Could quantum decoherence and measurement be deterministic phenomena?

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1. Advocacy for determinism

2. Apparatus hidden variables and Bell’s inequalities

3. A schematic model for deterministic quantum measurement

4. Faster-than-light communication

5. Conclusions and perspectives
Determinism in quantum mechanics... and beyond!

- Philosophical motivations for determinism
  - until recently, science was based on determinism: the same cause always produces the same effect
  - simpler timeless theories: the present moment “time capsule” [Barbour, 1999] contains both past and future because causally related to it

- Quantum theory apparently violates this principle
  - measurement: identical measurements on identical systems in identical states may lead to different results (eigenvalues of an observable, with computable probabilities)
  - decoherence: linear superposition of states randomly and irreversibly decoheres to a statistical mixture of states (i.e. to a random state with a computable probability)

- This happens when the quantum system interacts with a macroscopic system (e.g. a readable apparatus) with uncontrollable internal degrees of freedom (“environment”)
  - could this apparent randomness be actually determined by these degrees of freedom?
A striking example: $\alpha$-particle in cloud chamber

- **Spherical- ($s$-)wave $\alpha$ emitter**
  - kinetic energy $T_\alpha = \frac{\hbar^2 k^2}{2m_\alpha}$
  - $\alpha$-particle wave function $f(R) = \frac{e^{ikR}}{R}$
  - highly non local: $\alpha$ particle in all directions at the same time
  - but linear local tracks detected (wave function reduction)

- Einstein’s solution: quantum mechanics is **incomplete**: state of $\alpha$ particle = wave function $f(R)$ and hidden variable $\lambda$ which determines observed result (“God doesn’t play dice”)

- Problem: existence of $\lambda$ ⇒ Bell’s inequalities, violated by experiment

- Present paper: track direction determined instead by microscopic positions of molecules/“droplets to be” in cloud chamber
  - play the role of apparatus hidden variables $\Lambda$
  - random because of thermal agitation
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Apparatus hidden variables \( \Lambda \) violate Bell’s inequalities

- Einstein-Podolsky-Rosen (1935)
  Bohm-Aharonov experiment

- Mean correlation between spin 1 and 2 measured along directions \( \hat{a} \) and \( \hat{b} \)
  \[ E(\hat{a}, \hat{b}) \equiv \frac{4}{\hbar^2} \langle (s_1 \cdot \hat{a})(s_2 \cdot \hat{b}) \rangle \]

- Quantum mechanics prediction: \( E_Q(\hat{a}, \hat{b}) = -\hat{a} \cdot \hat{b} \)
  for entangled state \( |00\rangle = \frac{1}{\sqrt{2}} (|+\rangle \hat{u}_1 |-\rangle \hat{u}_2 - |-\rangle \hat{u}_1 |+\rangle \hat{u}_2) \)
  - violates Bell’s inequalities for particular \( \hat{a}, \hat{b}, \hat{c} \) [Bell, 1964]
  - but agrees with experiment (photons) [Aspect et al., 1982]

- Variables \( \Lambda_1, \Lambda_2 \) hidden in apparatuses: \( E_{\Lambda_1\Lambda_2}(\hat{a}, \hat{b}) = -\hat{a} \cdot \hat{b} \)
  \[ \Rightarrow \text{identical to standard quantum mechanics} \]
  \[ E_{\Lambda_1\Lambda_2}(\hat{a}, \hat{b}) = \sum_{\Lambda_1\Lambda_2} p(\Lambda_1)p(\Lambda_2) R(|\sigma_1\rangle, \hat{a}, \Lambda_1) R(|\sigma_2\rangle, \hat{b}, \Lambda_2) \]
  \[ = \frac{1}{2} \sum_{\Lambda_2} p(\Lambda_2) \left[ R(|-\rangle \hat{a}, \hat{b}, \Lambda_2) - R(|+\rangle \hat{a}, \hat{b}, \Lambda_2) \right] \]
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\(\alpha\)-particle scattering on single localized obstacle

- **Hypotheses on obstacle**
  - generic: hydrogen atom [Mott, 1926], supersaturated vapour alcohol droplet...
  - immobile at fixed position \(\alpha\) \((T_\alpha \gg T_{\text{thermal}})\)
  - internal Hamiltonian \(H\) and variables \(r\), two levels: \(\psi_0(r), E_0\) and \(\psi_1(r), E_1\) with \(\langle \psi_0 | \psi_1 \rangle = 0\)

- **Stationary \(\alpha\)-particle + obstacle coupled-channel wave function**

\[
\Psi(R, r) = f_0(R)\psi_0(r) + f_1(R)\psi_1(r)
\]

  - no obstacle excitation \(\Rightarrow f_0(R)\) has energy \(T_\alpha\)
  - obstacle excitation \(\Rightarrow f_1(R)\) has energy \(T'_\alpha = T_\alpha + E_0 - E_1 \equiv \frac{\hbar^2 k'^2}{2m_\alpha}\)

- **High-energy scattering \(\Rightarrow\) first-order Born expansion**

\[
\Psi(R, r) = f_0^{(0)}(R)\psi_0(r) + f_0^{(1)}(R)\psi_0(r) + f_1^{(1)}(R)\psi_1(r)
\]

  - \(f_0^{(0)}(R)\) = spherical wave
  - \(f_0^{(1)}(R), f_1^{(1)}(R)\) = peaked waves around direction \(\alpha\)
Wave-function normalization

- **Hypothesis:** α-particle (probability) flux $F$ at large distance independent of obstacle presence
  - without obstacle: $f(R) = \frac{e^{ikR}}{R}$
    \[ \Rightarrow F_{\text{without}} = 4\pi \frac{hk}{m_\alpha} \equiv 4\pi v_\alpha \]
  - with obstacle in $a$, defining $\theta \equiv \angle(a, R-a)$:
    \[
    \Psi(R, r) \sim C \frac{e^{ikR}}{R} \psi_0(r) + I_0(\theta) \frac{e^{ik|R-a|}}{|R-a|} \psi_0(r) + I_1(\theta) \frac{e^{ik'|R-a|}}{|R-a|} \psi_1(r)
    \]
    \[ \Rightarrow F = 4\pi |C|^2 v_\alpha + 2\pi v_\alpha \int_0^\pi d\theta \sin \theta |I_0(\theta)|^2 + 2\pi v'_\alpha \int_0^\pi d\theta \sin \theta |I_1(\theta)|^2 \equiv 4\pi v_\alpha (1-|C|^2) > 0 \]

- One has thus $|C|^2 < 1$, i.e. a flux reduction in spherical wave

\[ F_{\text{spherical}} = |C|^2 F_{\text{without}} \]

- could explain wave-function reduction in a deterministic way
- could be exploited for faster-than-light information transfer
\(\alpha\)-particle scattering on two (and more) localized obstacles

- Two obstacles ⇒ **second-order** Born expansion [Mott, Proc. R. Soc. 1926]

\[
\Psi(R, r_a, r_b) = \left[ f^{(0)}_{00}(R) + f^{(1)}_{00}(R) + f^{(2)}_{00}(R) \right] \psi_0(r_a)\psi_0(r_b) \\
+ f^{(1)}_{10}(R)\psi_1(r_a)\psi_0(r_b) + f^{(1)}_{01}(R)\psi_0(r_a)\psi_1(r_b) \\
+ f^{(2)}_{11}(R)\psi_1(r_a)\psi_1(r_b)
\]

- \(f^{(2)}_{11}(R)\) only significantly different from 0 iff \(a \propto b\)
- explains linear tracks from spherical wave
- track direction determined by droplet positions \(a\) and \(b\)

- \(N\) aligned obstacles ⇒ strong reduction of spherical-wave flux

\[
F_{\text{spherical}} \approx |C|^{2N} F_{\text{without}}
\]

⇒ explains wave-function reduction

- \(N\) randomly-distributed obstacles
  - direction of best-aligned obstacles singled out as measured track
  - deterministic explanation to apparently random track detection
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Wave-function reduction $\Rightarrow$ superluminal information?

- Presence of obstacle in direction $a$ reduces spherical wave amplitude in all other directions $\Rightarrow$ possible information transfer?
  - “0”: without obstacle $\Rightarrow$ no reduction
  - “1”: with obstacle $\Rightarrow$ reduction

- Spherical wave = highly non-local state $\Rightarrow$ reduction simultaneous in all directions $\Rightarrow$ possible faster-than-light information transfer?

- Practical implementation
  - replace $\alpha$ particle by electric dipole photon
  - replace droplet by tunable (Zeeman?) two-level single atom
  - first check: is the photon flux reduced when two-level system tuned?
  - if yes, second check: is this reduction instantaneous (fibre-optic delay)?
Conclusions and perspectives

- Schematic model for deterministic quantum measurement
  - spherical-wave alpha-particle detection in cloud chamber
  - direction of linear trajectory determined by best aligned droplets
  - “wave mechanics unaided” [Mott, 1926]

- Hidden variables $\Lambda = $ microscopic state of apparatus/environment
  - violate Bell’s inequalities, agree with standard quantum mechanics

- Wave-function non-locality $\Rightarrow$ instantaneous information transfer
  - presence of droplet in one direction
    - immediately affects normalization of spherical wave in all directions
  - practical implementation: photons, Zeeman tunable atoms, fiber optics

- Possible mistakes in present results
  - validity of coupled-channel and Born expansions?
  - validity of stationary scattering state formalism and flux interpretation?

- Theoretical developments
  - wave packets and time-dependent approach (1D, 3D)
  - microscopic description of (cold) polarisers
    $\Rightarrow$ use of Bell-pair non-locality with polarized photons?