Can Decoherence make quantum theories unfalsifiable? Understanding the quantum-to-classical transition without it

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EmQM15
Emergent Quantum Mechanics
OCTOBER 23rd–25th 2015 VIENNA
Can Decoherence make quantum theories unfalsifiable? Understanding the quantum-to-classical transition without it

Acknowledgment:

Bohmian dissipation

- Damiano Marian (UAB)
- Enrique Colomés (UAB)
- Guillem Albareda (UB)

Quantum-to-classical transition

- Albert Benseny (Japan)
- David Tena (UAB)
- Travis Norsen (USA)

Equation of motion for conditional wave function

Financial Support:

- Ministerio de Ciencia e Innovación under Project No. TEC2012-31330
- DURSI of the Generalitat de Catalunya under Contract No. 2009SGR783
- Grant agreement no: 604391 of the Flagship "Graphene-Based Revolutions in ICT and Beyond"
Introduction

What does decoherence mean?

Does it appear when dealing with open systems?
- Diagonalize “reduced” density matrix
- Continuous monitoring by the environment
- Environment induced superselection

Or it is also present in closed systems?
- Plank constant to zero
- Large number of particles
- Ehrenfest theorem

Does it appear at an ontological level of the theory? Or not?
- GRW “spontaneous” collapse
- Decohere(consistent) histories

Decoherence is somehow a “fuzzy” concept!

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How decoherence is modelled “FAPP”?

\[
\frac{d\hat{\rho}_S}{dt} = \frac{-i}{\hbar} \left[ \hat{H}_S, \hat{\rho}_S \right] + \hat{D}[\hat{\rho}_S]
\]

FAPP, decoherence (+ the many-body problem) make quantum theories universal and unfalsifiable

Good news for a quantum engineers! They can easily put the dissipation and irreversibility into their models.

Bad news for foundations of quantum mechanics! Unless they clarify or eliminate decoherence, it is difficult to test the universality of quantum theories.

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Within Bohmian mechanics:

1. Dissipation by invoking the fuzzy concept of decoherence

1.1. The Bohmian conditional wave function

1.2. Electron-phonon dissipation within Bohmian mechanics

2. Quantum-to-classical transition without invoking decoherence
1.1.- Conditional (Bohmian) wave function

Orthodox quantum theory:
An object cannot be a wave and a particle simultaneously!

Bohmian quantum theory:
But two objects can! Specially, if one is a wave and the other is a particle.

\[ \Phi(x_1,\ldots,x_N,t) = R(x_1,\ldots,x_N,t)e^{iS(x_1,\ldots,x_N,t)/\hbar} \]

Waves

\[ \sum_{a=1}^{N} \frac{\hbar}{2m} \frac{\partial^2}{\partial x_a^2} + U(x_1,\ldots,x_N,t) \] \( \Phi(x_1,\ldots,x_N,t) \)

Particles

\[ v_i(x_1,\ldots,x_N,t) = \frac{J_i(x_1,\ldots,x_N,t)}{\lvert \Psi(x_1,\ldots,x_N,t) \rvert^2} = \frac{1}{m} \frac{\partial S(x_1,\ldots,x_N,t)}{\partial x_i} \]

Non-Local

Contextual

unpredicatable and deterministic

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1.1.- Conditional (Bohmian) wave function

The many-particle wave function

\[ i\hbar \frac{\partial \Phi(x_1, x_2, ..., x_N, t)}{\partial t} = \left\{ \sum_{a=1}^{N} -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x_a^2} + U(x_1, x_2, ..., x_N, t) \right\} \Phi(x_1, x_2, ..., x_N, t) \]

The many-body problem

\[ i\hbar \frac{\partial \Psi(x_a, t)}{\partial t} = \left\{ -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x_a^2} + U(x_a, \vec{r}[t], t) + G(x_a, \vec{r}[b], t) \right\} \Psi(x_a, t) \]


Nature

The conditional wave function

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Usual single-particle Schrödinger equation:

\[ i\hbar \frac{\partial \Psi(x,t)}{\partial t} = \left\{ -\frac{\hbar^2}{2m^*} \frac{\partial^2}{\partial x^2} + U(x,t) \right\} \Psi(x,t) \]

“Conditional” single-particle Schrödinger equation:

\[ i\hbar \frac{\partial \Psi(x,t)}{\partial t} = \left\{ -\frac{\hbar^2}{2m^*} \frac{\partial^2}{\partial x^2} + U(x,t) + G(x,t) + iJ(x,t) \right\} \Psi(x,t) \]


Our goal:

Use \( G(x,t) \) and \( i\cdot J(x,t) \) to produce an electron changes from the state \( \{E, k\} \) to \( \{E', k'\} \)

\[ i\hbar \frac{\partial \Psi(x,t)}{\partial t} = \left\{ \frac{1}{2m^*} \left( -i\hbar \frac{\partial}{\partial x} + \lambda \Phi(t_1) \right)^2 + U(x,t) \right\} \Psi(x,t) \]
1.2. - Single-particle (conditional) dissipative wave functions

\( E_0 = 0.18 \text{ eV} \)
\( K_\lambda = -2.2 \times 10^8 \text{ m}^{-1} \)
\( T = 0.85 \text{ ps} \)
\( T_1 = 0.21 \text{ ps} \)

well = 4 nm
barr = 0.8 nm
Height = 0.5 eV

\[
i \hbar \frac{\partial \Psi(x,t)}{\partial t} = \left\{ -\frac{\hbar^2}{2m^*} \frac{\partial^2}{\partial x^2} + U(x,t) \right\} \Psi(x,t)
\]

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Scattering mechanisms (Fermi Golden Rule)

1.- Acoustic Phonons.
2.- Optical phonons (0.036 eV)
3.- Optical phonons (-0.036 eV),
4.- Impurities ($N_D=10^{17}$ cm$^{-3}$)

BITLLES:

Freely available at http://euroep.uab.es/bitlles

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Can decoherence make quantum theories unfalsifiable?
Understanding the quantum-to-classical transition without it

Within Bohmian mechanics:

1. Dissipation by invoking the fuzzy concept of decoherence

2. Quantum-to-classical transition without invoking decoherence
   2.1. A “frustrating” single-particle Bohmian attempt
   2.2. A natural many-particle Bohmian attempt for the center of mass
   2.3. A conditional wave function for the center of mass
2.1.- A “frustrating” single-particle Bohmian attempt

Classical and Bohmian similarities

.- Both deal with particles.
.- Both deal with single-experiments (not ensemble of experiments).
.- Both have no measurement postulate (it is just a type of interaction).

Rosen’s criteria:

\[ i\hbar \frac{\partial \Phi(x, t)}{\partial t} = \left\{ -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} + U(x, t) \right\} \Phi(x, t) \]


\[ \Phi^{\frac{r}{r}}(x, t) = R(x, t) e^{iS(x, t)/\hbar} \]

1.- Continuity equation:

\[ \frac{\partial R^2(x, t)}{\partial t} + \frac{\partial}{\partial x} \left( R^2(x, t) \cdot v(x, t) \right) = 0 \]

2.- Quantum Hamilton-Jacobi:

\[ \frac{\partial S(x, t)}{\partial t} + U(x) + \frac{1}{2m} \left( \frac{\partial S(x, t)}{\partial x} \right)^2 + Q(x, t) = 0 \]

3.- Mathematical condition:

\[ Q(x, t) = 0 \]
2.2. - A natural many-particle Bohmian attempt for the center of mass

The reason of the previous bad results is because and apple is not a single-particle system! **We Try a many-particle system!**

**1.- Many body system:**

\[
i\hbar \frac{\partial \Phi(x_1, x_2, \ldots, x_N, t)}{\partial t} = \left\{ \sum_{a=1}^{N} - \frac{\hbar^2}{2m} \frac{\partial^2}{\partial x_a^2} + U(x_1, x_2, \ldots, x_N, t) \right\} \Phi(x_1, x_2, \ldots, x_N, t)
\]

We study the transition for the center of mass! (not for an individual electron)

**2.- Center of mass:**

\[
y_1 = x_{cm} = \frac{1}{N} \sum_{i=1}^{N} x_i
\]
\[
y_j = x_j - \frac{\left( \sqrt{N} x_{cm} + x_1 \right)}{\sqrt{N} + 1} \quad j = 2, \ldots, N
\]

\[
i\hbar \frac{\partial \Psi(x_{cm}, y_2, \ldots, y_N, t)}{\partial t} = \left\{ - \frac{\hbar^2}{2N \cdot m} \frac{\partial^2}{\partial x_{cm}^2} - \frac{\hbar^2}{2m} \sum_{a=2}^{N} \frac{\partial^2}{\partial y_a^2} + U(x_{cm}, y_2, \ldots, y_N, t) \right\} \Psi(x_1, x_2, \ldots, x_N, t)
\]

2.2.- A natural many-particle Bohmian attempt for the center of mass

1.- Wave-equation for the center of mass of a many body system:

\[
\frac{i\hbar}{\partial t} \frac{\partial \Psi(x_{cm}, y_2, \ldots, y_N, t)}{\partial t} = \left\{ -\frac{\hbar^2}{2N \cdot m} \frac{\partial^2}{\partial x_{cm}^2} - \frac{\hbar^2}{2m} \sum_{a=2}^{N} \frac{\partial^2}{\partial y_a^2} + U(x_{cm}, y_2, \ldots, y_N, t) \right\} \Psi(x_1, x_2, \ldots, x_N, t)
\]

2.- Quantum Hamilton-Jacobi:

\[
0 = \frac{\partial S}{\partial t} + U + \frac{1}{2} M \cdot v_{cm}^2 + Q_{cm} + \sum_{j=2}^{N} \left( \frac{1}{2} m \cdot v_j^2 + Q_j \right)
\]

\[
v_j(x_{cm}, y, t) = \frac{1}{m} \frac{\partial S(x_{cm}, y_2, \ldots, y_N, t)}{\partial x_j}
\]

\[
v_{cm}(x_{cm}, y, t) = \frac{1}{N \cdot m} \frac{\partial S(x_{cm}, y_2, \ldots, y_N, t)}{\partial x_{cm}}
\]

\[
N \cdot m \frac{dX_{cm}[t]}{dt} = -\frac{\partial}{\partial x_{cm}} \left( U + Q_{cm} + \sum_{j=2}^{N} Q_j \right)
\]

2.2.- A natural many-particle Bohmian attempt for the center of mass

3.- Conditions for the Quantum-to-Classical transition of the center of mass:

\[ M \frac{dX_{cm}[t]}{dt} = -\frac{\partial}{\partial x_{cm}} \left( U + Q_{cm} + \sum_{j=2}^{N} Q_j \right) \]

\[ \approx -\frac{\partial}{\partial x_{cm}} U \]

\[ \lim_{N \to \infty} \frac{\partial}{\partial x_{cm}} U \propto N \]

\[ \lim_{N \to \infty} \frac{\partial}{\partial x_{cm}} Q_{cm} \propto \sqrt{N} \]

For particles with exchange interaction

\[ \lim_{N \to \infty} \sum_{j=2}^{N} \frac{\partial}{\partial x_{cm}} Q_j \approx \int_{-\infty}^{\infty} \frac{\partial}{\partial x_{cm}} Q_2 dx_2 \to 0 \]

Clear evidences for the ontological goal of quantum and classical re-unification

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### 2.2. - A natural many-particle Bohmian attempt for the center of mass

**Error(%) =** \( \frac{X_{cl}(t) - X(t)}{X_{cl}(t)} \) \times 100

<table>
<thead>
<tr>
<th>Particles</th>
<th>Time (s)</th>
<th>Position (m)</th>
<th>Energy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bosons</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Bosons**

**Parabolic potential**

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2.2.- A natural many-particle Bohmian attempt for the center of mass

\[
\text{Error} \% = 100 \frac{X_{CM}^{cl}(t) - X_{CM}(t)}{X_{CM}^{cl}(t)}
\]

<table>
<thead>
<tr>
<th>Particles</th>
<th>Time (s) \times 10^{-11}</th>
<th>Position (m)</th>
<th>Energy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bosons</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*quadratic potential*

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2.3.- A conditional wave function for the center of mass

How the quantum non-locality disappears?

Bohmian quantum theory: Non-local

.- Bohmian trajectories lives in physical space $\mathbb{R}^3$

.- Many-particle wave function lives in configuration space $\mathbb{R}^{3N}$

\[
N \cdot m \frac{dX_{cm}[t]}{dt} = -\frac{\partial}{\partial x_{cm}} \left( U + Q_{cm} + \sum_{j=2}^{N} Q_j \right)
\]

\[
N \cdot m \frac{dX_{cm}[t]}{dt} \approx -\frac{\partial}{\partial x_{cm}} U
\]
2.3. - A conditional wave function for the center of mass

How the quantum randomness disappears?

Bohmian quantum theory: unpredictable and deterministic

1\textsuperscript{st} experiment:

2\textsuperscript{nd} experiment:

3\textsuperscript{rd} experiment:

FAPP, predictable and deterministic evolution.

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2.3.- A conditional wave function for the center of mass

\[ i\hbar \frac{\partial \Psi(x_a, t)}{\partial t} = \left\{ -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x_a^2} + U(x_a, x_b[t], t), -Q(x_a, x_b[t], t) \right\} \Psi(x_a, t) \]

A new equation for an intermediate domain of physics where the behavior of the system is neither purely quantum nor classical.

\[ R(\dot{x}, t) \quad S(\dot{x}, t) \quad G(x_a, \dot{x}_b[t], t) + iJ(x_a, \dot{x}_b[t], t) \]
Three main messages:

Message 1.- Decoherence and the many-body problem makes quantum theories universal and unfalsifiable FAPP. This is a very attractive feature for a quantum engineer (http://europe.uab.es/bitlles), but a disgusting one for those interesting on foundations of quantum mechanics.

Message 2.- (main result)- Classical mechanics appears in a very natural way from Bohmian mechanics, when dealing with the center of masses of a very large number of particles with exchange symmetry.

Thank you very much for your attention