What is Quantum Theory?

Summer School on Physics and Philosophy of Time

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“Here time becomes space.”

“Zum Raum wird hier die Zeit.”

And now for something completely different.

Abstract: Physicists believe that at a fundamental level our world is governed by quantum theory. But despite the fact that quantum theory has been around for almost a century, it remains extremely controversial, and there is little agreement among physicists about its interpretation. There is a good reason for this: it is not at all clear what the physical theory that is quantum theory actually says about the world.

I think I can safely say that nobody understands quantum mechanics. (Richard Feynman, 1965)

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Quantum Mechanics (Part 1)

- N-particle system $\leftrightarrow$ Hilbert space $\mathcal{H}$ $\quad [= L^2(\mathbb{R}^{3N})]$
- state $\leftrightarrow$ $\psi \in \mathcal{H}$ $\quad [\psi = \psi(q) = \psi(\mathbf{q}_1, \ldots, \mathbf{q}_N)]$
- evolution $\leftrightarrow$ Schrödinger's equation

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

$$[\; H = -\sum_{k=1}^{N} \frac{\hbar^2}{2m_k} \Delta_k + V, \qquad \Delta_k = \nabla_k^2 \;]$$

Quantum Mechanics (Part 2)

"Measurement" Postulates

- Observables $\leftrightarrow$ self-adjoint operators A on $\mathcal{H}$

- measurement of A $\leftrightarrow$ spectral measures $\text{Prob}_A^\psi(da)$

$$E^\psi(A) = \langle \psi, A\psi \rangle$$

- measurement of $\underline{A}$ $\leftrightarrow$ spectral measures $\text{Prob}_{\underline{A}}^\psi(d\underline{a})$

$\underline{A} = (A_1, \ldots, A_m), \quad [A_i, A_j] = 0$

$$\text{Prob}_q^\psi(dq) = |\psi(q)|^2$$

- Collapse of the wave function:

$A|\alpha\rangle = \alpha|\alpha\rangle$,

$$\psi = \sum_{\alpha} c_{\alpha}|\alpha\rangle$$

"Measure" A and find a (with probability $|c_a|^2$)

$\Rightarrow$

$$\psi \to |a\rangle$$

What's with the quotes?

"Measurement", "Measure"

I too have many reasons to believe that the present quantum theory, inspite of its many successes, is far from the truth. This theory reminds me a little of the system of delusion of an exceedingly intelligent paranoiac concocted of incoherent elements of thought. (Einstein, 1952; letter to Daniel Lipkin)

With very few exceptions (such as Einstein and Laue) all the rest of the theoretical physicists were unadulterated asses and I was the only sane person left. (Erwin Schrödinger, 1959; letter to John Synge)

In the new, post-1925 quantum theory the ‘anarchist’ position became dominant and modern quantum physics, in its ‘Copenhagen interpretation’, became one of the main standard bearers of philosophical obscurantism. In the *new* theory Bohr’s notorious ‘complementarity principle’ enthroned [weak] inconsistency as a basic ultimate feature of nature, and merged subjectivist positivism and antilogical dialectic and even ordinary language philosophy into one unholy alliance. After 1925 Bohr and his associates introduced a new and unprecedented lowering of critical standards for scientific theories. This led to a defeat of reason within modern physics and to an anarchist cult of incomprehensible chaos. (Lakatos)

What is QT about?

What is real in QT?

?

? ψ ?

?

Is the wave function real (objective, ontic)?

Or does it merely represent our information, our state of knowledge and ignorance—like a probability distribution?

Is the wave function objective or subjective?

Is it ontic or epistemic?

Does the wave function of a physical system provide a complete description of that system?

Does measurement or observation play a fundamental role in QT?

Does measurement create reality?

Does a system have properties before they are measured . . . sometimes, all the time, never?

Does a quantum particle have a position before it is measured?

Should QT be a Quantum Theory Without Observers?

The concept of ‘measurement’ becomes so fuzzy on reflection that it is quite surprising to have it appearing in physical theory at the most fundamental level. ... [D]oes not any analysis of measurement require concepts more fundamental than measurement? And should not the fundamental theory be about these more fundamental concepts? (John Stewart Bell, 1981)

It would seem that the theory is exclusively concerned about "results of measurement", and has nothing to say about anything else. What exactly qualifies some physical systems to play the role of "measurer"? Was the wavefunction of the world waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer, for some better qualified system... with a Ph.D.? If the theory is to apply to anything but highly idealized laboratory operations, are we not obliged to admit that more or less "measurement-like" processes are going on more or less all the time, more or less everywhere. Do we not have jumping then all the time? (John Stewart Bell, 1990)

Is quantum randomness fundamental, or is QT in fact fundamentally deterministic?

What is the status of quantum nonlocality? Is QT local or non-local?

What is missing?

- a clear ontology

- an adequate ontology

- that does the job (correct predictions, explaining observed facts)

... conventional formulations of quantum theory, and of quantum field theory in particular, are unprofessionally vague and ambiguous. Professional theoretical physicists ought to be able to do better. Bohm has shown us a way. (John Stewart Bell)

Bohmian Mechanics

$$\psi = \psi(\mathrm{q}_1, \ldots, \mathrm{q}_N)$$

$$Q: \qquad \mathrm{Q}_1, \ldots, \mathrm{Q}_N$$

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

$$H = -\sum_{k=1}^{N}\frac{\hbar^2}{2m_k}\nabla_k^2 + V,$$

$$\frac{d\mathbf{Q}_k}{dt} = \frac{\hbar}{m_k}\mathrm{Im}\frac{\psi^*\nabla_k\psi}{\psi^*\psi}(\mathbf{Q}_1\ldots,\mathbf{Q}_N)$$

$$p = \hbar k$$

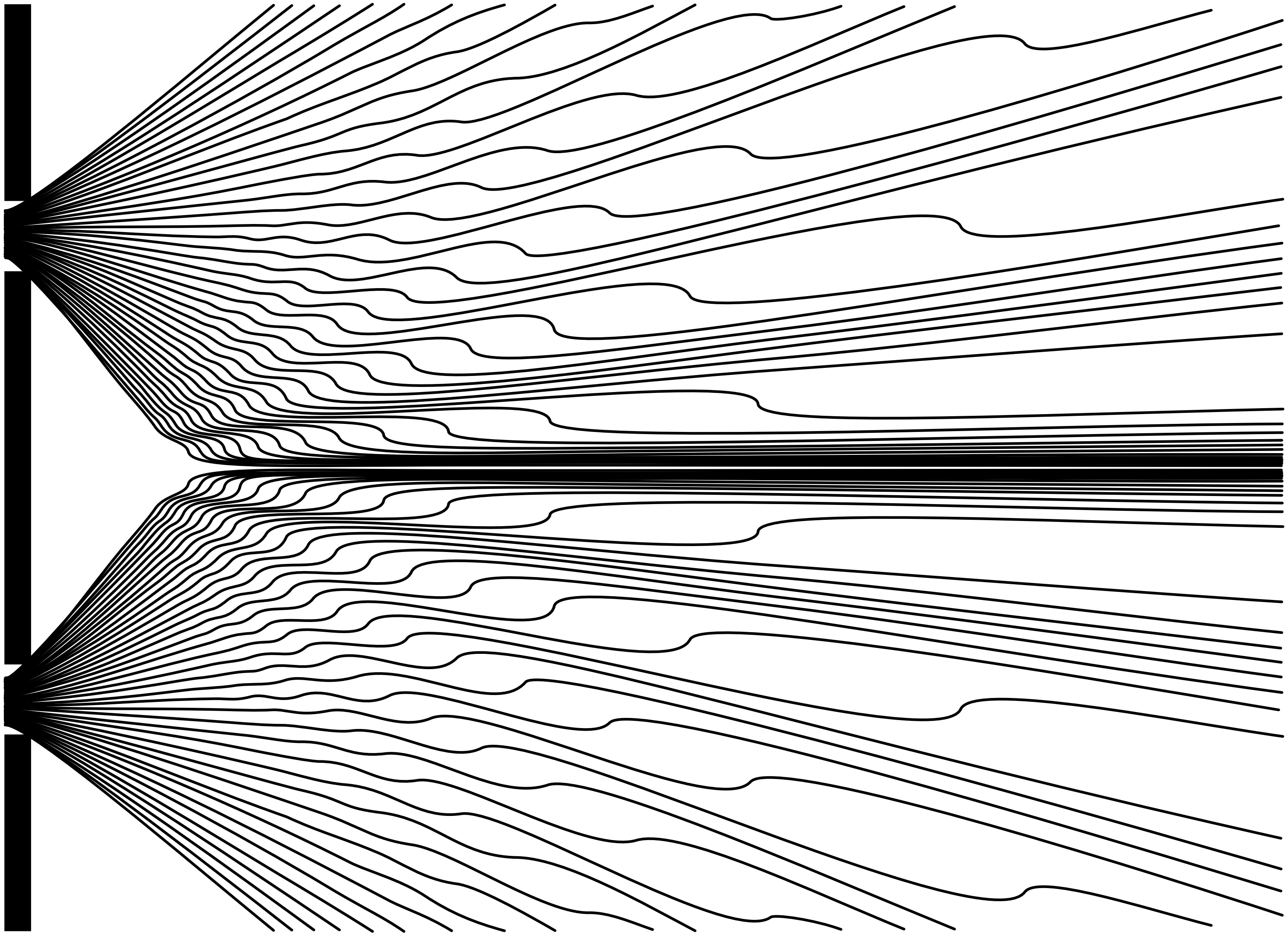
$\nearrow$

time evolution for ψ

$\searrow$

time evolution for Q

$$dQ/dt = \nabla S/m$$



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? De Broglie showed in detail how the motion of a particle, passing through just one of two holes in screen, could be influenced by waves propagating through both holes. And so influenced that the particle does not go where the waves cancel out, but is attracted to where they cooperate. This idea seems to me so natural and simple, to resolve the wave-particle dilemma in such a clear and ordinary way, that it is a great mystery to me that it was so generally ignored. (John Stewart Bell, 1986)

Implications of Bohmian mechanics:

- familiar (macroscopic) reality
- quantum randomness (Dürr, G, Zanghì)
- absolute uncertainty
- operators as observables
- the wave function of a (sub)system
- collapse of the wave packet
- quantum nonlocality

Bohmian Mechanics versus Bohmian Approach

- There is a clear primitive ontology (PO), and it describes matter in space and time.

- There is a state vector ψ in Hilbert space that evolves according to Schrödinger's equation.

- The state vector ψ governs the behavior of the PO by means of (possibly stochastic) laws.

- The theory provides a notion of a *typical* history of the PO (of the universe), for example by a probability distribution on the space of all possible histories; from this notion of typicality the probabilistic predictions emerge.

- The predicted probability distribution of the macroscopic configuration at time t determined by the PO agrees with that of the quantum formalism.

Absurdly, such theories are known as “hidden variable” theories. Absurdly, for there it is not in the wavefunction that one finds an image of the visible world, and the results of experiments, but in the complementary “hidden” (!) variables. Of course the extra variables are not confined to the visible “macroscopic” scale. For no sharp definition of such a scale could be made. The “microscopic” aspect of the complementary variables is indeed hidden from us. But to admit things not visible to the gross creatures that we are is, in my opinion, to show a decent humility, and not just a lamentable addiction to metaphysics. In any case, the most hidden of all variables, in the pilot wave picture, is the wavefunction, which manifests itself to us only by its influence on the complementary variables. (Bell, page 201)