Does protective measurement imply the reality of the quantum state?

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Protective measurement

- In 1993, Aharonov, Anandan and Vaidman introduced a method of determining the quantum state of a single copy of a quantum system, provided the system is *protected* during the course of measurement[1].
- Protection is a procedure for preventing the quantum state from changing during the course of a measurement. Two types:
  - Protection via the quantum Zeno effect.
  - Hamiltonian protection.

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- Protection is a procedure for preventing the quantum state from changing during the course of a measurement. Two types:
  - Protection via the quantum Zeno effect.
  - Hamiltonian protection.
- Does this imply the reality of the quantum state?

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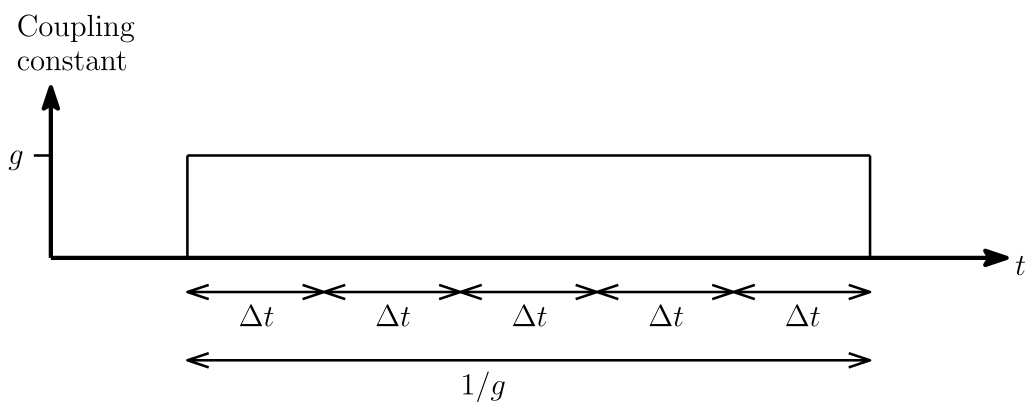
Zeno protected measurement

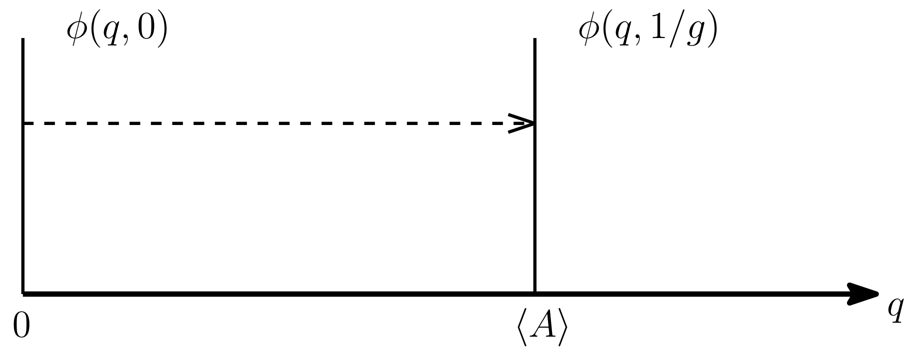
Alice Person trying to determine the quantum state
Bob Person who protects the quantum system.

- Bob sends Alice a quantum system prepared in a state $|\psi\rangle$.
- The protection: Every Δt Bob performs a measurement in a basis $\{|\psi_j\rangle\}$ that includes $|\psi\rangle$ as an eigenstate.
- To measure an observable, Alice couples it to a pointer system with wavefunction $\phi(q,t)$ and initial state $\phi(q,0) = \delta(q)$.

- To measure A, Alice couples the pointer to the system via a Hamiltonian $H = gAp$ for time $1/g$ s.t. $\Delta t \ll 1/g$.

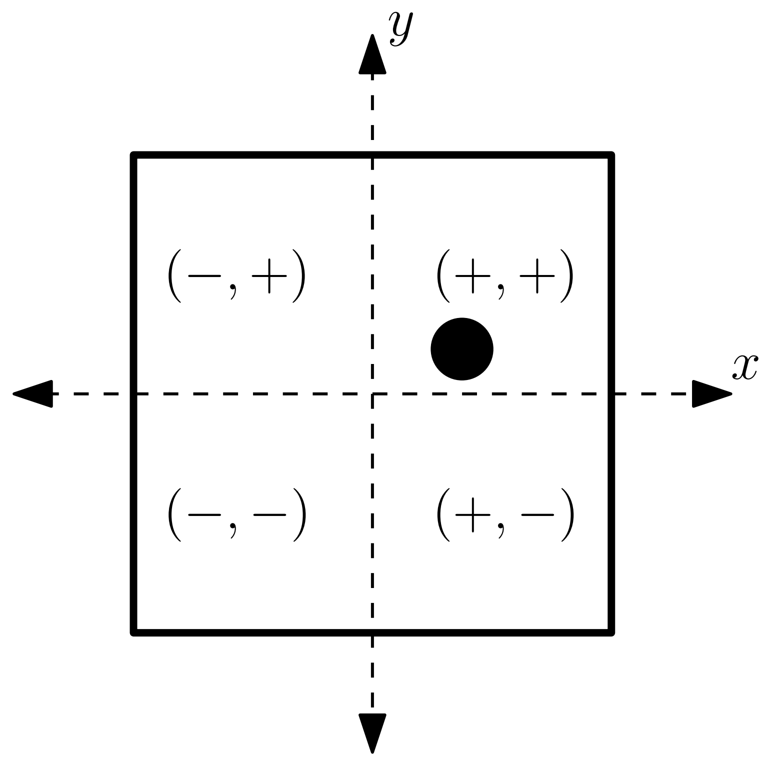


- When $\Delta t \to 0$, the pointer ends up pointing to $\langle A \rangle = \langle \psi | A | \psi \rangle$ and the system remains in state $|\psi\rangle$.



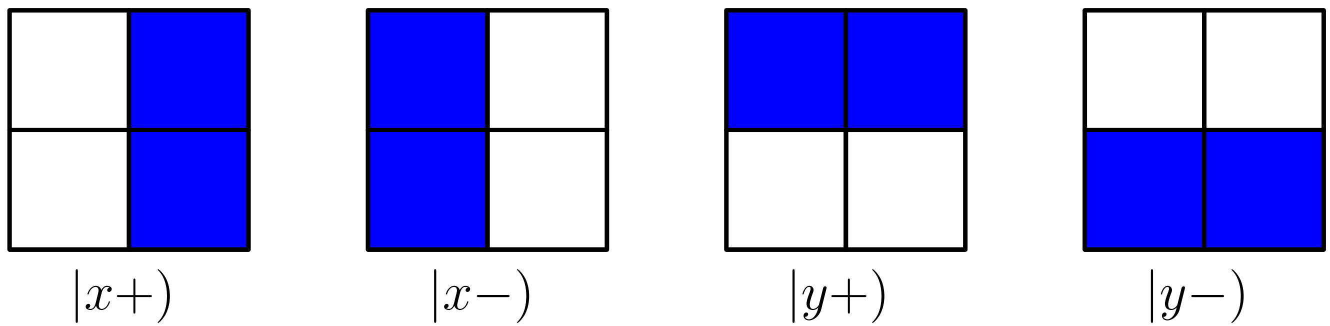
- Since the state of the system is unchanged, Alice can perform as many protective measurements of different observables as she likes.
- If she measures a tomographically complete set, she can determine the quantum state.
- So does this imply the reality of the quantum state?
- If we can do the same thing with classical probability distributions then the answer is no.

- System described by two classical random variables, X and Y, that take values ± 1 (or $\pm$ for short).
  - (x, y) denotes state in which $X = x$ and $Y = y$.
- Example: Ball in a box:



Toy model: Bob’s States

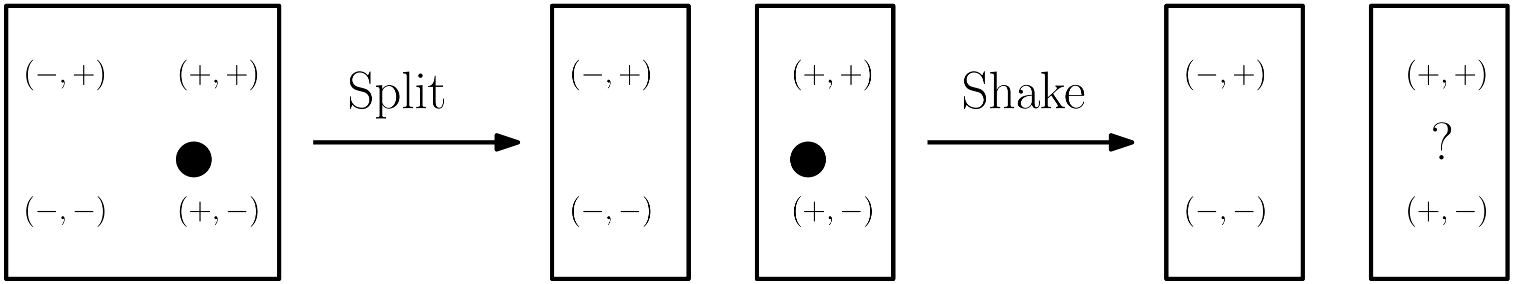
- Assume Bob can prepare the system in four different probability distributions:



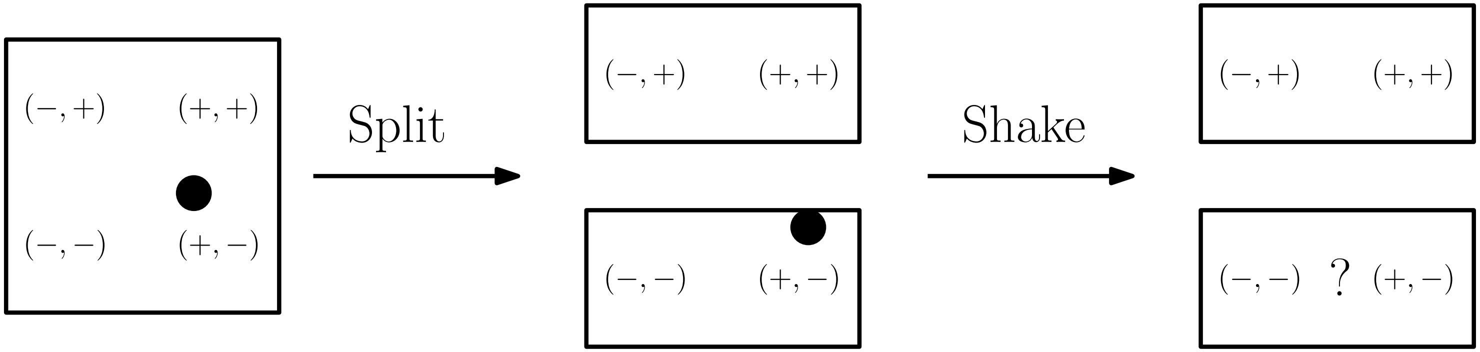
Distribution	$\langle X \rangle$	$\langle Y \rangle$
$\|x+)$	+1	0
$\|x-)$	-1	0
$\|y+)$	0	+1
$\|y-)$	0	-1

Toy model: Bob's Measurements

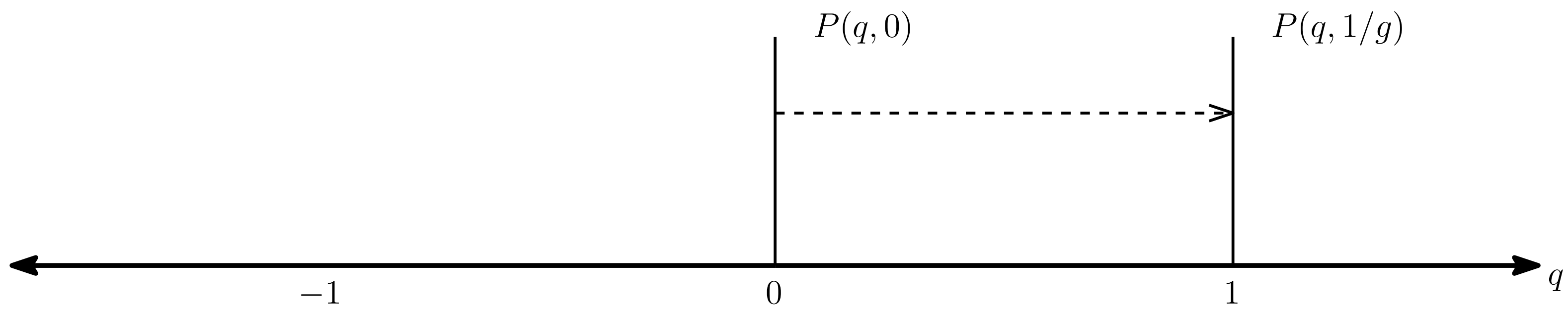
- X-measurement:



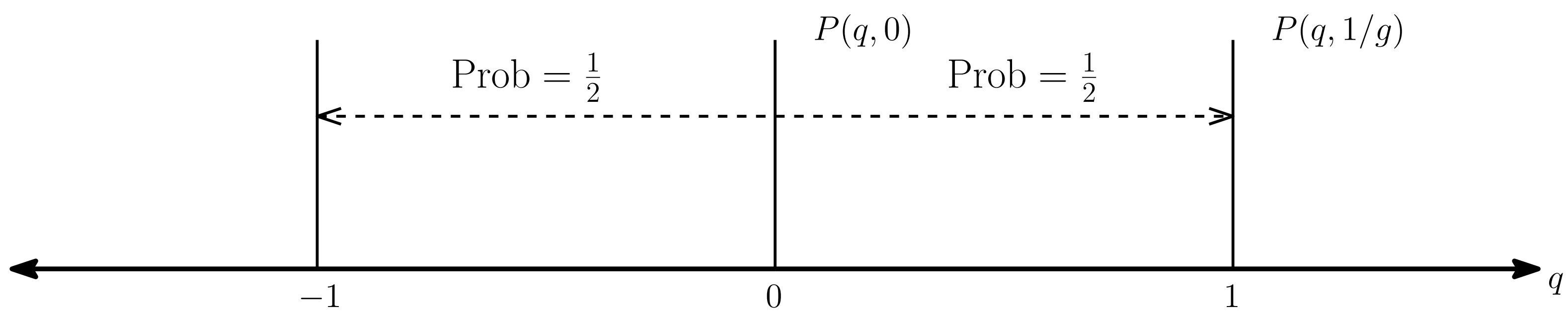
- Y-measurement:



- System is coupled to a classical pointer prepared in state $q = p = 0$ with Hamiltonian $H = gXp$ or $H = gYp$ for a time $1/g$.
- Without protection, for system prepared in $|x+)$, with $H = gXp$:



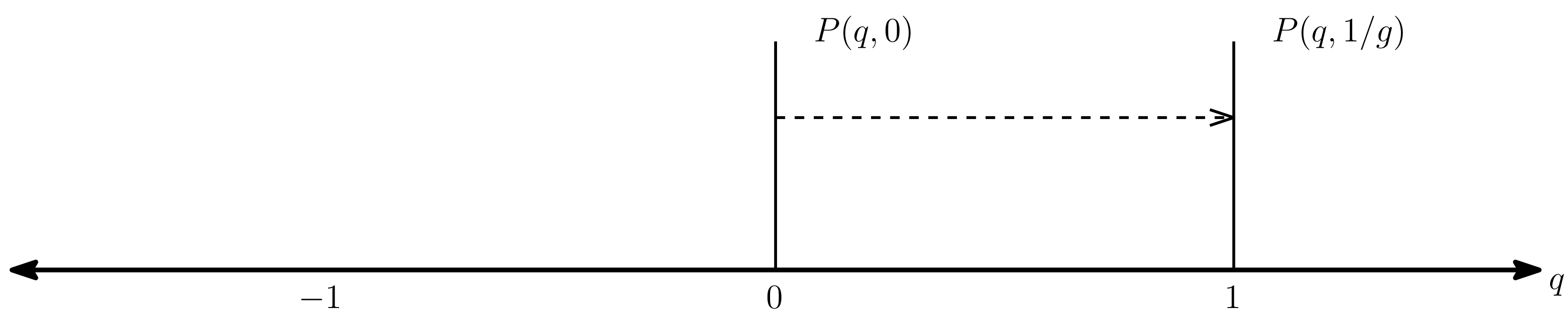
- and with $H = gYp$:



Toy model: Zeno protected measurement

- Now do the same thing whilst at the same time Bob is measuring X every $\Delta t = 1/gN$.

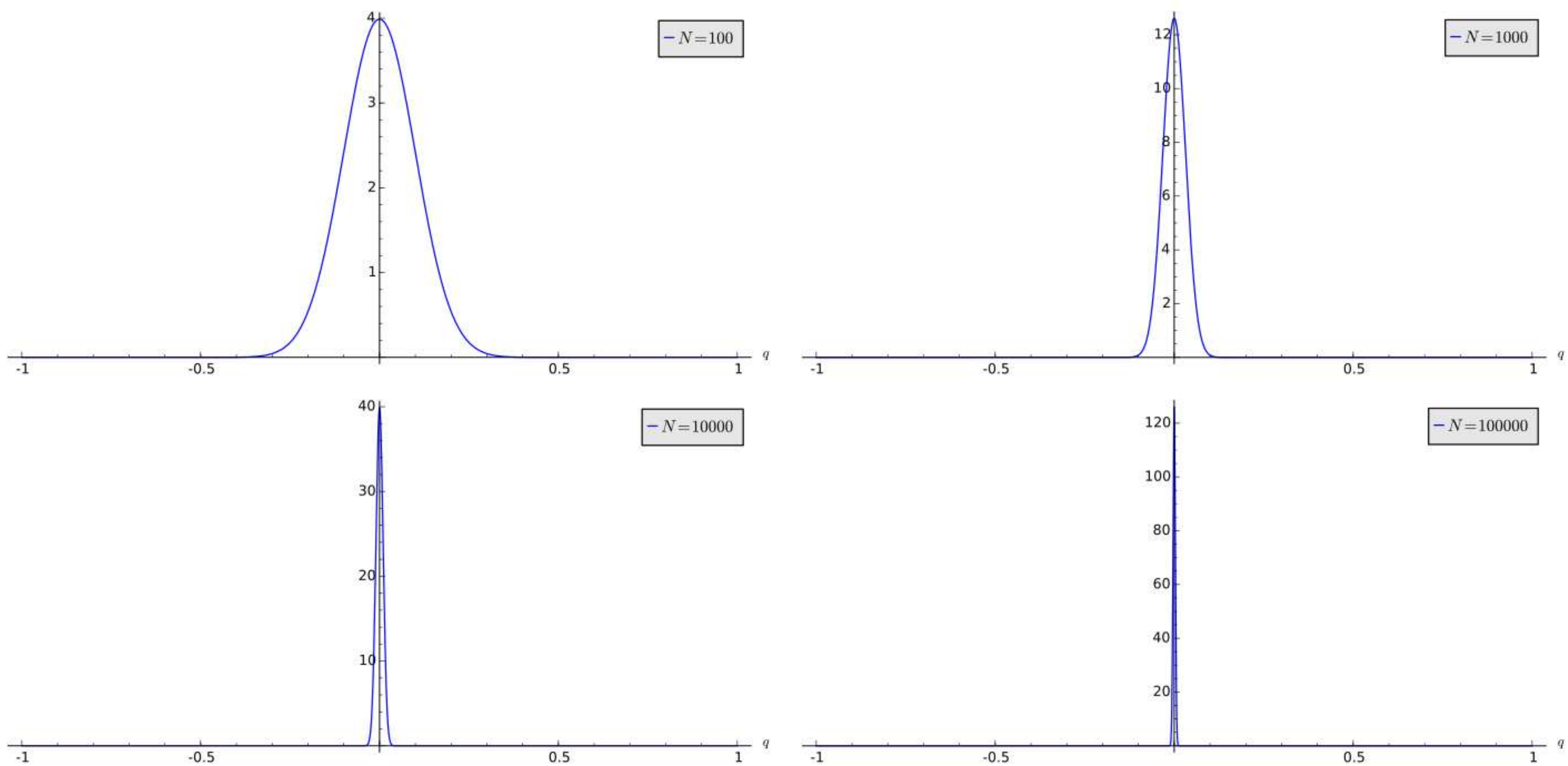
- For $H = gXp$, the pointer moves as before. The pointer is coupled to X, but Bob's measurement only affects Y.



- For $H = gYp$, every Δt the y-coordinate is randomized, so the pointer will keep going in the same direction or switch direction with probability $1/2$ each.
  - Pointer executes an N-step random walk with step size $1/N$.

Toy model: Zeno protected measurement

- For large N, distribution of final pointer position is $\approx \mathcal{N}(0, 1/N)$.
- Tends to $\delta(q)$ as $N \to \infty$.



- Implicit assumption that if a measurement does not change a quantum state then the measurement does nothing to the system when it is prepared in that state:
  - Not true in our model: Measuring X randomizes the y-coordinate even though distribution $|x+)$ is unchanged.

- Protective measurement is more like measuring N independently prepared systems than measuring just a single copy.

Other stuff in the paper

- Adding back-action to the Zeno toy model.
- Toy model for Hamiltonian protective measurements.
- Operational arguments for why protective measurement does not imply the reality of the quantum state:
  - Resource counting.
  - Protective measurement just implements an ordinary projective measurement in a basis for which the prepared state is an eigenstate.