Interpretation miniatures

Hrvoje Nikolić

Rudjer Bošković Institute, Zagreb, Croatia

Long version, 2016

- Discussions of quantum interpretations usually take a lot of words.

- Physicists only marginally interested in interpretations
do not have patience for long and obscure arguments.

- If you are one of them, this talk is for you:
Various aspects of interpretations are explained in a concise and simple (almost trivial) form.

- This format allows me to cover many (unrelated) topics.

Outline:

1. Copenhagen interpretations
 1.1 There is no Copenhagen interpretation
 1.2 Making sense of local non-reality

2. Many-world interpretation
 2.1 MWI is neither local nor non-local
 2.2 The Born rule cannot be derived
 2.3 The preferred basis problem
 2.4 Quantum suicide

3. Bohmian interpretation
 3.1 A dark-matter analogy
 3.2 Correlation vs causation
 3.3 A Bohmian theory of everything

4. Comparison of interpretations
 4.1 Who is puzzled by delayed choice?
 4.2 Time in quantum gravity
 4.3 Alternatives to non-locality

Appendix: Life is an organized disorder

1. COPENHAGEN INTERPRETATIONS

1.1 There is no Copenhagen interpretation

- Many physicists say that they prefer the “Copenhagen interpretation”.

- It does not mean that they all prefer the same interpretation.

- There are at least 4 different interpretations which are frequently called “Copenhagen”.

1. Shut up and calculate

- adopted by most practical physicists

2. Positivism

- QM is only about the results of measurements,
not about reality existing without measurements
- adopted by Bohr

3. Information interpretation

- wf does not represent reality, but only information about reality
- also called QBism
- similar to 2., but not the same

4. Collapse interpretation

- when measurement is performed, then wf collapses (von Neumann)

1.2 Making sense of local non-reality

- One interpretation of Bell theorem: local non-reality
- Physics is local, but there is no reality.

- Does it mean that nothing really exists?
- That would be a nonsense!

Here is what it should really mean:

- Physics is not a theory of everything.
- Something of course exists, but that's not the subject of physics.
- Physics is not about **reality** of nature,

it is only about what we can **say** about nature.

- In physics we should only talk about measurable stuff.
- It's important to talk also about non-measurable stuff, but just because it's important is not a reason to call it physics.

Bell theorem $\Rightarrow$ reality is non-local
- logically correct, but that is not physics

QM $\Rightarrow$ signal locality
- that is measurable, so that is physics

In short, "local non-reality" should mean:
- **Reality is non-local.**
- **Physics is about the measurable, which is local.**

- In that form, local non-reality does **not** necessarily need to be accepted, but at least can be reasonably debated.

2. MANY-WORLD INTERPRETATION

2.1 MWI is neither local nor non-local

The postulates:
1. Wave function $\psi(\mathbf{x}_1, \ldots, \mathbf{x}_n, t)$ is the only reality.
2. It always satisfies Schrödinger equation (no collapse).
- looks *deceptively* simple, *because people forget to read the fine print:*
3. Some auxiliary postulates (different versions of MWI).

- wf splitting into "many worlds" is **not postulated**; it is derived

- no collapse, no additional variables $\Rightarrow$ no action at a distance
$\Rightarrow$ **MWI is not non-local**.

However, it does **not** mean that MWI is local:
- A local quantity is something of the form $\phi(\mathbf{x}, t)$.
- There is no such quantity in MWI.
- wf does **not** live in the $(3+1)$-dimensional spacetime.
- wf lives in an abstract **higher**-dimensional space.

$\Rightarrow$ **MWI is neither local nor non-local.**

MWI is **alocal**.

2.2 The Born rule cannot be derived

The 2 main postulates of MWI can be rewritten as:
1. ψ is real (ontic)
2. ψ satisfies a linear equation

- Often claimed that from 1. and 2. one can derive the Born rule

$$\text{probability} = |\psi|^2 \tag{1}$$

Let me show that one cannot (by *reductio ad absurdum*):
Assume that one *can*
$\Rightarrow$ (1) for **any** ψ satisfying 1. and 2.
$\Rightarrow$ (for instance) valid when ψ = a water wave.
But that's absurd, (1) is not true for the water wave.
$\Rightarrow$ The assumption was wrong. *Q.E.D.*

- to derive the Born rule, one must assume something more
- that's why one needs *the "3rd postulate" (fine print)*

- there are various proposals for the additional assumptions
- neither of them looks sufficiently "natural"

Argument that Born rule is not natural in MWI:

- wf splits into two branches $\psi = \psi_1 + \psi_2$, both are real
- analogous to cell division in biology, both are real
- that's also how twin brothers are created, both are real

- suppose $|\psi_1|^2 > |\psi_2|^2$
- analogous to: brother-1 is bigger (fatter) than brother-2

- does it mean that brother-1 is more probable than brother-2?
- No! (If somebody told you that you and your twin brother have different weights, would you conclude that you are probably the fatter one?)
- by analogy: (ψ_1 more probable than ψ_2) also doesn't seem natural.

2.3 The preferred basis problem

- "the reality is $\psi(\mathbf{x}_1, \ldots, \mathbf{x}_n, t)$" – prefers the position basis
- perhaps reality is the basis independent object $|\psi\rangle$?

Leads to an even more serious preferred basis problem:

- to define separate worlds of MWI, one needs a preferred basis, e.g.

$$|\psi\rangle = |\text{live cat}\rangle + |\text{dead cat}\rangle$$

- claim in modern literature: preferred basis provided by decoherence
- however, decoherence requires a split of system into subsystems (the measured system and the environment)
- but if $|\psi\rangle$ is all what exists $\Rightarrow$ such a split is not unique.

MWI claiming that $|\psi\rangle$ is all what exists cannot resolve the basis problem, and thus cannot define separate worlds.

- some additional structure is needed
(e.g. observers of Copenhagen interpretation,
or particles of Bohmian interpretation)

2.4 Quantum suicide

- proposed to be an experimental test of MWI (e.g. Tegmark, 1998)
- play Russian roulette with a quantum random mechanism

- MWI: there is always a branch in which you survive

⇒ you will **always** see that you survive

(For some reason, no believer in MWI has tried this experiment.)

Critique: Even if MWI was true, that would not be a proof!

- suppose you play **classical** Russian roulette
- either you see nothing (because you are dead), or see that you survive
- after playing many times, if you will see anything, you will see that you **always** survive

⇒ **For players who can make observations, there is no difference between quantum and classical Russian roulette.**

3. BOHMIAN INTERPRETATION

3.1 A dark-matter analogy

Bohmian interpretation: deterministic particle trajectories guided by ψ.
- If it s true, then why trajectories cannot be observed?

Analogous to dark matter (astrophysics):
- If dark matter exists, then why it cannot be observed?

Both questions have a similar answer.

Indirect detection:
- sufficient that **exists influence** on something else ("detector")

Direct detection:
- humans tend not to be absolutely convinced that something exists, until they are able to detect the exact **place** where it exists.
$\Rightarrow$ need to know where does the influence **comes from**!

Non-dark matter (stars):
- we observe light from the object
- light is a wave $\Rightarrow$ it has direction of propagation
$\Rightarrow$ easy to determine where does it come from
$\Rightarrow$ observation is **direct**

Dark matter:
- does not produce (or interact with) light
- observed by static gravitational field produced by dark matter
- static gravitational field does not have direction of propagation

⇒ cannot easily determine where does the field come from

⇒ observation is **indirect**

⇒ Indirect detection of dark matter is considered
less convincing than direct detection of non-dark matter.

Analogy with Bohmian particles:
- there is evidence for Bohmian particles (observations can be explained by it, but there are also other explanations)
- non-local quantum potential similar to gravitational static potential (does not have direction of propagation)

⇒ cannot easily determine where does potential come from

⇒ cannot easily determine **position** of Bohmian particle

⇒ evidence for Bohmian particles is only **indirect**

3.2 Correlation vs causation

- To defend locality of QM, often said that “only” **correlations** are non-local; there is no true non-local **causation**.

- Bohmian interpretation accused for being “too much” non-local, by involving a true nonlocal causation.

- But what exactly the difference between correlation and causation is?

I argue that there is no substantial difference at all:

- For simplicity, consider perfect correlation:
Whenever system A has property P1, system B has property P2 (whenever one particle has spin up, the other particle has spin down.)

- But Bohmian non-locality also has this form:
Whenever one particle has this position, other particle has that velocity.

$\Rightarrow$ There is no difference between perfect correlation and causation.
$\Rightarrow$ Bohmian interpretation is not more non-local than standard correlation interpretation.

3.3 A Bohmian theory of everything

Bohmian mechanics very successful for non-relativistic QM, but:
- non-locality: how can it be compatible with relativity?
- continuous trajectories: how can it be compatible with particle creation/destruction?

A key to the answer: Bohmian interpretation of **phonons**:

- sound satisfies a wave equation

$$\frac{1}{c_s^2}\frac{\partial^2\psi}{\partial t^2} - \nabla^2\psi = 0$$

- Lorentz invariant (with velocity of sound c_s instead of c)
- quantum theory of phonons is a QFT (phonon creation/destruction)

Fundamental theory (from condensed-matter perspective):
- fundamental particles: electrons and nuclei
- described by non-relativistic QM
- no creation/destruction of fundamental particles
- Lorentz invariance and QFT are **emergent**
  (derived from non-relativistic QM)
- phonon is a quasi-particle (not "true" particle)

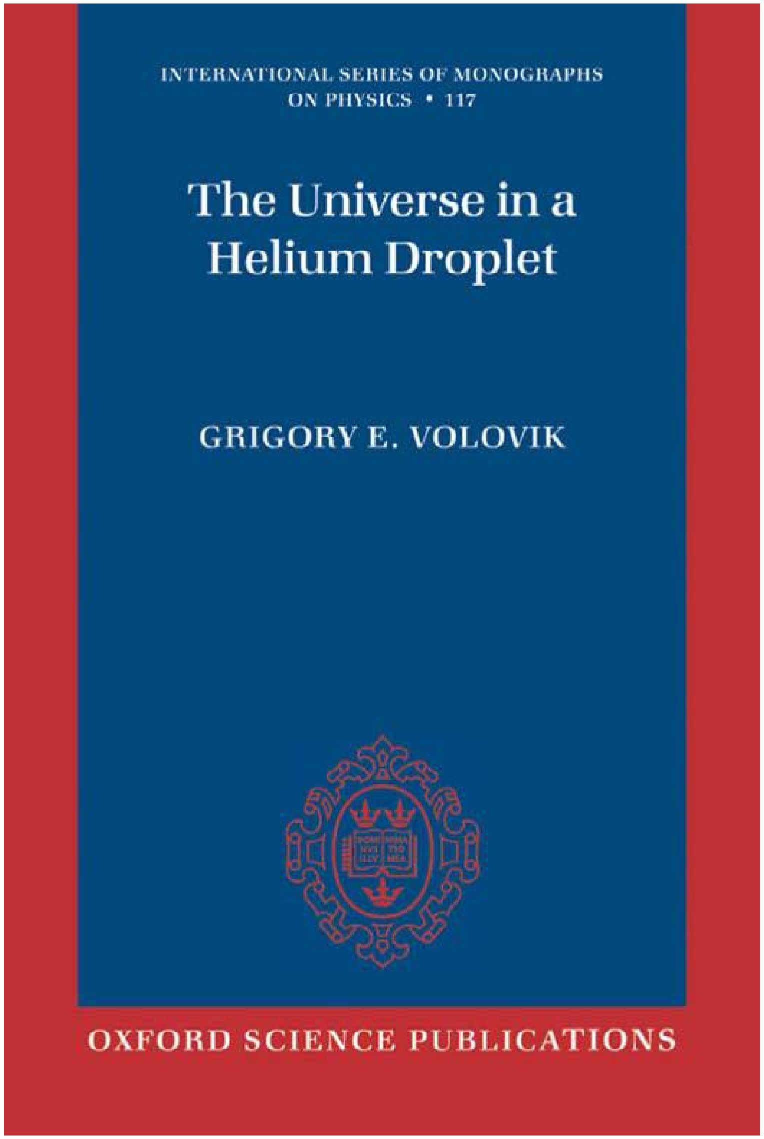
Bohmian interpretation of phonons:
- no trajectories for phonons
- trajectories only for electrons and nuclei
$\Rightarrow$ fundamental theory is non-relativistic Bohmian mechanics

Suggests a Bohmian theory of everything (ToE):

- Perhaps **all** relativistic particles of the Standard Model
  (photons, electrons, quarks, gluons, Higgs, ...)
  are really **quasi-particles**
- Perhaps the truly fundamental particles (as yet unknown)
  are described by non-relativistic QM

$\Rightarrow$ Non-relativistic Bohmian mechanics is a natural ToE:
- trajectories only for those truly fundamental particles

-Many **qualitative** features of Standard Model (SM) can be realized in condensed matter:



-Raises optimism that even **quantitative** features of SM can be derived from some non-relativistic quantum theory.

4. COMPARISON OF INTERPRETATIONS

4.1 Who is puzzled by delayed choice?

- many physicists seem puzzled by delayed choice experiments (DCE)
- apparently, such experiments seem to change the past

- I compare 7 major interpretations of QM
- **Neither** of them supports the change of past!

1. Shut up and calculate:
- only calculate probabilities of **final** outcomes
- no calculation and no talk about the past

2. Positivist interpretation:
- only talk about the measured
- past is not measured

$\Rightarrow$ nothing to say about the past

3. Collapse interpretation:

- wf collapse happens **at the time of measurement**
- before that, evolution described by Schrödinger equation

$\Rightarrow$ measurement does not affect the past

4. Information interpretation:

- wf represents knowledge about the system
- predicts probabilities of measurement in the **future**
- says nothing about **un-performed** measurements in the past

5. Statistical ensemble interpretation:

- QM says nothing about individual particles
- only about **measured** statistical ensembles
- if past is not measured, it says nothing about the past

6. Many-world interpretation:

- evolution always described by Schrödinger equation

$\Rightarrow$ no change of the past

7. Bohmian interpretation:

- wf evolves according to Schrödinger equation
- particle guided by wf

$\Rightarrow$ particle does not change its past.

Niels Bohr said:

"*If QM hasn't profoundly shocked you, you haven't understood it yet.*"

I would add:

If DCE shocked you more than the rest of QM,
you haven't understood the rest of QM yet.

4.2 Time in quantum gravity

Classical general relativity:
- gravity has negative energy, so total Hamiltonian $H = 0$

Quantum gravity (instead of Schrödinger equation):

$$H\Psi = 0$$

$\Rightarrow$ Ψ does not depend on time.
- Then where time-dependence comes from?
- Considered to be a **big** problem in quantum gravity!

- I show that **all** major interpretations of QM
(except perhaps MWI) **trivially** resolve the problem.

1. "Copenhagen"-collapse interpretation (von Neumann)
- wf collapse (due to observation) introduces additional time evolution
- observation itself not described by physics

2. "Copenhagen" interpretation with classical macro-world. (Bohr)
- QM valid only for micro-world
- time dependence due to classical laws for macro-world

3. Instrumental "Copenhagen" interpretation (e.g. Peres)
- QM only a tool to predict probabilities of measurement outcomes for given measurement preparations
- measurement preparations freely chosen by experimentalists
- experimentalists themselves not described by QM
- free manipulations by experimentalists introduce additional time-dependence

4. Objective collapse (GRW)
- time evolution due to stochastic (observer-independent) wf collapse

5. Hidden variables (Bohm)

- observed physical object is not Ψ
- observed physical object is made of time-dependent "hidden" variables

6. Statistical ensemble (Ballentine)

- Ψ does not describe individual systems
- time-dependence is property of individual systems

7. Consistent histories (Griffiths)

- Ψ is a tool to assign probability to a given history
- the history is time-dependent

8. Many worlds (Everett)

- $\Psi(x_1, \ldots, x_N)$ does not depend on t
- however, x_1 may be position of a clock observable
- the origin of time more subtle than in other interpretations

4.3 Alternatives to non-locality

- Does Bell theorem imply non-locality?
- No, there are many alternatives!
- However, each alternative introduces something very strange
  (perhaps much stranger than non-locality itself)

1. Copenhagen local non-reality
- physics is local, but physics is not about reality

2. many worlds
- reality is not non-local, but also not local (in the 3-space)

3. super-determinism ('t Hooft)
- reality is local and deterministic, but initial conditions are fine tuned

4. backward causation (transactional interpretation)
- reality is local, but there are signals backwards in time

5. consistent histories (Griffiths)
- reality is local, but classical propositional logic is replaced
  by a different logic: (A true) & (B true), but (A & B) not true

6. solipsistic hidden variables (H.N.)
- reality is local, but only observers (not the observed objects) are real

Appendix: Life is an organized disorder

- 2nd law of thermodynamics: order diminishes with time.
- Life: order seems to grow with time.

$\Rightarrow$ Life seems to contradict the 2nd law.

The standard explanation:
- 2nd law: total entropy of the **whole** system must increase
- entropy of a subsystem does not need to increase.
- Life works at the expense of increasing entropy of the environment.

Not satisfying:
- Suppose you see a spontaneous (i.e. without human assistance) assembly of a micro-chip,

accompanied with a large increase of environment entropy.

- Would you be surprised? Of course you would!
- But you should not be, according to the standard explanation.

$\Rightarrow$ Something is missing in this explanation;

- Life is more than a donor of entropy.

Life is a **complex** system $\Rightarrow$ statistical physics is not enough.
- life is a **self-organized** system
- self-organization is **spontaneous**
- means that self-organization is **very likely**

$\Rightarrow$ life evolves towards a **more probable** state
- but more probable state has larger statistical entropy

(far from equilibrium $\Rightarrow$ not the same as thermodynamic entropy)
$\Rightarrow$ statistical entropy increases in life **itself** (not only in its environment)
$\Rightarrow$ life: organization **increases**, but order **decreases**

In a nutshell:
- Organization (complex systems) and order (statistical physics) are not the same.
- **Life is an organized disorder**.

5. CONCLUSION

For interpretations, a short explanation
is sometimes better than a long one
(less is more)