5 \times 10^{-4}$

Cavity Drive = $5.0 \times 10^{-4}$ photons

$(I_m^g - I_m^e)/(2\sigma) = 0.046$

Courtesy of Michel Devoret (manuscript in preparation)
**MEASUREMENT WITH \( \bar{n} = 1.1 \times 10^{-1} \)**

Courtesy of Michel Devoret (manuscript in preparation)

Histogram of measurement outcomes

Cavity Drive = 1.1e-01 photons

\( (I_m^g - I_m^e)/(2\sigma) = 0.543 \)
MEASUREMENT WITH $\bar{n} = 5 \times 10^{-1}$

Courtesy of Michel Devoret (manuscript in preparation)

Histogram of measurement outcomes

tomography along X, Y, Z after measurement

Cavity Drive = 5.1e-01 photons

$(l_m^g - l_m^e)/(2\sigma) = 1.223$
**MEASUREMENT WITH $\bar{n} = 5$**

Courtesy of Michel Devoret (manuscript in preparation)

Histogram of measurement outcomes

Cavity Drive = 5.0e+00 photons

$$\frac{(I_m^g - I_m^e)}{(2\sigma)} = 4.100$$

Tomography along X, Y, Z after measurement
Non-decaying (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

\[
\frac{(\Delta I)^2}{4S_I} \ll \Omega
\]

(“reason”: attraction to left/right states)

Direct experiment is difficult

A.K., PRB-1999
Indirect experiment: spectrum of persistent Rabi oscillations

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

(const + signal + noise)

peak-to-pedestal ratio = 4\(\eta\) \(\leq\) 4

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: \(\langle z^2 \rangle = 1 \) (!!!)

integral under the peak ⇔ variance \(\langle z^2 \rangle\)

amplifier noise ⇒ higher pedestal, poor quantum efficiency, but the peak is the same!!!

\(\eta\) ≤ 1

\(S_I(\omega)/S_0\)

[Diagram showing the spectrum and parameters]

\(\Omega\) - Rabi frequency

\(C = (\Delta I)^2 / HS_I\)

C=13

\(\Omega = 2H\)

\(C\)

\(\omega / \Omega\)

\(S_I(\omega)\)

\(\eta\ll1\)

\(O\) - qubit

\(C\) - qubit

\(I\) - detector

\(I(t)\)

\(\xi(t)\)

\(\xi\) is Bloch coordinate

(demonstrated in Saclay expt.)
Saclay experiment


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

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

Palacios-Laloy et al., 2010

\[ \bar{n} = \frac{\Delta S}{4S} \sim 10^{-2} \]

Pre-amplifier noise temperature \( T_N = 4 \text{ K} \)

\[ \frac{1}{1 + \frac{2T_N}{\hbar \omega}} \approx 0.03 \]

\[ \bar{n} = 0.23 \]

\[ \bar{n} = 1.56 \]

Theory by dashed lines, very good agreement
Violation of Leggett-Garg inequalities

In time domain

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

\[
K(\tau_1) + K(\tau_2) - K(\tau_1 + \tau_2) \leq 1 \quad \Rightarrow \quad 2K(\tau) - K(2\tau) \leq 1
\]

\[
f_{\text{LG}}(0) = K(0) = \langle z^2 \rangle \quad \langle z^2 \rangle = 1.01 \pm 0.15
\]

\[
f_{\text{LG}}(17 \text{ ns}) = 1.44 \pm 0.12 \quad \text{Ideal } f_{\text{LG,max}} = 1.5
\]

Standard deviation \( \sigma = 0.065 \Rightarrow \text{violation by } 5\sigma \)
Quantum feedback control of persistent Rabi oscillations

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

\[ z(t) = \cos[\Omega t + \varphi(t)] \quad \text{for } \eta = 1 \]

Phase noise \( \Rightarrow \) finite linewidth of the spectrum

**Goal:** produce persistent Rabi oscillations without phase noise by synchronizing with a classical signal

\[ z_{\text{desired}}(t) = \cos(\Omega t) \]

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

\[ S_I = S_0 + \frac{\Delta I^2}{4} S_{zz} + \frac{\Delta I}{2} S_{\xi z} \]

integral \( \langle z^2 \rangle = \frac{1}{2} + \frac{1}{2} = 1 \)

integral \( \langle z^2 \rangle = \frac{1}{2} \)
Several types of quantum feedback

Bayesian

Best but very difficult
(monitor quantum state and control deviation)

Direct

as in Wiseman-Milburn (1993)
(apply measurement signal to control with minimal processing)

“Simple”

Imperfect but simple
(do as in usual classical feedback)

Berkeley-2012 experiment: “direct” and “simple”

Ruskov & A.K., 2002

A.K., 2005

ΔH_{fb} / H = F \times \Delta \phi

ΔH_{fb} / H = F \sin(\Omega t) \times \left( \frac{I(t) - I_0}{\Delta I/2} - \cos \Omega t \right)

\eta_{eff} = \frac{1}{C} \eta \frac{\tau_a}{(2\pi/\Omega)^10}

C = 0.1

\tau_a = (2\pi/\Omega)^10

\eta = 1

C = 1

 average

feedback signal

control stage (barrier height)

comparison circuit

qubit

cos

detector

Bayesian equations

environment

feedback strength

feedback fidelity

relation phase

C = C_{det} = 1

C_{env} / C_{det} = 0, 0.1, 0.5

\tau_a = 0

feedback strength

Ruskov & A.K., 2002

control

\eta = 1

\Delta H_{fb} \sim \frac{F}{H} \times \phi_m

feedback strength

feedback fidelity

F/C (feedback strength)

F (feedback strength)

feedback fidelity

F (feedback strength)

feedback fidelity

feedback strength

feedback fidelity
Quantum feedback of Rabi oscillations


(Phase-sensitive paramp)
Paramp BW 10 MHz, Cavity LW 8 MHz, Rabi freq. 3 MHz,
Meas. dephasing 0.25 MHz, Env. dephasing 0.05 MHz

Courtesy of Irfan Siddiqi
STABILIZED RABI OSCILLATIONS

Feedback OFF

Feedback ON

Courtesy of Irfan Siddiqi
STILL GOING…

- Single quadrature measurement
- Operate with measurement dephasing dominant
- Appearance of narrow peak when PLL operational

Courtesy of Irfan Siddiqi
STATE TOMOGRAPHY

- Observe expected rotation in the X,Z plane
- Observe Bloch vector reduced to 50% of maximum

Courtesy of Irfan Siddiqi
FEEDBACK EFFICIENCY

\[ D = \frac{2}{1 - \frac{F}{\eta \Gamma / \Omega_R}} + \frac{\Gamma / \Omega_R}{F} \]

- \( D \): “feedback efficiency”
- \( F \): feedback strength
- \( \eta \): detector efficiency (0-1)
- \( \Gamma \): dephasing rate
- \( \Omega_R \): Rabi frequency

- Analytics do not include delay time, finite bandwidth, \( T_1 \)
- Numerics include delay and bandwidth \( \rightarrow \) good agreement
Conclusions

● 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)

● Five superconducting experiments so far:
  - partial collapse,
  - uncollapse,
  - monitoring of non-decaying Rabi oscillations,
  - quantum feedback of persistent Rabi oscillations,
  - partial measurement with continuous result

● Hopefully something useful in future