Bricmont, Bohm, and Bell

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What is so bad about Copenhagen quantum mechanics?

- It posits two realms: “speakable and unspeakable” (John Bell).
- It leans towards exaggerated positivism.
- It leans towards paradoxes, in particular
  - in the terminology of “measurement” and “observable”
  - in the concept of complementarity.
- It claims incorrectly that non-paradoxical theories are impossible.
- It suffers from the quantum measurement problem.
- It remains unclear about what is real and how reality works.

What are the alternatives to the Copenhagen interpretation (CI)?

- Bohmian mechanics (1952)
- GRW theory of spontaneous wave function collapse (1986)
- many worlds (in Schrödinger's version, rather than Everett's)

What is so bad about the Copenhagen interpretation?

Problematical CI: Two realms (1)

In CI, the world is separated into two realms:

macroscopic
= "classical" (CI terminology)
= "speakable" (Bell).
No superpositions; e.g., pointers always point in definite directions.
The macro realm is described by the classical positions and momenta of objects;
when isolated, it is governed by classical mechanics;
at "measurement," it records the outcome.

microscopic
= "quantum" (CI terminology)
= "unspeakable" (Bell).
No definite facts; e.g., an electron does not have a definite position.
The micro realm is described by wave functions;

when isolated, it is governed by the Schrödinger equation;
at "measurement", it undergoes collapse of the wave function.

Problematical CI: Two realms (2)

macroscopic	microscopic

- It is not precisely defined where the border between micro and macro lies. What is the exact number of particles required for an object to be "macroscopic"? This vagueness is unproblematical in Bohmian mechanics, GRW theory, or classical mechanics, but problematical in CI as it enters the laws of nature.
- What counts as a measurement and what does not? Unproblematical when we only want to compute the probabilities of outcomes of a given experiment because it will practically not affect the computed probabilities. But problematical when it enters the laws of nature.
- The special role played by measurements in the laws is implausible and artificial. Even if a precise definition of what counts as a measurement were given, it would not seem believable that during measurement other laws than normal are in place.
- The separation of the two realms, without the formulation of laws that apply to both, is against reductionism. If we think that macro objects are made out of micro objects, then the separation is problematical.

Problematical CI: leans towards exaggerated positivism

Positivism: What is not observable (or not observed) is not real (or unscientific, or meaningless).

Werner Heisenberg (1958):

"We can no longer speak of the behavior of the particle independently of the process of observation."

Feynman (1959) did not like that:

"Does this mean that my observations become real only when I observe an observer observing something as it happens? This is a horrible viewpoint. Do you seriously entertain the thought that without observer there is no reality? Which observer? Any observer? Is a fly an observer? Is a star an observer? Was there no reality before 10^9 B.C. before life began? Or are you the observer? Then there is no reality to the world after you are dead? I know a number of otherwise respectable physicists who have bought life insurance."

Richard Feynman (1918–1988)

Problematical CI: Language of "measurement"

CI uses the words "measurement" and "observable," and emphasizes the analogy suggested by them (e.g., that the momentum operator is analogous to the momentum variable in classical mechanics).

Inappropriate

These words suggest that there was a value of the observable A that was merely discovered (i.e., made known to us) in the experiment, whereas in fact the outcome is often only created during the experiment. (Even more so in CI, which insists that the wave function is complete, than in Bohmian mechanics.)

John Bell (1990): "The word [measurement] has had such a damaging effect on the discussion, that I think it should now be banned altogether in quantum mechanics."

Problematical CI: Complementarity

Einstein (1949):

"Despite much effort which I have expended on it, I have been unable to achieve a sharp formulation of Bohr's principle of complementarity."

Complementarity: In the micro realm, reality is paradoxical (contradictory) but the contradictions can never be seen (and are therefore not problematical) because of the Heisenberg uncertainty relation.

In order to compute a quantity of interest (e.g., the wave length of light scattered off an electron), we use both Theory A (e.g., classical theory of billiard balls) and Theory B (e.g., classical theory of waves) although A and B contradict each other. It is impossible to find one Theory C that replaces both A and B and explains the entire physical process. Instead, we should leave the conflict between A and B unresolved and accept the idea that reality is paradoxical.

Problematical CI: Are non-paradoxical theories impossible?

CI claims that it is impossible to provide any coherent (non-paradoxical) realist theory of what happens in the micro realm.

Heisenberg (1958):

"The idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist, independently of whether or not we observe them [...], is impossible."

W. Heisenberg (1901–1976)

Bohmian mechanics is a counter-example to this claim.

Problematical CI: The quantum measurement problem (1)

Consider a "quantum measurement" of the operator A during $[t_1, t_2]$.
System + apparatus form a quantum system of 10^{25} electrons, protons and neutrons, with a wave function Ψ governed by the Schrödinger equation.

$$\Psi(t_1) = \psi \otimes \phi$$

with ψ = wave fct of system, ϕ = "ready" state of apparatus.
Expand ψ in eigenfunctions of A,

$$\psi = \sum_\alpha c_\alpha \psi_\alpha, \quad A\psi_\alpha = \alpha\psi_\alpha, \quad \|\psi_\alpha\| = 1.$$

If $\psi = \psi_\alpha$ then the outcome is certain to be α; set $\Psi_\alpha(t_1) = \psi_\alpha \otimes \phi$; then $\Psi_\alpha(t_2)$ = a state in which apparatus displays outcome α.
Returning to general $\psi = \sum_\alpha c_\alpha \psi_\alpha$, since the Schrödinger equation is linear,

$$\Psi(t_2) = \sum_\alpha c_\alpha \Psi_\alpha(t_2),$$

a superposition of states corresponding to different outcomes, and not a random state corresponding to a unique outcome.

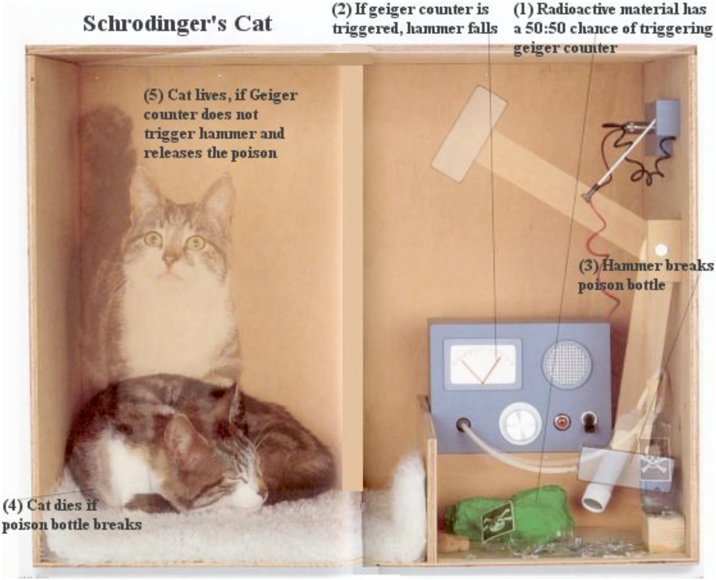
Problematical CI: The quantum measurement problem (2)

John Bell: "The problem is: AND is not OR."

Upshot

There is a conflict between the following assumptions:

- In each run of the experiment, there is a unique outcome.
- The wave function is a complete description of a system's physical state.
- The evolution of the wave function of an isolated system is always given by the Schrödinger equation.


Schrodinger's Cat
(2) If geiger counter is triggered, hammer falls
(1) Radioactive material has a 50:50 chance of triggering geiger counter
(5) Cat lives, if Geiger counter does not trigger hammer and releases the poison
(3) Hammer breaks poison bottle
(4) Cat dies if poison bottle breaks

Alternatives to Copenhagen

Bohmian mechanics

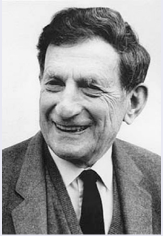
- takes the word "particle" literally: The k-th particle has position $\mathbf{Q}_k(t) \in \mathbb{R}^3$ at time t.
- The complete description of a system is $(\mathbf{Q}_1, \ldots, \mathbf{Q}_N, \psi)$.
- The equation of motion is the simplest possible:

$$\frac{d\mathbf{Q}_k}{dt} = \frac{\text{probability current}}{\text{probability density}}$$

with current $= (\hbar/m_k)\ \mathrm{Im}\ \psi^* \nabla_k \psi$
and density $= |\psi|^2$.

- ψ evolves according to the Schrödinger eq.

$$i\hbar \frac{\partial \psi}{\partial t} = H\psi$$

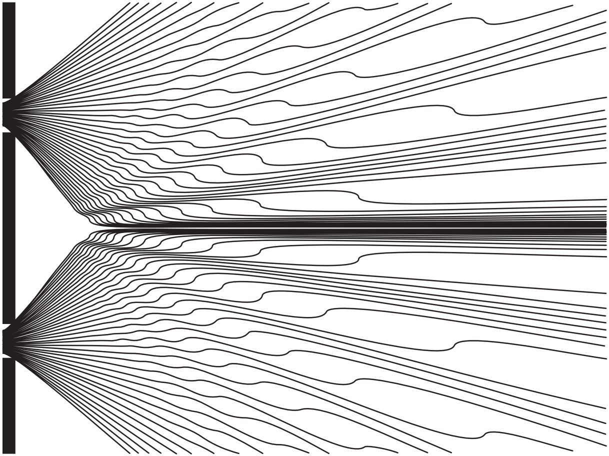


David Bohm
(1917–1992)

Like it or don't, it actually works: Inhabitants of a universe governed by Bohmian mechanics with $|\psi|^2$-distributed initial configuration would observe exactly the probabilities predicted by the quantum formalism.

Bohmian mechanics

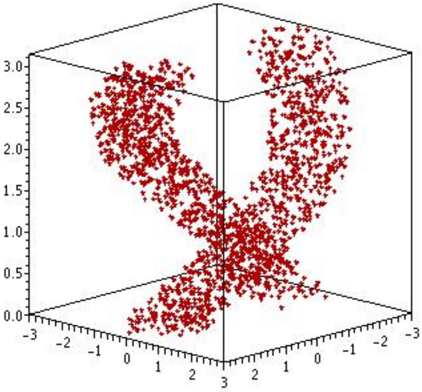
Wave–particle dualism in the literal sense: there is a wave, and there is a particle. The path of the particle depends on the wave.



Shown: A double-slit and 80 possible paths of Bohm's particle. The wave passes through both slits, the particle through only one.

Spontaneous collapse

e.g., the "GRW flash theory":



Instead of Bohm's world lines, there are world points in space-time, called "flashes." A macroscopic object consists of a galaxy of flashes.

Spontaneous collapse: GRW theory

Key idea:

The Schrödinger equation is only an approximation, valid for systems with few particles ($N < 10^4$) but not for macroscopic systems ($N > 10^{23}$). The true evolution law for the wave function is non-linear and stochastic and avoids superpositions (such as Schrödinger's cat) of macroscopically different contributions.

Put differently, regard the collapse of ψ as a physical process governed by mathematical laws.

GianCarlo Ghirardi (born 1935)

Explicit equations by Ghirardi, Rimini, and Weber (1986)

The predictions of the GRW theory deviate very very slightly from the quantum formalism. At present, no experimental test is possible.

GRW's stochastic evolution for ψ

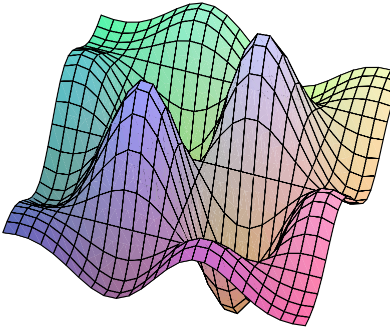
- is designed for non-relativistic quantum mechanics of N particles
- meant to replace Schrödinger eq as a fundamental law of nature
- involves two new constants of nature:
  - $\lambda \approx 10^{-15}\,\mathrm{sec}^{-1}$, called collapse rate per particle.
  - $\sigma \approx 10^{-7}\,\mathrm{m}$, called collapse width.
- Def: ψ evolves as if an observer outside the universe made, at random times with rate $N\lambda$, quantum measurements of the position observable of a randomly selected particle with inaccuracy σ.
- "rate $N\lambda$" means that
  prob(an event in the next dt seconds) $= N\lambda\, dt$.
- more explicitly: Schrödinger evolution interrupted by jumps of the form

$$\psi_{T+} = e^{-\frac{(\mathbf{q}_k-\mathbf{q})^2}{4\sigma^2}}\psi_{T-}\,,$$

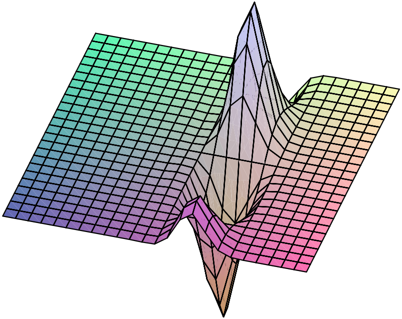
  i.e., multiplication by a Gauss function with random label k, center $\mathbf{q}$ and time T.
- A flash occurs at $(T,\mathbf{q})$ for each collapse.

GRW's spontaneous collapse

before the "spontaneous collapse":



and after:



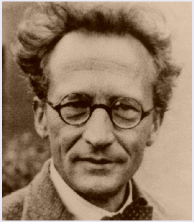
Many worlds

Schrödinger proposed this theory in 1925:

Matter is distributed continuously in space with density

$$m(\mathbf{q},t) = \sum_{k=1}^{N} \int_{\mathbb{R}^{3N}} \delta^3(\mathbf{q}-\mathbf{q}_k)\,|\psi_t(q)|^2\,dq\,.$$

ψ_t evolves according to the Schrödinger eq.



E. Schrödinger (1887–1961)

He soon abandoned this theory because he thought it made wrong predictions. But actually, it is a many-worlds theory making right predictions: it implies the quantum formalism.

For Schrödinger's cat, $\psi = \frac{1}{\sqrt{2}}\psi_{\text{dead}} + \frac{1}{\sqrt{2}}\psi_{\text{alive}}$,
it follows that $m = \frac{1}{2}m_{\text{dead}} + \frac{1}{2}m_{\text{alive}}$.
There is a dead cat and a live cat, but they are like ghosts to each other (they do not notice each other), as they do not interact. So to speak, they live in parallel worlds.

Many worlds

Not knowing about Schrödinger's proposal, Everett advocated a many-worlds view in 1957, but with an unclear (or inadequate) ontology: His idea was that for wave functions such as Schrödinger's cat's, both cats are in the wave function, so both cats exist.

Everett contributed substantially to the analysis of probabilities in a many-world framework.

Hugh Everett (1930–1982)

Bohmian mechanics is the simplest, most straightforward, elegant, convincing, natural option:

- "Particle" means particle.
- It would seem odd that the wave fct is defined on *configuration space* if there was no configuration.
- John Bell (1984): "Is it not clear from the smallness of the scintillation on the screen that we have to do with a particle? And is it not clear, from the diffraction and interference patterns, that the motion of the particle is directed by a wave?"

Benefits of Bohmian mechanics

- resolve the paradoxes of QM
- obtain an explanation of QM
- provide a theory about the foundations of QM that can be understood as clearly as classical mechanics—
  a "quantum theory without observers" (K. Popper)
- use this theory as a clean mathematical basis to turn "folklore" knowledge into theorems
- make QM easier to learn
- fight mysticism about QM, unwarranted claims, and bad philosophy

Thank you for your attention