Irreversibility and the quantum arrow of time

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Outline

1. Thermodynamic arrow of time
   - Characterization of irreversibility
   - Observation in a driven quantum system
2. Reversing the arrow of time
   - Thermodynamics with initial correlations
   - Observation in a bipartite quantum system

Arrow of time

Macroscopic processes have a preferred direction *in* time

"Heat flows from hot to cold"

➔ reversed process does not spontaneously occur

➔ *irreversibility*

In thermodynamics: mean entropy production is positive

irreversible if $\langle\Sigma\rangle > 0$ reversible if $\langle\Sigma\rangle = 0$ impossible if $\langle\Sigma\rangle < 0$

➔ *arrow of time* (Eddington 1927)

Two asymmetries: that of a process *in* time and that of time itself

Simple example: reversed movie (Jarzynski 2011)

Arrow of time

(Quasi) reversible processes

Here: entropy production $\langle \Sigma \rangle \simeq 0$ (during duration of experiment)

"Lectures on thermodynamics" George Porter 1965 (Nobel 1968)

Arrow of time

Irreversible processes

Here: entropy production $\langle\Sigma\rangle > 0$ (reversal not observed)

"Lectures on thermodynamics" George Porter 1965 (Nobel 1968)

Apparent paradox

Macroscopic systems made of microscopic particles (atoms)

Microscopic laws of physics are reversible

Example: Newton's law of motion

$$m\frac{d^2x}{dt^2} = F$$

Reversal: $t \to t' = \tau - t \qquad dt' = -dt \qquad dt'^2 = dt^2$

- ➔ also true for Maxwell, Schrödinger, ...
- ➔ Question: how to *explain* macroscopic irreversibility?

Apparent paradox

Processes in nature are described by:

i) laws of physics → fixed

ii) initial (boundary) conditions → random

Newton 1687, Wigner 1963

Examples:

- planetary orbits = ellipses (law)
- quasi circular in our solar system (initial condition)
- all planets orbit in the same direction (initial condition)

Apparent paradox

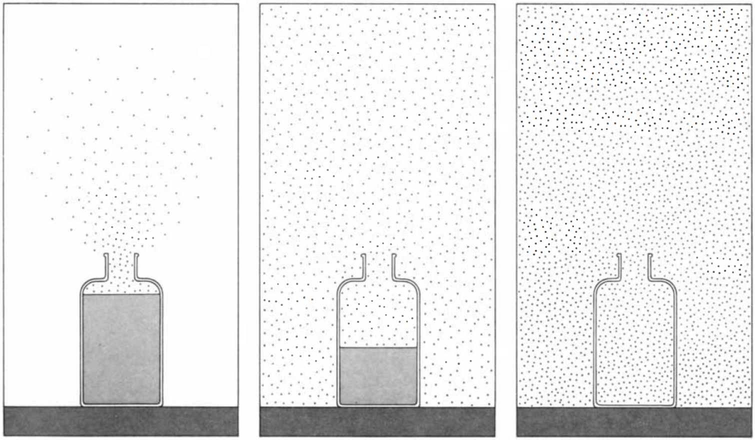
Resolution:

➔ initial conditions break time reversal (Boltzmann 1877)

"From the fact that the differential equations of mechanics are left unchanged by reversing the sign of time ..., Herr Ostwald concludes that the mechanical view of the world cannot explain why natural processes run preferentially in a definite direction. But such a view appears to me to overlook that mechanical events are determined not only by differential equations but also by initial conditions."

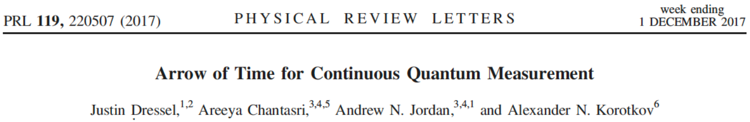
Irreversibility in a many-particle system

Bottle of perfume:



Initial state breaks time reversal — reversal unlikely for 10^{24} particles

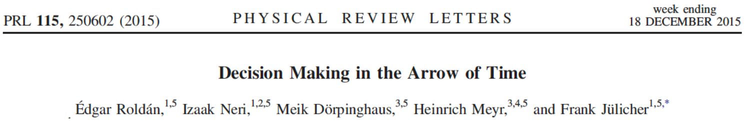
Arrow of time in the 21st century



PRL **119,** 220507 (2017) PHYSICAL REVIEW LETTERS week ending 1 DECEMBER 2017

Arrow of Time for Continuous Quantum Measurement

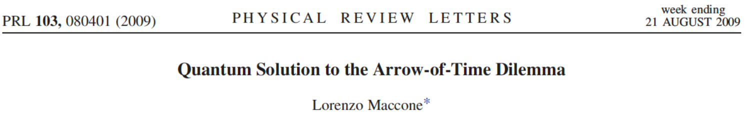
Justin Dressel,[1,2] Areeya Chantasri,[3,4,5] Andrew N. Jordan,[3,4,1] and Alexander N. Korotkov[6]



PRL **115,** 250602 (2015) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2015

Decision Making in the Arrow of Time

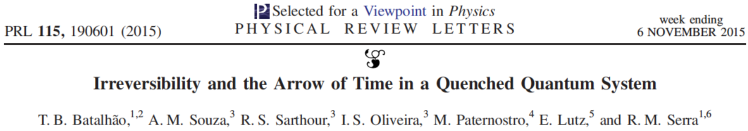
Édgar Roldán,[1,5] Izaak Neri,[1,2,5] Meik Dörpinghaus,[3,5] Heinrich Meyr,[3,4,5] and Frank Jülicher[1,5,*]



PRL **103,** 080401 (2009) PHYSICAL REVIEW LETTERS week ending 21 AUGUST 2009

Quantum Solution to the Arrow-of-Time Dilemma

Lorenzo Maccone[*]



Selected for a Viewpoint in *Physics*

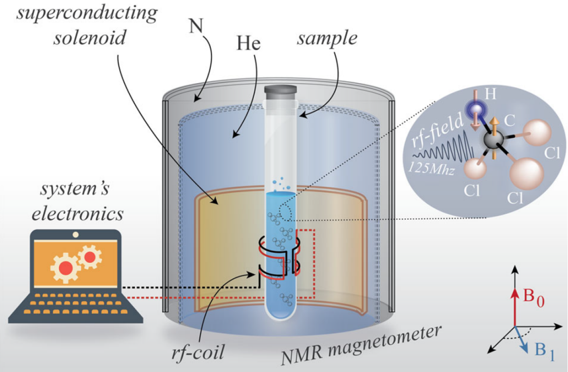
PRL **115,** 190601 (2015) PHYSICAL REVIEW LETTERS week ending 6 NOVEMBER 2015

Irreversibility and the Arrow of Time in a Quenched Quantum System

T. B. Batalhão,[1,2] A. M. Souza,[3] R. S. Sarthour,[3] I. S. Oliveira,[3] M. Paternostro,[4] E. Lutz,[5] and R. M. Serra[1,6]

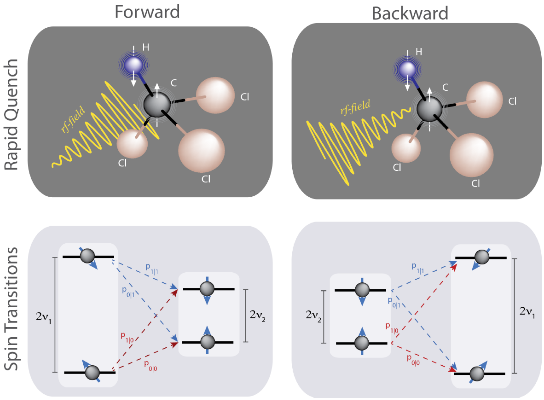
Experimental observation

Spin-1/2 driven by an external magnetic field: (Batalhão PRL 2015)



Experimental observation

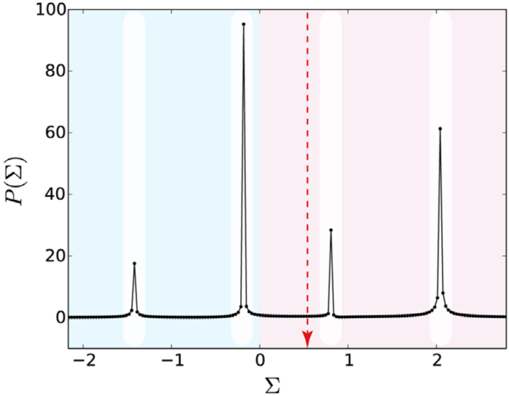
Spin-$1/2$ driven by an external magnetic field: (Batalhão PRL 2015)



Unitary dynamics with $\mathcal{H}_t^{\mathrm{F}} = 2\pi\hbar\,\nu(t)\left[\sigma_x^{\mathrm{C}}\cos\phi(t) + \sigma_y^{\mathrm{C}}\sin\phi(t)\right]$

Experimental observation

Nonequilibrium entropy production: $\Sigma = \beta(W - \Delta F)$

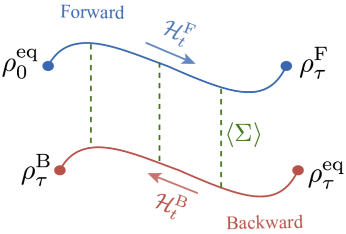


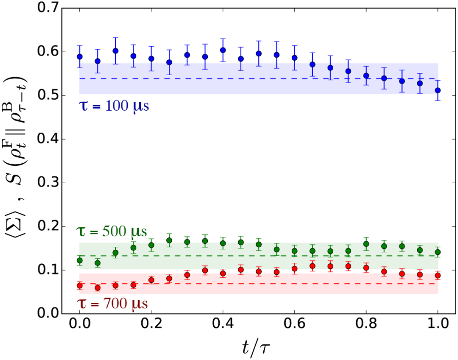
➔ experimental proof of $\langle \Sigma \rangle \geq 0$ for driven quantum system

Experimental observation

Mean entropy production: (Deffner-Lutz PRL 2011)

$$\langle\Sigma\rangle = S(\rho_t^F \| \rho_{\tau-t}^B) = \mathrm{tr}[\rho_t^F \ln \rho_t^F - \rho_t^F \ln \rho_{t-\tau}^B]$$





→ experimental demonstration of the arrow of time

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Reversing the arrow of time

Conventional thermodynamics:

systems are assumed to be initially uncorrelated

➔ preferred direction of the arrow of time

Theoretical suggestion:

consider systems that are initially correlated

➔ direction of the arrow of time could be reversed

that is, heat could spontaneously flow from cold to hot

(Partovi PRE 2008, Jennings-Rudolph PRE 2010, PRL 2012)

Reversing the arrow of time

Reversing the arrow of time

Concrete example: two qubits A and B

$$\rho_{AB} = \rho_A \otimes \rho_B + \alpha \left(|01\rangle\langle 10| + |10\rangle\langle 01|\right)$$

Properties:

- $\rho_{A,B}$ are thermal states at inverse temperature $\beta_{A,B}$
- for $\alpha = 0$ uncorrelated and for $\alpha \neq 0$ correlated
- reduced qubit states always locally thermal
- thermal contact via random partial swaps in Z direction, $\mathcal{S}(\theta) = \exp[i\theta(X_A Y_B + Y_A X_B)/2]$ (Scarani PRL 2002)

Thermodynamics of initially correlated systems

Heats for the bipartite systems:

$$\beta_A Q_A + \beta_B Q_B \geq \Delta I(A:B)$$

where $I(A:B) = S_A + S_B - S_{AB} \geq 0$ is the mutual information

Initially uncorrelated spins: $\Delta I(A:B) \geq 0$

$$Q_B(\beta_B - \beta_A) \geq 0 \quad \Longrightarrow \quad Q_B \geq 0 \qquad (T_A \geq T_B)$$

➔ standard arrow of time

Initially correlated spins: $\Delta I(A:B) \leq 0$

$$Q_B(\beta_B - \beta_A) \leq 0 \quad \Longrightarrow \quad Q_B \leq 0 \qquad (T_A \geq T_B)$$

➔ reversal of the arrow of time

Thermodynamics of initially correlated systems

Heat for spin B:

$$\Delta\beta Q_B = \Delta I(A:B) + S(\rho_A^\tau||\rho_A) + S(\rho_B^\tau||\rho_B)$$

where $S(\rho_i^\tau||\rho_i) = \mathrm{Tr}_i\, \rho_i^\tau(\ln\rho_i^\tau - \ln\rho_i) \geq 0$ is the relative entropy

that is, the entropy production in each spin

Criterion for reversal:

$$\Delta I(A:B) \leq -S(\rho_A^\tau||\rho_A) - S(\rho_B^\tau||\rho_B)$$

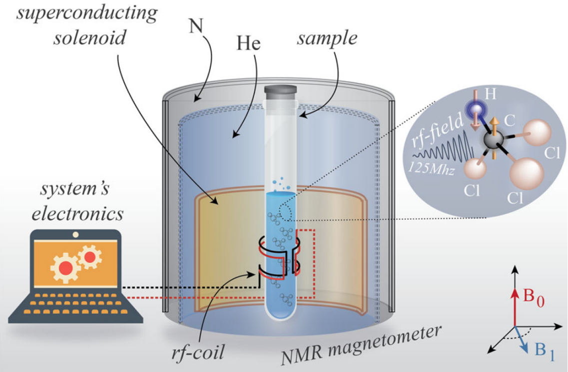
➔ decrease of mutual information compensates entropy production

➔ trade off between entropy and information

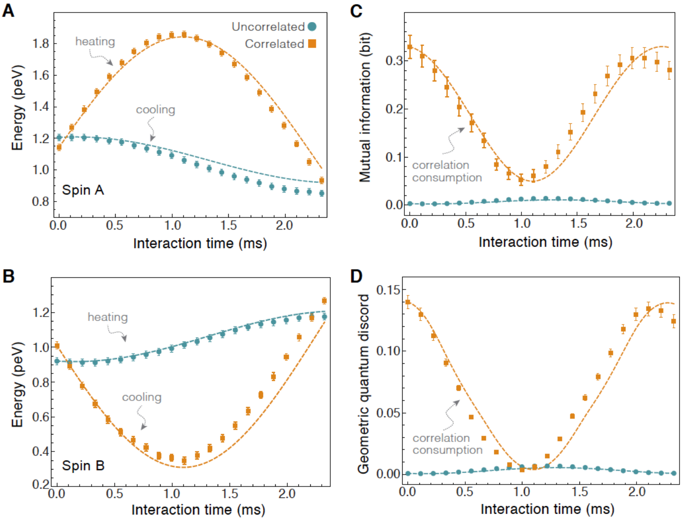
(Lloyd PRE 1989, Sagawa-Ueda PRL 2012, Koski PRL 2014)

Experimental observation

Two coupled thermal spins-1/2



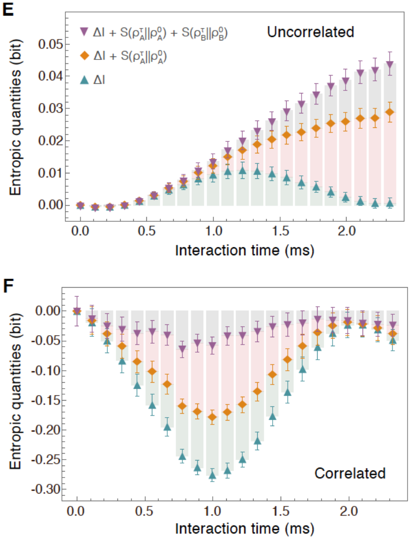
Experimental observation



➔ local second law does not apply when (nonlocal) correlations

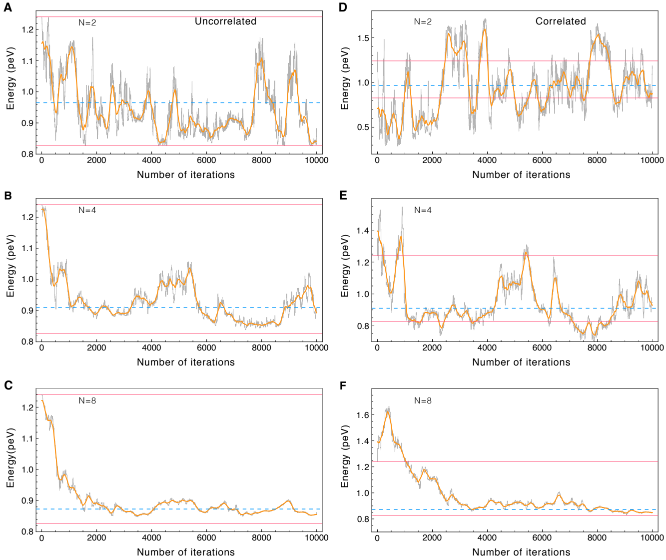
Experimental observation

Heat for spin B: $\Delta\beta Q_B = \Delta I(A:B) + S(\rho_A^\tau||\rho_A) + S(\rho_B^\tau||\rho_B)$



➔ trade off between information and entropy

Numerical simulation for larger systems 1 × N



- ➔ reversals still occur

Summary

- arrow of time is not an abstract, philosophical concept
  - ➔ it can be quantified and observed in the lab
- may be reversed for quantum correlated systems
  - ➔ trade off between information and entropy
  - ➔ is a relative concept and allows control of heat flow
- local second law fails in presence of (nonlocal) correlations
  - ➔ subtle interplay of quantum and thermodynamics