Emergence of the classical world from quantum physics: Schrödinger cats, entanglement, and decoherence

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Outline of the talk

- Decoherence and the classical limit of the quantum world
- Entanglement and decoherence: new experimental results
- Multiparticel systems and decoherence
1926: “At first sight it appears very strange to try to describe a process, which we previously regarded as belonging to particle mechanics, by a system of such proper vibrations.” Demonstrates that “a group of proper vibrations” of high quantum number $n$ and of relatively small quantum number differences may represent a particle executing the motion expected from usual mechanics, i.e. oscillating with a constant frequency.
Schrödinger on the classical limit

1935: “An uncertainty originally restricted to the atomic domain has become transformed into a macroscopic uncertainty, which can be resolved through direct observation... This inhibits us from accepting in a naive way a `blurred model' as an image of reality... There is a difference between a shaky or not sharply focused photograph and a photograph of clouds and fogbanks.”
Quantum measurement
Quantum measurement
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Quantum measurement

Linear evolution:

\[ |\text{BEFORE}\rangle = (|\psi_1\rangle + |\psi_2\rangle)|\uparrow\rangle/\sqrt{2} \]
Quantum measurement

Linear evolution:

\[ |\text{BEFORE} \rangle = \frac{(|\Psi_1 \rangle + |\Psi_2 \rangle)\uparrow}{\sqrt{2}} \]

\[ |\text{AFTER} \rangle = \frac{(|\Psi_1' \rangle \rightarrow + |\Psi_2' \rangle \leftarrow)}{\sqrt{2}} \]
Quantum measurement

Linear evolution:

\[
|\text{BEFORE}\rangle = \frac{|\Psi_1\rangle + |\Psi_2\rangle|\uparrow\rangle}{\sqrt{2}}
\]

\[
|\text{AFTER}\rangle = \frac{(|\Psi_1\rangle|\rightarrow\rangle + |\Psi_2\rangle|\leftarrow\rangle)}{\sqrt{2}}
\]
Quantum measurement

Linear evolution:

$$|\text{BEFORE}\rangle = \left( |\Psi_1\rangle + |\Psi_2\rangle \right) |\uparrow\rangle / \sqrt{2}$$
Quantum physics and localization

“Let $\Psi_1$ and $\Psi_2$ be two solutions of the same Schrödinger equation. Then $\Psi = \Psi_1 + \Psi_2$ also represents a solution of the Schrödinger equation, with equal claim to describe a possible real state. When the system is a macrosystem, and when $\Psi_1$ and $\Psi_2$ are `narrow’ with respect to the macro-coordinates, then in by far the greater number of cases, this is no longer true for $\Psi$. Narrowness in regard to macro-coordinates is a requirement which is not only independent of the principles of quantum mechanics, but, moreover, incompatible with them.”

Letter from Einstein to Born, January 1, 1954
Why interference cannot be seen?
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- **Decoherence**: entanglement with the environment - same process by which quantum computers become classical computers!
Why interference cannot be seen?

- **Decoherence**: entanglement with the environment - same process by which quantum computers become classical computers!
- **Dynamics of decoherence**: related to elusive boundary between quantum and classical world
Decoherence dynamics

\[ \frac{1}{\mathcal{N}} (|\alpha\rangle + |-\alpha\rangle) \]

\[ \rightarrow \frac{1}{2} (|\alpha\rangle \langle\alpha| + |-\alpha\rangle \langle-\alpha|) \]

Observing the Progressive Decoherence of the “Meter” in a Quantum Measurement

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(Received 10 September 1996)
Decoherence dynamics

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Decoherence dynamics

\[ \frac{1}{\mathcal{N}} (|\alpha\rangle + |-\alpha\rangle) \rightarrow \frac{1}{2} (|\alpha\rangle\langle\alpha| + |-\alpha\rangle\langle-\alpha|) \]

Exponential decay: \[ t_{\text{dec}} \approx t_{\text{cav}} / |\alpha|^2 \]
Dynamics of entanglement

- Multiparticle system, initially entangled, with individual couplings of particles to independent environments: each particle undergoes decay, dephasing, diffusion.
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- How is local dynamics related to nonlocal loss of entanglement?
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- How is local dynamics related to nonlocal loss of entanglement?

- How does loss of entanglement scale with number of particles?
Dynamics of entanglement

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- How is local dynamics related to nonlocal loss of entanglement?

- How does loss of entanglement scale with number of particles?

- Need measure of entanglement!
Entangled and separable states

Separable states:

- Pure states:
  \[ |\Psi_{12...n}\rangle = |\psi_1\rangle \otimes |\psi_2\rangle \otimes \ldots |\psi_n\rangle \]

  \[ \rho_{12...n} = \sum_{\mu} p_\mu \rho_1^\mu \otimes \rho_2^\mu \otimes \ldots \rho_n^\mu \]
  \[ 0 \leq p_\mu \leq 1 \]

Entangled state: non-separable
Entangled and separable states

- **Separable states:**
  - **Pure states:**
    \[ |\Psi_{12...n}\rangle = |\psi_1\rangle \otimes |\psi_2\rangle \otimes \ldots |\psi_n\rangle \]
  - **Mixed states (R. F. Werner, PRA, 1989):**
    \[ \rho_{12...n} = \sum_\mu p_\mu \rho_1^\mu \otimes \rho_2^\mu \otimes \ldots \rho_n^\mu \]
    \[ 0 \leq p_\mu \leq 1 \]

- **Entangled state:** non-separable

Bell states - Maximally entangled states: complete ignorance on each qubit

- **Bell states:**
  - \[ |\Psi_{\pm}\rangle = \frac{1}{\sqrt{2}} (|01\rangle \pm |10\rangle) \]
  - \[ |\Phi_{\pm}\rangle = \frac{1}{\sqrt{2}} (|00\rangle \pm |11\rangle) \]
Entangled and separable states

- **Separable states:**
  - **Pure states:**
    \[
    |\Psi_{12...n}\rangle = |\psi_1\rangle \otimes |\psi_2\rangle \otimes \ldots |\psi_n\rangle
    \]
  - **Mixed states (R. F. Werner, PRA, 1989):**
    \[
    \rho_{12...n} = \sum_{\mu} p_{\mu} \rho_1^{\mu} \otimes \rho_2^{\mu} \otimes \ldots \rho_n^{\mu}
    \]
    \[
    0 \leq p_{\mu} \leq 1
    \]

- **Entangled state: non-separable**

  **Bell states - Maximally entangled states:** complete ignorance on each qubit

  |\Psi_{\pm}\rangle = \frac{1}{\sqrt{2}} (|01\rangle \pm |10\rangle) \\
  \[
  |\Phi_{\pm}\rangle = \frac{1}{\sqrt{2}} (|00\rangle \pm |11\rangle)
  \]

\[
\rho_{A,B} = \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}
\]
Schrödinger on Entanglement

*Naturwissenschaften* **23**, 807 (1935)

“This is the reason that knowledge of the individual systems can decline to the scantiest, even zero, while that of the combined system remains continually maximal. Best possible knowledge of a whole does not include best possible knowledge of its parts - and that is what keeps coming back to haunt us.”
Measures of entanglement for pure states

Von Neumann entropy

\[
S_N(\rho_r) = -\text{Tr} [\rho_r \log_2 \rho_r]
\]

\[\rho_r \rightarrow \text{reduced density matrix of } A \text{ or } B\]

Linear entropy

\[
S_L(\rho_r) = 2 \left(1 - \text{Tr} \rho_r^2\right)
\]

Separable state (two qubits):

\[
S(\rho_r) = 0
\]

Maximally entangled state:

\[
\rho_A = \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \Rightarrow S(\rho_A) = 1
\]
A mathematical interlude: partial transposition of a matrix

Transposition: a positive map $T : \rho \rightarrow \rho^T$

\[
\begin{pmatrix}
\rho_{00} & \rho_{01} \\
\rho_{10} & \rho_{11}
\end{pmatrix}
\rightarrow
\begin{pmatrix}
\rho_{00} & \rho_{10} \\
\rho_{01} & \rho_{11}
\end{pmatrix}
\]

Matrix in computational basis: $\{\ket{00}, \ket{01}, \ket{10}, \ket{11}\}$

Does not change eigenvalues!
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Partial transposition:
\( 1_A \otimes T_B : \rho \rightarrow \rho^{T_B} \)

Example:
\[
|\Phi_{\pm}\rangle = \frac{1}{\sqrt{2}} (|00\rangle \pm |11\rangle)
\]

\[
\frac{1}{2}
\begin{pmatrix}
1 & 0 & 0 & \pm 1 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\pm 1 & 0 & 0 & 1
\end{pmatrix}
\rightarrow
\frac{1}{2}
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Negative eigenvalue!

\[
\frac{1}{2} \begin{pmatrix}
1 & 0 & 0 & \pm 1 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\pm 1 & 0 & 0 & 1
\end{pmatrix} \rightarrow \frac{1}{2} \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 0 & \pm 1 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\]

$\Lambda = -1/2$
Mixed states: Separability criterium

- If $\rho$ is separable, then the partially transposed matrix is positive (Asher Peres, PRL, 1996):

$$\rho = \sum_{i} p_i \rho_i^A \otimes \rho_i^B \Rightarrow \rho^{T_B} = \sum_{i} p_i \rho_i^A \otimes (\rho_i^B)^T$$

- For 2X2 and 2X3 systems, $\rho$ is separable iff it remains a density operator under the operation of partial transposition (Horodecki family 1996) - that is, it has a partial positive transpose (PPT)
Negativity as a measure of entanglement

\[ \mathcal{N}(\rho_{AB}) \equiv 2 \sum_i |\lambda_{i-}| \]

\( \lambda_{i-} \rightarrow \) Negative eigenvalues of partially transposed matrix
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\[ \mathcal{N} = 1 \text{ for a Bell state} \]
Negativity as a measure of entanglement

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\( \lambda_i^- \rightarrow \) Negative eigenvalues of partially transposed matrix

\( \mathcal{N} = 1 \) for a Bell state

Dimensions higher than 6: \( \mathcal{N} = 0 \) does not imply separability!
Mixed states: Concurrence

\[ C = \max \{0, \Lambda\}, \]
\[ \Lambda = \sqrt{\lambda_1} - \sqrt{\lambda_2} - \sqrt{\lambda_3} - \sqrt{\lambda_4}, \]
\[ \lambda_i's \Rightarrow \text{eigenvalues (positive), in decreasing order, of} \]
\[ \hat{\rho}(\sigma_y \otimes \sigma_y) \hat{\rho}^* (\sigma_y \otimes \sigma_y). \]

(conjugation in the computational basis)

\[ C = 1 \Rightarrow \text{maximally entangled} \quad C = 0 \Rightarrow \text{separable} \]
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(conjugation in the computational basis)

Pure states: \[ C = \sqrt{2(1 - \text{Tr}\rho_r^2)} \]

\[ C^2 \rightarrow \text{Tangle} \]

\[ C = 1 \Rightarrow \text{maximally entangled} \quad C = 0 \Rightarrow \text{separable} \]
Relation between concurrence and negativity

Two qubits


Boundary of separability: independent of the entanglement measure
A paradigmatic example: Atomic decay


- Qubit states: $|0\rangle \leftrightarrow |g\rangle, |1\rangle \leftrightarrow |e\rangle$

- "Amplitude channel":

\[
|g\rangle_S \otimes |0\rangle_E \rightarrow |g\rangle_S \otimes |0\rangle_E \\
|e\rangle_S \otimes |0\rangle_E \rightarrow \sqrt{1-p}|e\rangle_S \otimes |0\rangle_E + \sqrt{p}|g\rangle_S \otimes |1\rangle_E
\]

\[p = 1 - \exp(-\Gamma t)\]

Usual master equation for decay of two-level atom, upon tracing on environment (Markovian approximation)

Weisskopf and Wigner (1930)!
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Usual master equation for decay of two-level atom, upon tracing on environment (Markovian approximation)

Weisskopf and Wigner (1930)!

Our strategy: follow evolution as a function of \( p \), not \( t \)

Apply evolution to two qubits, take trace with respect to environment degrees of freedom, find evolution of two-qubit reduced density matrix, calculate entanglement
Realization of amplitude map with photons

\[ |g\rangle|0\rangle \rightarrow |g\rangle|0\rangle \]
\[ |e\rangle|0\rangle \rightarrow \sqrt{1-p}|e\rangle|0\rangle + \sqrt{p}|g\rangle|1\rangle \]

Sagnac-like interferometer
Realization of amplitude map with photons

\[ |H\rangle |0\rangle \rightarrow |H\rangle |0\rangle \]
\[ |V\rangle |0\rangle \rightarrow \sqrt{1 - p} |V\rangle |0\rangle + \sqrt{p} |H\rangle |1\rangle \]

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Realization of amplitude map with photons

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Realization of amplitude map with photons

\[
\begin{align*}
\cos 2\theta \ket{V} + \sin 2\theta \ket{H} & \\
\ket{H} \ket{0} & \rightarrow \ket{H} \ket{0} \\
\ket{V} \ket{0} & \rightarrow \sqrt{1 - p} \ket{V} \ket{0} + \sqrt{p} \ket{H} \ket{1}
\end{align*}
\]

\[
p = \sin^2(2\theta)
\]
Realization of amplitude map with photons

\[
\begin{align*}
\cos 2\theta |V\rangle + \sin 2\theta |H\rangle &
\end{align*}
\]

\[
|H\rangle |0\rangle &\rightarrow |H\rangle |0\rangle \\
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\]

\[
p = \sin^2(2\theta)
\]

Tomography

Sagnac-like interferometer
Investigating the dynamics of entanglement
“Sudden death” of entanglement

\[ |\Psi(0)\rangle = \alpha |gg\rangle + \beta |ee\rangle \]

\[ \mathcal{N}(p = 0) = 2|\alpha\beta| \]

\[ C = \max \{0, \Lambda\} \]
“Sudden death” of entanglement

\[ |\Psi(0)\rangle = \alpha |gg\rangle + \beta |ee\rangle \]

\[ N(p = 0) = 2|\alpha\beta| \]

\[ \Lambda \]

"Entanglement Sudden Death" (Yu and Eberly)
Role of environment

- Usually one traces out environment, and one looks at irreversible evolution of system.
- As entanglement decays and eventually disappears, what is its imprint onto the environment?
Measuring the environment?

Experimental investigation of the dynamics of entanglement: Sudden death, complementarity, and continuous monitoring of the environment

A. Salles, F. de Melo, M. P. Almeida, M. Hor-Meyll, S. P. Walborn, P. H. Souto Ribeiro, and L. Davidovich

PIYGICAL REVIEW A 78, 022322 (2008)
Role of environment

- Usually one traces out environment, and one looks at irreversible evolution of system
- Our setup allows in principle access to environment
- Is it useful to watch the environment?
Quantum Darwinism describes the proliferation, in the environment, of multiple records of selected states of a quantum system—pointer states.

Detailed study of the environment uncovers essential trait of the classical world!
Simple model

Amplitude channels

O. Jiménez Farías et al., PRL 109, 150403 (2012)
G. H. Aguilar et al., PRL 113, 240501 (2014)
G. H. Aguilar et al., PRA 89, 022339 (2014)
\[ C[p] = \max \{0, \Lambda\} \]
Fidelity with respect to state

\[ |D\rangle = \frac{1}{\sqrt{6}} (|0000\rangle + |1111\rangle + |0011\rangle + |1100\rangle + |0110\rangle + |1001\rangle) \]

Dicke state with second and fourth qubits flipped
Fidelity with respect to state

\[ |D\rangle = \frac{1}{\sqrt{6}}(|0000\rangle + |1111\rangle + |0011\rangle + |1100\rangle + |0110\rangle + |1001\rangle) \]

Dicke state with second and fourth qubits flipped

Genuine multipartite!

Decay of entanglement for $N$ qubits, other environments?

$|\Psi_0\rangle = \alpha |0\rangle \otimes^N + \beta |1\rangle \otimes^N$

- Independent individual environments
Results for amplitude damping

- Bipartitions $k : N - k$

- Critical transition probability for which negativity vanishes (same for all partitions):
  $$p_c^{AD}(k) = |\alpha/\beta|^{2/N}$$
  State fully separable at this point!

- Smaller than 1 if $|\alpha/\beta| < 1 \Rightarrow$ finite-time disappearance of entanglement

- Critical value approaches 1 when $N \rightarrow \infty$

- Does entanglement become more robust when number of qubits increases?
Does entanglement become more robust with increasing $N$?

$$|Ψ₀⟩ = α|0⟩^⊗N + β|1⟩^⊗N$$

$$\mathcal{E}_i^D \rho_i = (1 - p) \rho_i + (p) \frac{1}{2}$$
Is ESD relevant for many particles?

\[ |\Psi_0\rangle = \alpha|0\rangle^\otimes N + \beta|1\rangle^\otimes N \]

\[ \mathcal{E}_i^D \rho_i = (1 - p)\rho_i + (p)1/2 \]
Is ESD relevant for many particles?

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\[ \mathcal{E}_i^D \rho_i = (1 - p) \rho_i + (p) 1/2 \]

\[ \Lambda(p) \sim \exp(-pN) \Lambda(0) \]
Generalization: Graph states

- At each vertex, place a qubit in the state \( \frac{|0\rangle + |1\rangle}{\sqrt{2}} \)
- Apply control-Z gate between two connected vertices:
  \[
  \frac{|0\rangle + |1\rangle}{\sqrt{2}} \otimes \frac{|0\rangle + |1\rangle}{\sqrt{2}} \rightarrow \frac{|00\rangle + |01\rangle + |10\rangle - |11\rangle}{2}
  \]
- Universal states for measurement-based quantum computation (Raussendorf and Briegel)

Generalization: Graph states

- Any convex bi- or multi-partite entanglement quantifier (no increase under LOCC)
- For a large class of quantum channels, and any partition, total entanglement is determined by entanglement of boundary qubits (connected by gray lines)
- Lower bounds for entanglement depend only on number of boundary qubits
Key Issues Review

Open-system dynamics of entanglement: a key issues review

Leandro Aolita¹, Fernando de Melo² and Luiz Davidovich³
EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues
Find It Is Not 'Complete'
Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of
'the Physical Reality' Can Be
Provided Eventually.

PRINCETON, N. J., May 3.—Professor Albert Einstein will attack science's important theory of quantum mechanics, a theory of which he was a sort of grandfather. He concludes that while it is "correct" it is not "complete."

With two colleagues at the Institute for Advanced Study here, the noted scientist is about to report to the American Physical Society what is wrong with the theory of quantum mechanics, it has been learned exclusively by Science Service.

The quantum theory, with which science predicts with some success inter-atomic happenings, does not meet the requirements for a satisfactory physical theory, Professor Einstein will report in a joint paper with Dr. Boris Podolsky and Dr. N. Rosen.
Collaborators: entanglement dynamics
Collaborators: quantum metrology

Gabriel Bié
Marcio Taddei
Camille Latune
Bruno Escher

Nicim Zagury
Ruynet Matos Filho
THANKS!