Title: A Final Boundary Condition: Several Implications for the Universe

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Abstract: In classical mechanics, only the initial state of the system is needed to determine its time evolution. Additional information on the final state is either redundant or inconsistent. In quantum mechanics, however, the initial state does not convey all measurementsâ€™ outcomes. Only when augmented with a final quantum state, which can be understood as propagating backwards in time, a richer, more complete picture of quantum reality is portrayed.
This time-symmetric view leads to a subtle kind of a local hidden-variables theory, where true collapse never occurs, yet can be effectively observed. Moreover, the Born rule and the borderline between classical and quantum systems can be derived from, respectively, the requirements of stability and â€œmacroscopic robustness under time-reversal.â€™â€™ The significant role of macroscopic systems in amplifying and recording quantum outcomes then directly follows.
Some possible cosmological consequences of this construction are discussed, especially those related to the breakdown of the â€œPigeonhole principleâ€• and our on-going work on the concept of â€œQuantum Holismâ€•.

The talk will be partially based on:
1. Y. Aharonov, E. Cohen, E. Gruss, T. Landsberger, Quantum Stud.: Math. Found. 1 (2014) 133-146.
2. Y. Aharonov, E. Cohen, A.C. Elitzur, Ann. Phys. 355 (2015) 258-268.
3. Y. Aharonov, E. Cohen, to be published in â€œQuantum Nonlocality and Realityâ€•, M. Bell and S. Gao (Eds.), Cambridge University Press, arXiv:1504.03797.
4. E. Cohen, Y. Aharonov, to be published in â€œQuantum Structural Studies: Classical Emergence from the Quantum Levelâ€•, R.E. Kastner, J. Jeknic-Dugic, G. Jaroszkiewicz (Eds.), World Scientific Publishing Co., arXiv:1602.05083.

University of BRISTOL

A Final Boundary Condition: Several Implications for the Universe

Eliahu Cohen

Concepts and Paradoxes in a Quantum Universe, PI, June 2016

Outline

- Motivation – 4 not-so-easy-problems
- Preliminaries
- Two routes for setting the micro-macro boundary
- The cosmological boundary conditions and the two-time "collapse" mechanism

Based on

- E. Cohen, Y. Aharonov, Quantum to Classical Transitions via Weak Measurements and Post-Selection, in "Quantum Structural Studies: Classical Emergence from the Quantum Level", arXiv:1602.05083
- Y. Aharonov, E. Cohen, E. Gruss, T. Landsberger, Measurement and Collapse within the Two-State-Vector Formalism, Quantum Stud.: Math. Found. 1 , 133-146 (2014)
- Y. Aharonov, E. Gruss, Two-time interpretation of quantum mechanics, arXiv:quant-ph/0507269
- P.C.W. Davies, Quantum Weak Measurements and Cosmology, arXiv:1309.0773.
- Y. Aharonov, E. Cohen, A.C. Elitzur, Can a future choice affect a past measurement outcome?, Ann. Phys. 355 258-268 (2015)
- Some new thoughts

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Four Problems at a Glance

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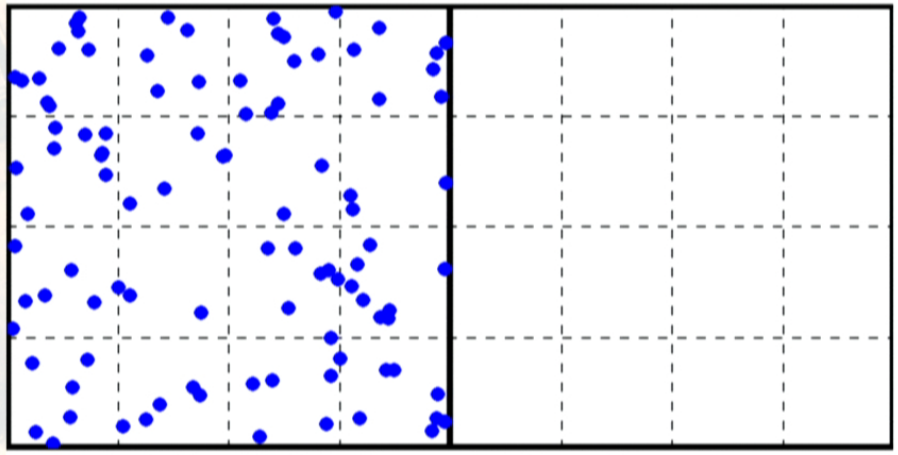
Four problems at a glance

- Symmetry under time reversal
- Collapse and the measurement problem
- Nonlocality
- Many-particle configuration space

1. Symmetry under time-reversal

Thermodynamic Arrow of Time



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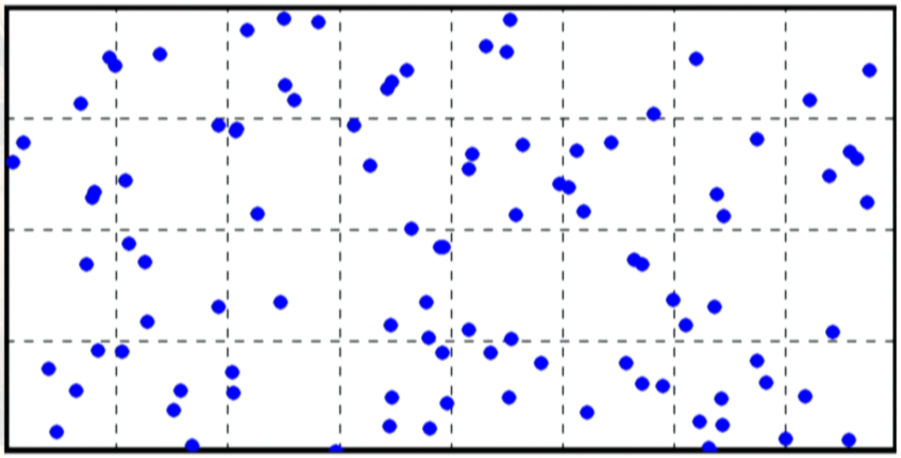
1. Symmetry under time-reversal

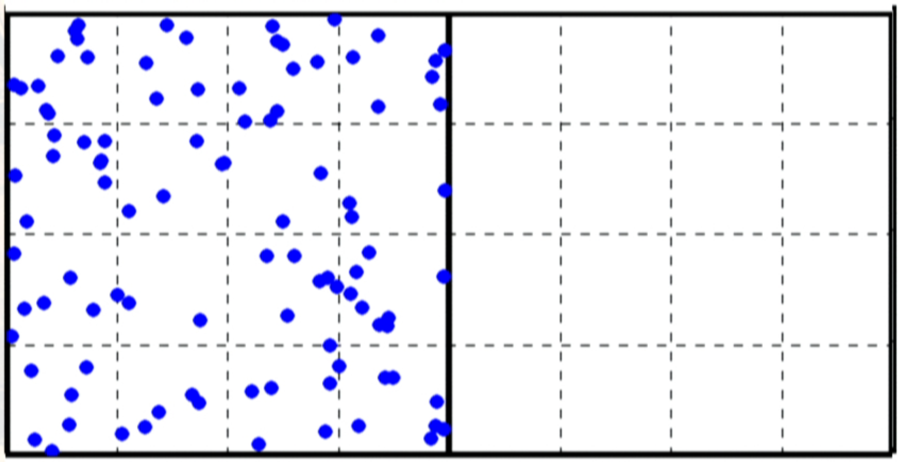
Thermodynamic Arrow of Time



The thermodynamic arrow of time can be defined in terms of stability under random perturbations

1. Symmetry under time-reversal

Thermodynamic Arrow of Time



The thermodynamic arrow of time can be defined in terms of stability under random perturbations

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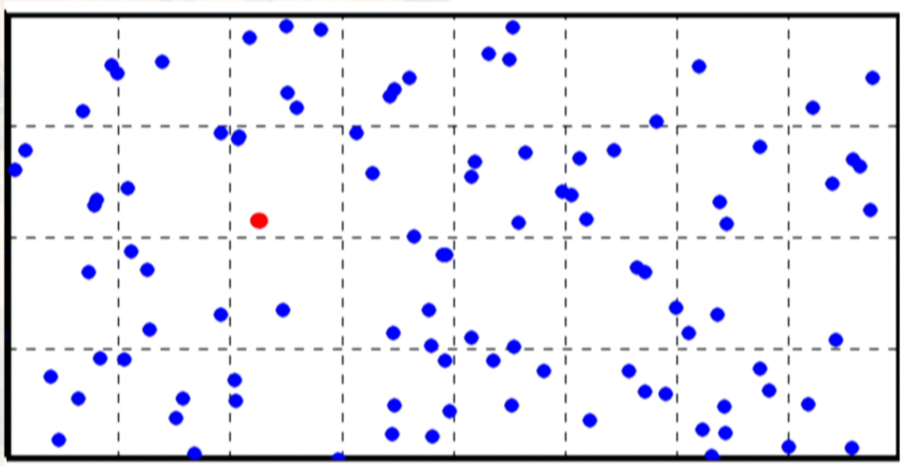
1. Symmetry under time-reversal-cont.

Quantum Arrow of Time



Can be flipped with an appropriate post-selection and a macroscopic record of information

1. Symmetry under time-reversal-cont.

More arrows of time

- Cosmological
- Radiative
- Time irreversibility in black holes
- More...
- A possible approach for treating all of them: adding a final boundary condition

2. Collapse

- Hermitian Hamiltonians give rise to unitary time evolution:

$$U(t_f,t_i) = T\exp(-\frac{i}{\hbar}\int_{t_i}^{t_f} H dt)$$

- This evolution is clearly reversible with: $U^{-1}(t_f,t_i) = U^{\dagger}(t_f,t_i) = U(t_i,t_f)$
- The wavefunction, carrying all the information of the quantum system is reversibly evolved without any losses.

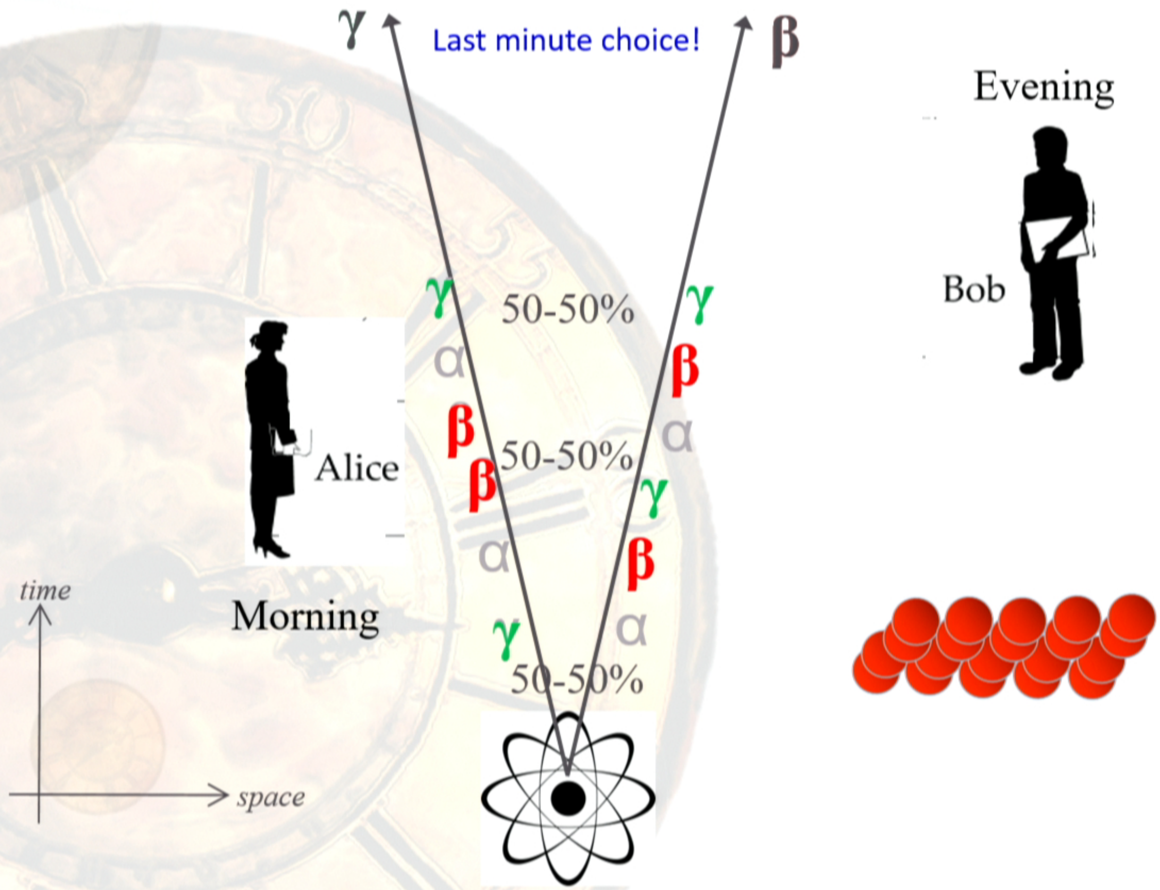
2. Collapse-cont.

- Until the non-unitary collapse which apparently prevents time reversal and inevitably leads to information loss.

"The reduction postulate is an ugly scar on what would be a beautiful theory if it could be removed"
Kurt Gottfried

3. Nonlocality

3. Nonlocality-cont.



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Y. Aharonov, E. Cohen, A.C. Elitzur, *Ann. Phys.* 355 258-268 (2015)

4. Configuration space

- Very different from the human experience
- Foreign to GR and QFT
- Still in progress...
- See also recent works of Sutherland and Wharton

Preliminaries

von Neumann Measurement-1/2

- System- $|\Psi_{in}\rangle$, measuring device- $|\Phi_{in}\rangle$ (both quantum)
- Assume that: $\Phi_{in}(x_d) = \exp(-x_d^2 / 2\sigma^2)$
- von Neumann measurement of *A*: $H = g(t) A p_d$

  where $\int_0^T g(t)dt = g_0$ is the coupling strength and p_d is the momentum of the measuring device
- When $g_0 = 1$ we get after post-selection of $|\Psi_{fin}\rangle$:

$$\langle \Psi_{fin} | e^{-(i/\hbar) A p_d} | \Psi_{in} \rangle \Phi_{in}(x_d) = \sum_i \langle \Psi_{fin} | a_i \rangle \langle a_i | \Psi_{in} \rangle \Phi_{in}(x_d - a_i)$$

  where $A|a_i\rangle = a_i |a_i\rangle$
- For an ideal measurement σ is very small
- Then $\Phi_{in}(x_d - a_i)$ is orthogonal to $\Phi_{in}(x_d - a_j)$ for $i \neq j$

von Neumann Measurement-2/2

- The measurement problem – Why does this lead in practice to a single outcome?

- The preferred basis problem – The representation

$$\langle \Psi_{fin} | e^{-(i/\hbar)Ap_d} | \Psi_{in} \rangle \Phi_{in}(x_d) = \sum_i \langle \Psi_{fin} | a_i \rangle \langle a_i | \Psi_{in} \rangle \Phi_{in}(x_d - a_i)$$

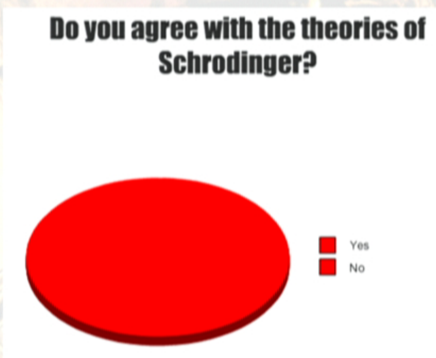
  is not unique.

- Does Decoherence, i.e. inserting the environment states $|e_i\rangle$ to the above sum, solve these problems?

  Let's try a **two-times decoherence** scheme!

The Measurement Problem

- How does the wavefunction "collapse"?
- How is the preferred basis chosen?
- How is the specific measurement outcome chosen?
- How to determine the "limit between classical and quantum physics"?
- What is the origin of the Born Rule?



Is the Cat dead or alive?

Is the Ket dead or alive?

Two-time Decoherence answers:
Alive, but suppressed!

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Many Worlds?

- When utilizing the Many-Worlds Interpretation, collapse is eliminated.
- Nature returns to be local and deterministic. Dynamics is purely unitary again
- **However**, our basic requirement for simplicity is not satisfied: We hav to believe in the existence of infinitely many entangled worlds we will never be able to see
- Other conceptual and moral difficulties arise
- Is there an alternative?

Initial and Final Conditions

- In classical mechanics, only $\vec{r}(t_i)$ and $\vec{v}(t_i)$ are needed
- Additional information on $\vec{r}(t_f)$ and $\vec{v}(t_f)$ is either redundant or inconsistent
- In quantum mechanics, $\psi(\vec{r},t_i)$ does not tell us all measurements' outcomes
- What happens when we add information about measurements at some $t = t_f$?
  - We are able to address troubling issues such as nonlocality and the measurement problem
  - We find an interesting underlying quantum reality!

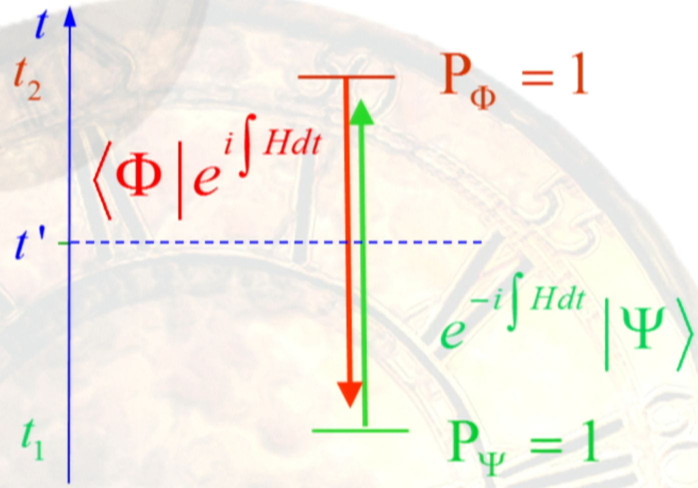
Why Use a Backwards Evolving State?

- For describing the past of quantum systems[1]
- As a helpful tool in quantum computation (PostBQP=PP)[2,3]
- For explaining collapse and the measurement problem[4]
- For addressing the information paradox in black holes[5]
- For deriving new predictions in Quantum Cosmology[6]
- For understanding quantum couterfactuals[7,8]
- For discussing time travel (P-CTCs)[9]
- For addressing special quantum games[10]

[1] L. Vaidman, Phys. Rev. A 87, 052104 (2013)
[2] S. Aaronson, *P. Roy. Soc. A-Math. Phy.* 461, 3473 (2005)
[3] G. Castagnoli, Int. J. Theor. Phys. 48, 857 (2009)
[4] Y. Aharonov, E. Cohen, E. Gruss, T. Landsberger, *Quantum Stud.: Math. Found.* 1 , 133 (2014)
[5] G.T. Horowitz, J. Maldacena, *JHEP* 2004.02, 008 (2004)
[6] P. Davies, arxiv:1309.0773
[7] A.C. Elitzur, E. Cohen, Int. J. Quantum Inf. 12, 1560024 (2015)
[8] E. Cohen, A.C. Elituzr, , J. Phys.: Conf. Ser. 626 012013 (2015)
[9] S. Lloyd, L. Maccone, R. Garcia-Patron, V. Giovannetti, Y. Shikano, Phys. Rev. D 84, 025007 (2011)
[10] G.F. Weng, Y. Yu, Quantum Inf. Process. 15, 147 (2016)

+Bennett&Schumacher

The Two-State-Vector Formalism



$$\langle \Phi | \quad | \Psi \rangle$$

Courtesy of Lev Vaidman

Weak Measurements-1/4

- if σ is now very large, we have ($\Delta P_d \approx \hbar / \sigma$):

$$\langle \Psi_{fin} | e^{-(i/\hbar) A p_d} | \Psi_{in} \rangle \Phi_{in}(x_d) \approx \langle \Psi_{fin} | 1 - (i/\hbar) A p_d | \Psi_{in} \rangle \Phi_{in}(x_d) =$$

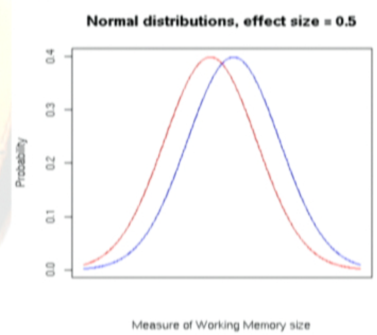
$$= \langle \Psi_{fin} | \Psi_{in} \rangle [1 - (i/\hbar) \langle A \rangle_w \, p_d] \Phi_{in}(x_d) \approx$$

$$\approx \langle \Psi_{fin} | \Psi_{in} \rangle e^{-(i/\hbar) \langle A \rangle_w p_d} \, \Phi_{in}(x_d) = \langle \Psi_{fin} | \Psi_{in} \rangle \Phi_{in}(x_d - \langle A \rangle_w)$$

$$\langle A \rangle_w \equiv \frac{\langle \Psi_{fin} | A | \Psi_{in} \rangle}{\langle \Psi_{fin} | \Psi_{in} \rangle}$$

$\Phi_{in}(x_d)$

$\Phi_{in}(x_d - \langle A \rangle_w)$



Weak Measurements-4/4

- All our classical experience is related to weak measurements!

  When measuring average quantities we use the interaction Hamiltonian $H_{\text{int}} = \sum_{i=1}^{N} g^i(t) \frac{A^i}{N} p^i{}_d$

- Moreover, if for instance $\overline{S_x} \equiv \frac{\hbar}{2} \frac{\sum_{i=1}^{N} \sigma^i{}_x}{N}$

- Then $\lim_{N\to\infty} [\overline{S_x}, \overline{S_y}] = \lim_{N\to\infty} i\hbar \frac{\overline{S_z}}{N} = 0$

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All cosmological measurements are weak

- Like all measurements of macroscopic objects, cosmological observations are naturally weak
- The detection of few photons by our devices has a negligible back action on the remote stars emitting them
- These measurements are not only partial but highly uncertain

All cosmological measurements are weak

- Like all measurements of macroscopic objects, cosmological observations are naturally weak
- The detection of few photons by our devices has a negligible back action on the remote stars emitting them
- These measurements are not only partial but highly uncertain
- However, as often happens in weak measurements, the $\sqrt{N}$ comes to the rescue and enables to meaningfully discuss

Cosmological Boundary Conditions

- The early universe was characterized by a period of inflation. Hence a de-Sitter invariant vacuum state (e.g. Bunch-Davies) seems appropriate $|0_{in}\rangle$
- If the universe is indeed dominated by dark energy it would reach again a de-Sitter invariant vacuum state in its end $|0_{out}\rangle$
- These states are non-orthogonal and cannot be related by a unitary transformation $U(t_f,t_i)|0_{in}\rangle \neq |0_{out}\rangle$
- Dynamics at intermediate times might be determined then by both according to DeWitt's suggestion:

$$G_{\mu\nu} = \frac{\langle 0_{out}|U^{\dagger}(t_f,t)T_{\mu\nu}U(t,t_i)|0_{in}\rangle}{\langle 0_{out}|0_{in}\rangle}$$

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When could this be especially interesting?

- **“pigeonhole scenario” –** Correlations emerge out of pre- and post-selected states which are product states

- **“Atom of Holism scenario”** – Correlations are eliminated in pre- and post-selected states containing entanglement

A Single Ideal Measurement-1/2

- Let our system (particle+measuring device+environment) be initially described by: $|\psi(t_0)\rangle = (\alpha|1\rangle + \beta|2\rangle)|READY\rangle|\varepsilon_0\rangle$
- A von-Neumann measurement in t_1 entangles the particle with the measuring device: $|\psi(t_1)\rangle = (\alpha|1\rangle|I\rangle + \beta|2\rangle|II\rangle)|\varepsilon_0\rangle$
- Then, in the course of a short time t_d, the preferred pointer state is selected and amplified by a multi-particle environment: $|\psi(t_1 + t_d)\rangle = \alpha|1\rangle|I\rangle|\varepsilon_1\rangle + \beta|2\rangle|II\rangle|\varepsilon_2\rangle$ when $|\varepsilon_1\rangle, |\varepsilon_2\rangle$ are two almost orthogonal environment states
- This is a macroscopic amplification of the quantum measurement

Y. Aharonov, E. Cohen, E. Gruss, T. Landsberger, *Quantum Stud.: Math. Found.* 1 , 133 (2014)

A Single Ideal Measurement-2/2

- Here's the crucial part. Let the backward-evolving state at t_f contain only a single term of the preferred pointer basis: $\langle\psi(t_f)| = \langle\phi|\langle I|\langle\varepsilon_1|$
- Hence, within the TSVF our system will be described by the two-state:

$\langle\phi|\langle I|\langle\varepsilon_1|(\alpha|1\rangle|I\rangle|\varepsilon_1\rangle + \beta|2\rangle|II\rangle|\varepsilon_2\rangle)$ for all $t_1 + t_d \le t \le t_f$

- This is essentially a future choice of $|I\rangle$, since the reduced two-time density matrix is: $\rho_{reduced} \approx |1\rangle \otimes |I\rangle\langle\phi| \otimes \langle I|$
- Reality is effectively described by a single outcome!
- It follows that any measurement we could do during intermediate times, would have been determined by the combination of initial and final boundary conditions

Y. Aharonov, E. Cohen, E. Gruss, T. Landsberger, *Quantum Stud.: Math. Found.* 1 , 133 (2014)

Generalizations

- Encoding multiple sequential measurements (shown in the paper)
- Using continuous pointers (straightforward generalization)
- Measuring mixed states (straightforward generalization)
- Intermediate dynamics (straightforward generalization)
- Gradual collapse of the macroscopic world (sets the micro-macro borderline!)

Y. Aharonov, E. Cohen, E. Gruss, T. Landsberger, *Quantum Stud.: Math. Found.* 1 , 133 (2014)

Macroscopic Objects also Collapse-1/2

- The restoration of macroscopic events and the success of time-reversal were possible due to the redundant encoding of microscopic events in the environment (error-correction codes again?)
- What will happen in case the environment collapses by itself?
- The above arguments can be repeated as long as we remember two key-factors:
  - Collapse never leads to an orthogonal state.
  - There cannot be "too many collapses" - It is impossible to individually measure $N>>1$ degrees of freedom

Y. Aharonov, E. Cohen, E. Gruss, T. Landsberger, *Quantum Stud.: Math. Found.* 1 , 133 (2014)

Macroscopic Objects also Collapse-2/2

- The state after decoherence is again: $\left|\psi(t_1+t_d)\right\rangle = \alpha\left|1\right\rangle\left|I\right\rangle\left|\varepsilon_1\right\rangle + \beta\left|2\right\rangle\left|II\right\rangle\left|\varepsilon_2\right\rangle$
- But now we assume that out of the *N>>1* environmental degrees of freedom *n<<N* collapse, i.e. $\left|\varepsilon_i(N)\right\rangle \to \prod_{j=1}^{n}\left|C_i^{(j)}\right\rangle\left|\varepsilon_i(N-n)\right\rangle$
- We denote also: $\left\langle C_1^{(j)}\middle|\varepsilon_1^{(j)}\right\rangle = \gamma_1^{(j)} \neq 0,\ \left\langle C_2^{(j)}\middle|\varepsilon_2^{(j)}\right\rangle = \gamma_2^{(j)} \neq 0$
- The final state is again some: $\left\langle\psi(t_f)\right| = \left\langle\phi\right|\left\langle I\right|\left\langle\varepsilon_1\right|$
- We define the Robustness Ratio by:

$$R \equiv \frac{\Pr(right)}{\Pr(wrong)} = \frac{\prod_{j=1}^{n}\gamma_1^{(j)}}{\left|\left\langle\varepsilon_1(N-n)\middle|\varepsilon_2(N-n)\right\rangle\right|^2\prod_{j=1}^{n}\gamma_2^{(j)}} \simeq \left|\left\langle\varepsilon_1(N-n)\middle|\varepsilon_2(N-n)\right\rangle\right|^{-2} >> 1$$

- It assures us that for a large enough *N* (determining the classical-quantum limit) time can be successfully reversed

Y. Aharonov, E. Cohen, E. Gruss, T. Landsberger, *Quantum Stud.: Math. Found.* 1 , 133 (2014)

Summary

- The combination of final boundary condition+weak measurements is known to be very fruitful in microscopic scales:
  - A richer notion of reality arises
  - New effects are being predicted and successfully tested
- We claimed now it is also very important at large scales:
  - Might explain the apparent collapse, measurement problem and Born rule
  - Might save time-reversal symmetry and allow restoration of information
  - Might shed some light on nonlocality

  (and... it does not precludes free-will – arXiv:1512.06689)

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Bottom line

What Yakir has shown us

is a subtle local hidden variables theory

with a built-in collapse mechanism

and a natural micro-macro transition

Thank you!

Any Questions?

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arXiv.org

http://arxiv.org/abs/1602.05083

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