Title: The arrow of time for continuous quantum measurements

Date: Jun 20, 2016 02:00 PM

URL: http://pirsa.org/16060037

Abstract: The question of the time reversibility of quantum mechanics with measurements is one that has been debated for some time. In this talk, I will present new work exploring our ability to distinguish the forward from the time-reverse measurement records of continuous quantum measurements. The question involves both the conditions for the time-reversibility of the quantum trajectory equations of motion, as well as statistical distinguishability of the arrow of time. I will present the case with and without postselection on the final state, and connect the issue to a similar topic in nonequilibrium statistical physics. This work generalizes and pushes the two-time reformulation of quantum mechanics developed by Yakir Aharonov and collaborators beyond arbitrarily weak measurements. I will also discuss how this proposal can be implemented with continuously monitored superconducting quantum circuits.

In collaboration with Alexander Korotkov, Justin Dressel, Areeya Chantasri, and Kater Murch

Funded by the John Templeton Foundation.

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The arrow of time for continuous quantum measurements

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Concepts and Paradoxes in a Quantum Universe

Funding for this and related work:

John Templeton Foundation

LPS The Laboratory for Physical Sciences

National Science Foundation WHERE DISCOVERIES BEGIN

Army Research Office

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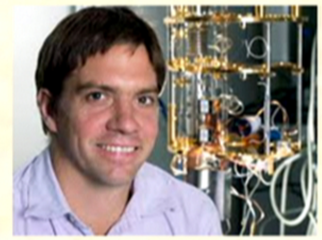

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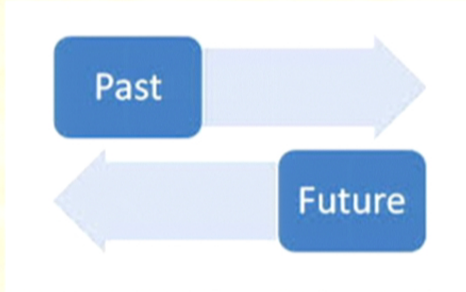
Outline

- Review of time symmetry in classical physics
- Review of time symmetry in statistical physics
- Quantum measurement breaks time symmetry
- Restoring time symmetry: Janus measurement sequences
- Arrow of time (?)

Arrow of time in classical physics

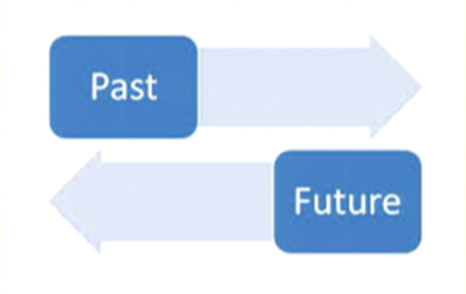


$$\frac{dp}{dt} = -\frac{\partial H}{\partial q} \qquad \qquad \frac{dp}{dt} = -\frac{\partial H}{\partial q}$$

$$\frac{dq}{dt} = \frac{\partial H}{\partial p} \qquad t \rightarrow -t \qquad \frac{dq}{dt} = \frac{\partial H}{\partial p}$$

$$p = \frac{dq}{dt} \rightarrow -p$$

Arrow of time in classical physics



Time reversal in quantum physics

Must complex conjugate the wavefunction to keep the Schrodinger equation invariant.

$$i\hbar\frac{\partial\psi(x,t)}{\partial t} = \hat{H}\psi(x,t)$$

$$t \rightarrow -t$$

$$\psi \longrightarrow \psi^*$$

and

$$\hat{H} \rightarrow \hat{H}^*$$

This is the same as exchanging "bras" and "kets"

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CHAPMAN UNIVERSITY 1861

Why conjugate the H?

Reminder: Although Hermitian, sometimes Hamiltonian's are complex.

Example: In the presence of a magnetic field, **B**, with corresponding vector potential **A**

$$\mathbf{B} = \nabla \times \mathbf{A}$$

$$\hat{p} \rightarrow \hat{p} + e\mathbf{A}$$

$$\hat{p} = -i\hbar\nabla \rightarrow -\hat{p}$$

Under time reversal

So

$$\mathbf{A} \rightarrow -\mathbf{A}$$ or $$\mathbf{B} \rightarrow -\mathbf{B}$$

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Time reversal in quantum physics

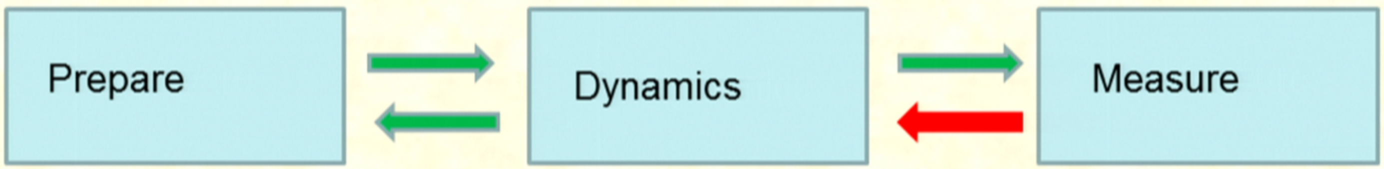
What about decoherence?

In principle, decoherence can be time-reversed microscopically since it is unitary on the larger system, but plays the role of a "quantum friction", effectively introducing an arrow of time into a single system.

What about measurement?

"We are dealing with [a quantum] event that makes itself known by an **irreversible** act of amplification, by an indelible record, an act of registration."
-John Wheeler

Measurement seems fundamentally asymmetric

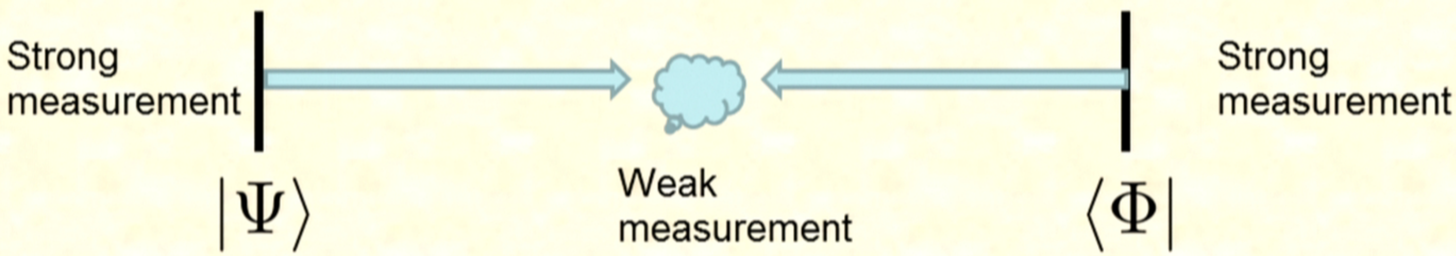


Wavefunction collapse introduces an asymmetry – If you learn something, can you unlearn it?

Ways to Restore the time symmetry

- The way of Aharonov and collaborators (dating back to 1964):

Introduce a future boundary condition via postselection, and consider only projective measurements in the past and future, and arbitrarily weak measurements in the present.



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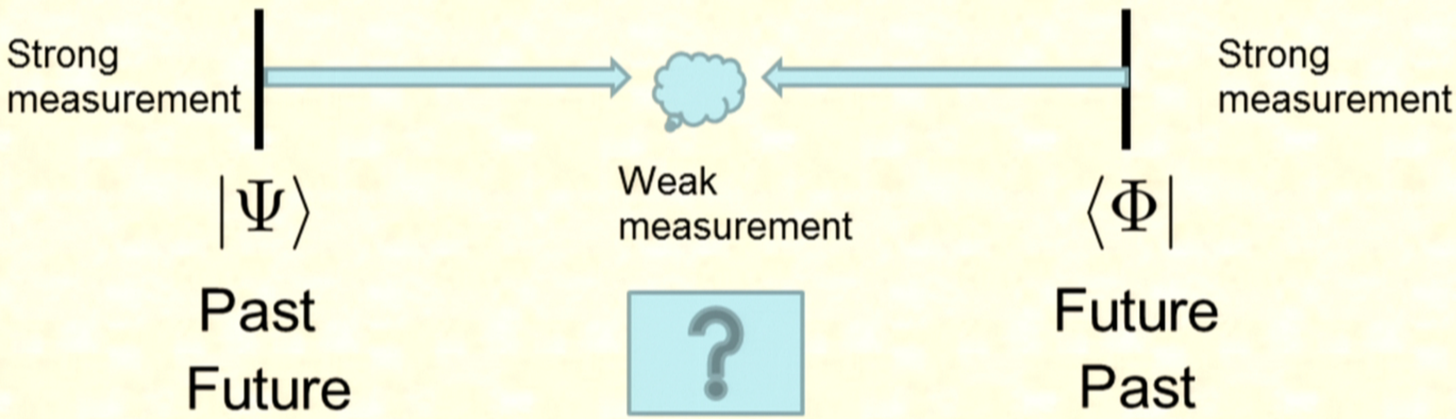


Our way to restore the time symmetry - uncollapse

- Based on concept of measurement reversal. Closer to the previous examples of time symmetry since it involves a time-continuous differential equation. **Korotokov & ANJ, PRL 2006; ANJ & Korotkov, Cont. Phys. 2010**

Introduce a generalized measurement for a small time step, and ask what it takes to reverse it:

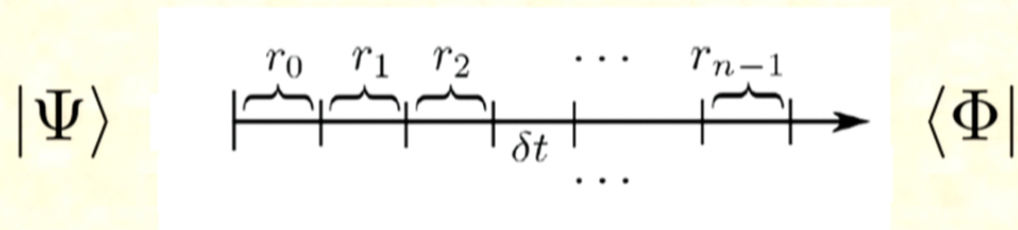
$$M_b M_a \propto \mathbf{1}$$

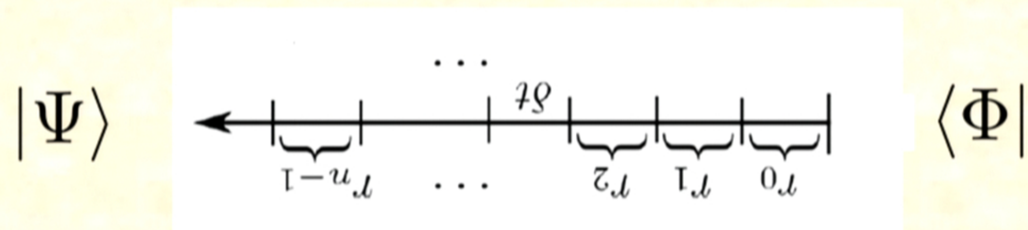
$|\Psi\rangle$ → Generalized measurement A, with result a → $|\Psi'\rangle$ (partial collapse) → Generalized measurement B, with result b → $|\Psi\rangle$

$|\Psi'\rangle$ → …with result b' → $|\Psi''\rangle$

$$|\Psi'\rangle \propto M_a|\Psi\rangle$$

Consider series of time continuous measurements





It is *possible* to choose the "upside down" measurements, so that for every (potentially different) *forward measurement* with result r_j we apply a (potentially different) *backward measurement*, where a possible outcome corresponds to the inverse measurement operator.

Conditions for time symmetry restored:

Given a ***forward Janus*** measurement sequence

$$M_{r_N} \ldots M_{r_2} M_{r_1} |\Psi\rangle \propto |\Phi\rangle$$

We demand a ***backward Janus*** measurement sequence:

$$\langle\Phi| M_{r_1} M_{r_2} \ldots M_{r_N} \propto \langle\Psi|$$

That is, the Janus measurement sequence must involve a sequence of measurements which has a *possible* outcome, such that that measurement satisfies:

$$M_{r_i} \propto M^{-1}_{r_{N-i}}$$

(Any additional unitary dynamics is reversed in the usual way).

Simple example of qubit being continuously measured

Here, the situation is especially easy to experimentally realize, because the forward measurements are simply related to the backward measurements. The measurement outcomes become approximately continuous, $r_i \rightarrow r(t)$
For a short time δt

any measurement operator of the form $M_{r(t)} \propto 1 + \delta t\, r(t)\mathbf{A}$

can be inverted at short time simply by taking exactly the same kind of measurement, but negating the measurement result:

$$\rotatebox{180}{$r(t)$} \;=\; -r(T-t)$$

Time symmetric equations of motion of the quantum state

$$\dot{x} = -\Omega z - xzr/\tau,$$
$$\dot{y} = -yzr/\tau,$$
$$\dot{z} = \Omega x + (1 - z^2)r/\tau,$$

τ is the characteristic measurement timescale.

Consider "diffusive Rabi limit", where the effect of measurement is to introduce phase diffusion on the qubit state.

Conditions for time-symmetric equations of motion:

$$t \rightarrow -t \qquad r(t) \rightarrow -r(t)$$

(Inverting the non-dynamics)

$$\Omega \rightarrow -\Omega$$

(Inverting the Unitary dynamics)

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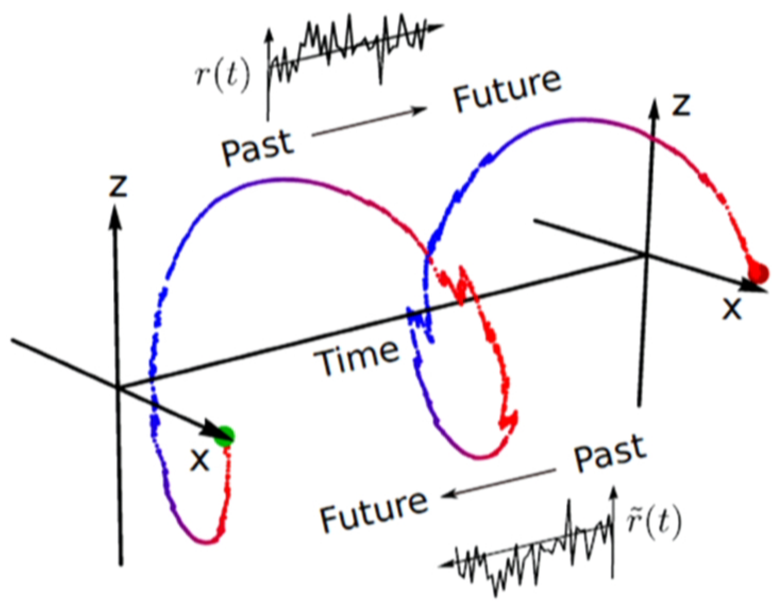
Movie watched forwards and backwards with both "video" and "audio"



Now the dynamics is time-symmetric. Is there still an arrow of time?

In the simplest case: Yes, a statistical one, since the probability density of going forward versus backwards will be different.

Let's play a game – I will show you a movie of the quantum trajectory, and you have to guess if I'm playing it (A) forward or (B) backwards from the probability of the results. (Just like the pool game earlier)

Define the forward distribution of the results $P_F(r)$, and backward distribution of results $P_B(r)$; then use Bayes rule to find:

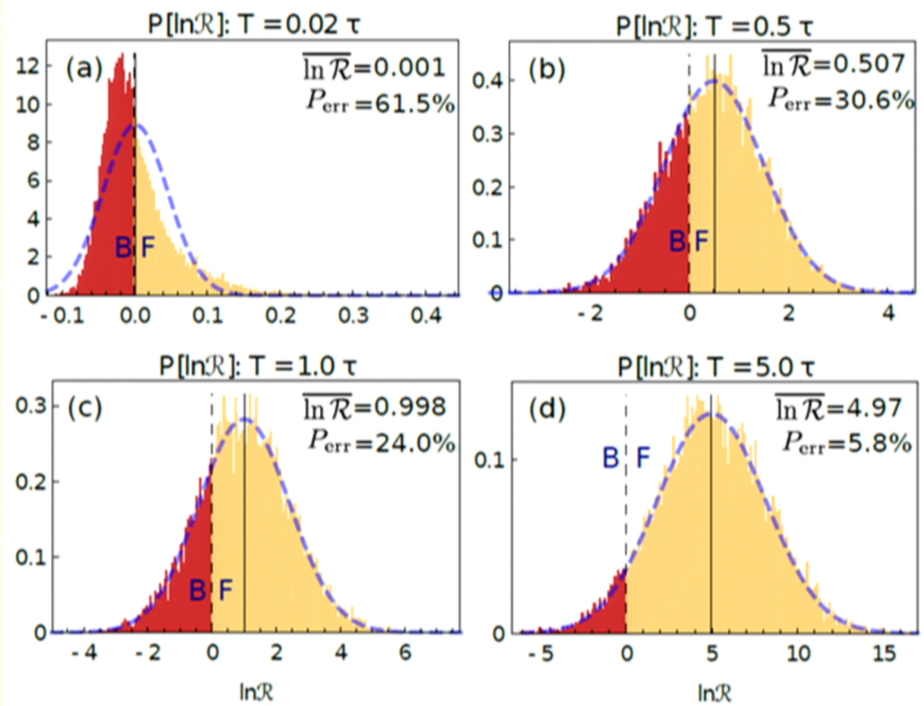
$$P(F|r(t)) = \frac{P(r(t)|F)P(F)}{P(r(t)|F)P(F)+P(r(t)|B)P(B)}$$

Likelihood of a forward versus backward movie, given record

$$P(F|r(t)) = \frac{\mathcal{R}}{1+\mathcal{R}}, \quad \mathcal{R} = \frac{P_F}{P_B}$$

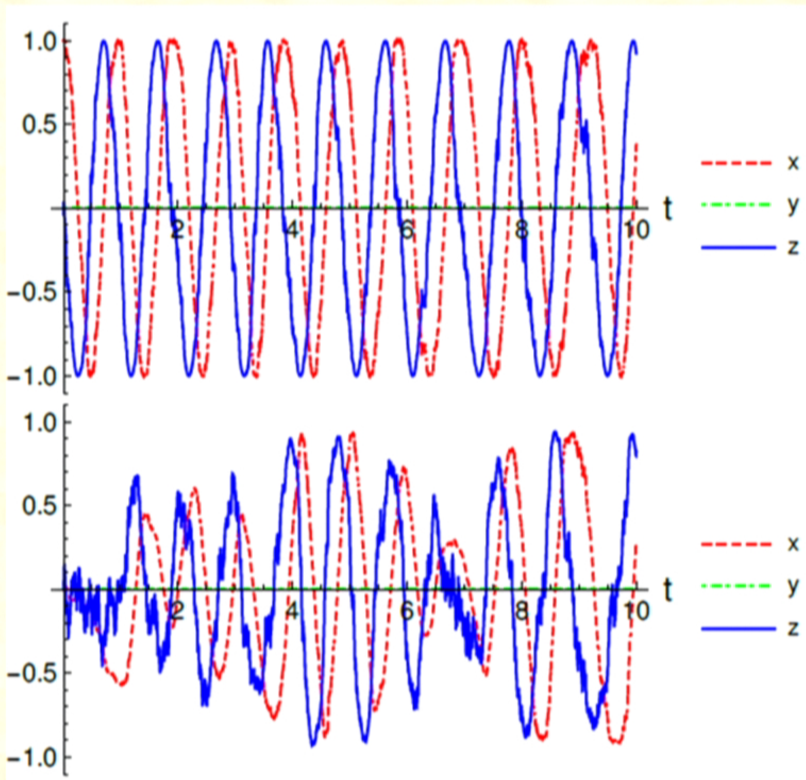
$$D(P_F \| P_B) = \int \mathcal{D}r \, P_F \ln(P_F/P_B)$$

$$D(P_F \| P_B) \approx \frac{T}{\tau}$$



Examples of seemingly backwards-in-time trajectories

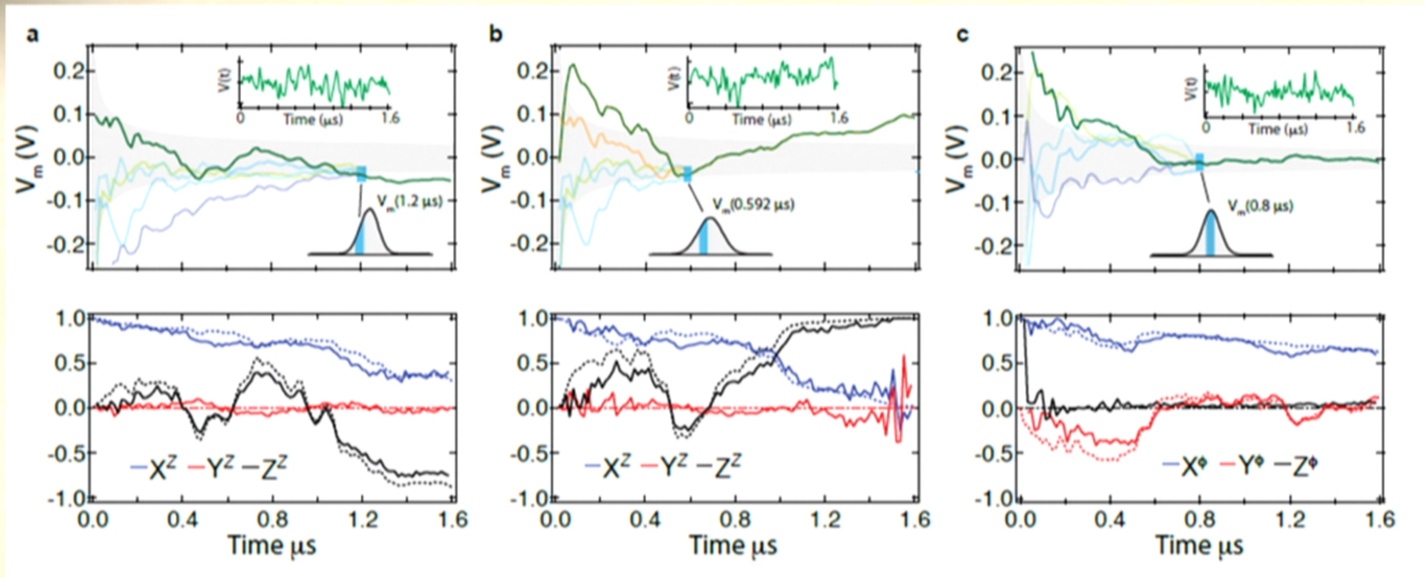
Time is measured in microseconds, with T=5, τ=2.



$\ln \mathcal{R} \approx -3.06$

$\ln \mathcal{R} \approx -2.42$

Quantum Trajectories in 3D Transmons



Continuously tomographic validation of quantum trajectories of a qubit.

Murch, Siddiqi, *et al.* Nature 2013

To be Investigated:

What changes if I add in postselection on the final boundary condition? (i.e., I select both boundary conditions beforehand, and discard all trajectories that don't end where I want them to).

What is the time symmetry of the most likely paths?

How general is this example? Are physical systems where a simple time-reverse of the measurement dynamics possible have special significance?

What does this mean for retrodictive / retrocausal quantum mechanics?

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Summary

- Reviewed ideas in time symmetric physics
- Developed a new paradigm for reestablishing time symmetry in the presence of a sequence of generalized measurements.
- Showed how this can work even in a continuous measurement of a qubit.
- Proposed an superconducting quantum circuit experiment to verify these predictions.

Past

Future