# Quantum Information Viewed by a Theoretical Physicist

Lajos Diósi

Wigner Center, Budapest

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# Frontlines of Quantum Theory 1900-2000-...

- black-body radiation
- atoms, molecules
- electron
- condensed matter
- electrodynamics
- nuclei
- elementary particles
- gravitation ?
- cosmology ?
- **information**
- living material?
- brain, consciousness?

# When I Started my Studies ...

- Quantumness meant quantizedness (discrete energies, gaps, etc.
- State vector $\Psi$ was extensively and exclusively used, density matrix $\hat{\rho}$ was only taught for spins and Gibbs-ensembles.
- Shannon information theory gained limited interest in physics.
- Single system quantum mechanics was taught, but was not testable.

Today

- Quantumness means entanglement, quantum enhancement in informatics, computation, metrology, etc.
- Density matrix $\hat{\rho}$ is recognized and taught as the generic representative of quantum state.
- Quantum information is exciting physics. So Shannon is taught.
- Single system quantum mechanics is directly testable.

# No-cloning, Linearity

Wootters and Zurek (1982): Cloning a single unknown qubit,

$$\hat{\rho} \longrightarrow \hat{\rho} \otimes \hat{\rho} \text{ is impossible.}$$

Believed to guarantee quantum security protocols.

Gisin (1990): Any non-linear modification of QM,

$$\hat{\rho} \longrightarrow \mathrm{Nonlin}(\hat{\rho}) \text{ leads to FTL signalling.}$$

Believed to be an exciting quantum paradox.

Wisdom 10-20 yy later: the same things hold classically!

## Everyday wisdom in classical statistics

$$\mathbf{x} \longrightarrow \textbf{CLASSICAL BLACK BOX MACHINE} \longrightarrow \mathbf{y}$$

**The distribution $\rho'(\mathbf{y})$ is a linear map of $\rho(\mathbf{x})$.**

Nobody would challenge linearity. Cloning, $\rho(x) \to \rho(x)\rho(x)$ is forbidden. FTL would be derived if anyone challenged linearity.

## No everyday wisdom in quantum statistics. Therefore ...

... sometimes we are challenging the linearity of

$$\hat{\mathbf{x}} \longrightarrow \textbf{QUANTUM BLACK BOX MACHINE} \longrightarrow \hat{\mathbf{y}}$$

Non-linearity contradicts to the statistical interpretation of $\hat{\rho}$. The linearity of quantum operations

$$\hat{\rho} \longrightarrow \mathcal{M}\hat{\rho}$$

is rooted deeper than we thought before.

# Peres-Horodecki Entanglement Criterion

Werner (1989): Mixed state is separable (unentangled) iff:

$$\hat{\rho}_{AB} = \sum w_\lambda \hat{\rho}_A^\lambda \otimes \hat{\rho}_B^\lambda$$

No easy-to-apply analytic separability test until
Peres observation (1995): Partial transpose

$$(\mathcal{I} \otimes \mathcal{T})\hat{\rho}_{AB} = \sum w_\lambda \hat{\rho}_A^\lambda \otimes \mathcal{T}\hat{\rho}_B^\lambda$$

of separable state is a legal density matrix while this is not true for non-separable states.

Peres-Horodecki (1995): A two-qubit bipartite $\hat{\rho}_{AB}$ is separable iff its partial transpose is non-negative.

# Peres-Horodecki Entanglement Criterion

Separability: physical feature; transpose $\hat{\rho} \to \mathcal{T}\hat{\rho}$ is a math option.
We need the physical meaning for $\mathcal{T}$!
Wigner (1931): Time-reversal operator is anti-unitary.
$\mathcal{T}$ is equivalent with time-reversal operation.

**Peres-Horodecki criterion, for theoretical physicist:**

Two-qubit $\hat{\rho}_{AB}$ is separable iff its **partial time-reversal** is non-negative.

Partial time-reversal of a two-qubit entangled state is not a state.
Exciting physical implication: **Reversal of local time arrow**

$$\uparrow \text{ in region A} \qquad \downarrow \text{ in region B}$$

is possible in classical cosmology. It is **forbidden in QM.**

# Factorization vs Period Finding

Feynman (1982): Exponential slowdown of classical simulation

Shor quantum algorithm (1994): Exponential speedup of number factorization

Breaking RSA (1976) cryptography becomes possible.
**Theoretical physicist insight is different.**
Exponential speedup of what?
Factorization = Period Finding (plus a few boring algebraic steps)

**Shor quantum algorithm for theoretical physicist: Exponential speedup of period finding.**

Exponential speedup of pattern recognition.
Toward understanding animal, human intellect.

# Quantum Circuit language

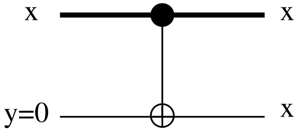
## von Neumann detector (1932)

System $\Psi(x)$, $x=?$. Detector $\phi(y)$ is peaked around $y=0$.
Coupling $H_I=\delta(t)x(i\partial/\partial y)$.

$$\Psi(x)\phi(y)\Longrightarrow\Psi(x)\phi(y+x)$$

$\phi$ becomes peaked around $x$.

## von Neumann detector (2000-...)

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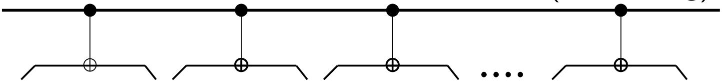
Discretized scheme of time-continuous detection (monitoring):



# Summary

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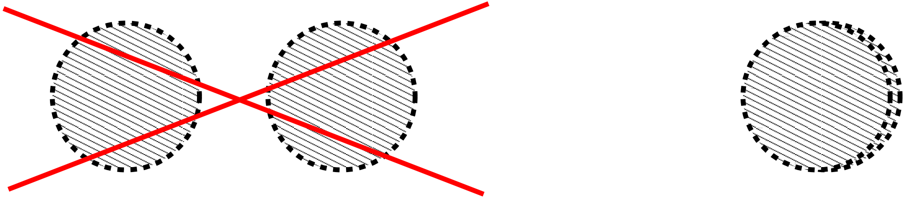
Quantum information has changed and reformed our understanding quantum mechanics. It sharpened and deepened our insight into the foundations (I gave very occasional and unfairly personal examples). The fruitful and fertilizing impact of quantum information on physics, on **learning and teaching** quantum mechanics will surely continue in the coming years. Keep eyes open: **in qubit there can be more physics than information**.

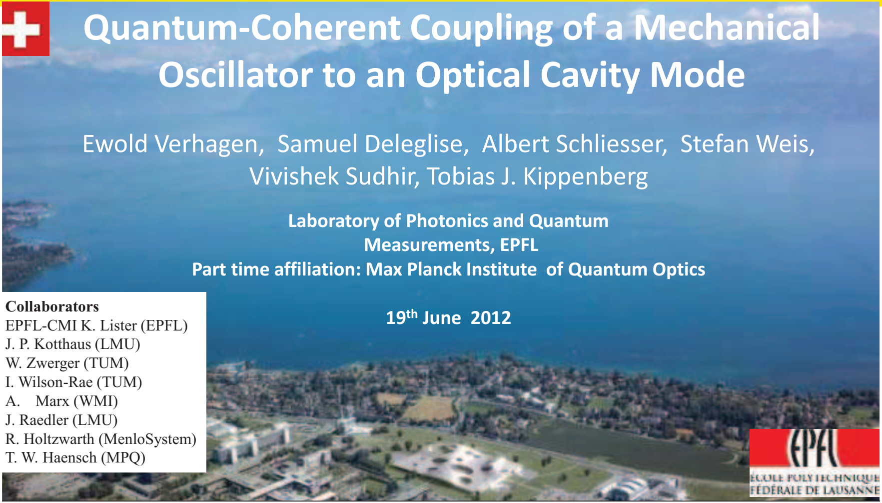
# Who Eliminates the Schrödinger Cat?

Mechanical Schrödinger Cat



D. (1987), Penrose (1996):
Hypothetic, gravity-related decoherence/collapse.
Strength heavily depends on mass resolution: collapse takes hours or milliseconds.

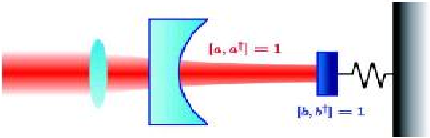
# Optomechanics, state of art June 2012

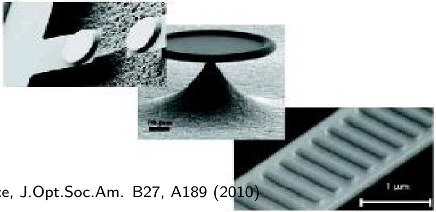



Marie Curie ITN

# Monitoring the Cat: Nano-Quantum-Mechanical Experiments

- Vibrating micro-mirror (Leiden)
- Levitating micro-dielectrics (Vienna-Garching)
- ... on space satellite (Vienna-Garching-Pasadena)
- Silica micro-resonator (Garching-Pasadena)



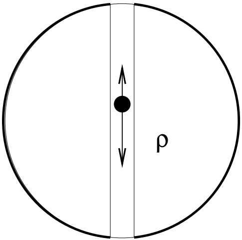




Aspelmeyer et al.: Quantum Optomechnanics - Throwing a Glance, J.Opt.Soc.Am. B27, A189 (2010)

Currently: $10^{-12}$g-1g, kHz-GHz, mK — but $\mu$K needed!

# DP and Beyond DP

Newton oscillator




$\rho \sim 1 \mathrm{g/cm}^3$

$\omega_G = \sqrt{G\rho} \sim 10^{-4}/\mathrm{s}$

period ~1h

$\rho_{nucl} \sim 10^{12} \mathrm{g/cm}^3$

$\omega_G^{nucl} = \sqrt{G\rho_{nucl}} \sim 10^{2}/\mathrm{s}$

period ~1ms

* * *

G–related (DP) model predicts collapse rate

$\omega_G$ in He superfluid

$\omega_G^{nucl}$ in condensed matter

Proposal beyond DP–model: 1) Newton gravity is caused by DP–collapse.
2) Gravity's emergence rate is the collapse rate.

Consequence: Newton field of a moving condensed source is delayed by ms's.
Newton field of a moving He tank would be delayed by about 1h.

Next: What components (short/long range) are delayed?
Minimum model of emergence is needed for the experimental proposal.

Theoretical stress: violation of equivilance principle, momentum conservation, etc.