DO WE REALLY UNDERSTAND QUANTUM MECHANICS?

COMPRENONS-NOUS VRAIMENT LA MECANIQUE QUANTIQUE?

VARIOUS INTERPRETATIONS OF QUANTUM MECHANICS

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INTRODUCTION

- Historical summary
- The deterministic dynamics of quantum mechanics
- Relations with macroscopic uniqueness; decoherence

VARIOUS INTERPRETATIONS OF QUANTUM MECHANICS

1. Bohr, von Neumann

2. Pragmatism in laboratories

3. Statistical interpretation, informational interpretation

4. Many other interpretations: modal, relational, transactional, contextual, etc.

5. De Broglie-Bohm (dBB)

6. Modified Schrödinger dynamics

7. Everett

Historical introduction
Three periods

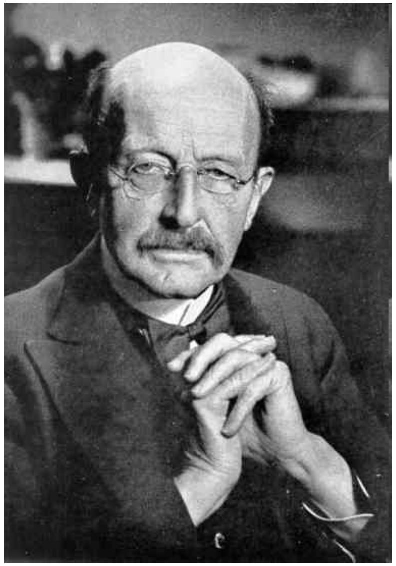
M. Jammer, *The Conceptual Development of Quantum Mechanics*, Mc Graw Hill (1966), second edition (1989)

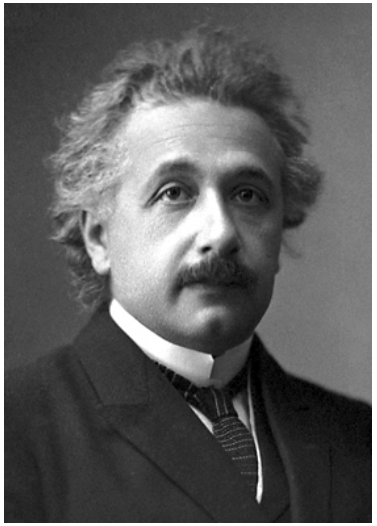
M. Jammer, *The Philosophy of Quantum Mechanics*, Wiley (1974).

O. Darrigol, *From c-numbers to q-numbers : The classical analogy in the history of quantum theory* (Berkeley : University of California Press, 1992)

G. Bacchiagaluppi and A. Valentini, *Quantum Theory at the Crossroads: Reconsidering the 1927 Solvay Conference*, Cambridge University Press (2009).

« Prehistory »: Planck, Einstein, Bohr, Heisenberg





Undulatory period, de Broglie, Schrödinger

Synthesis: Copenhagen and standard interpretations

1. Dynamical equations of quantum mechanics

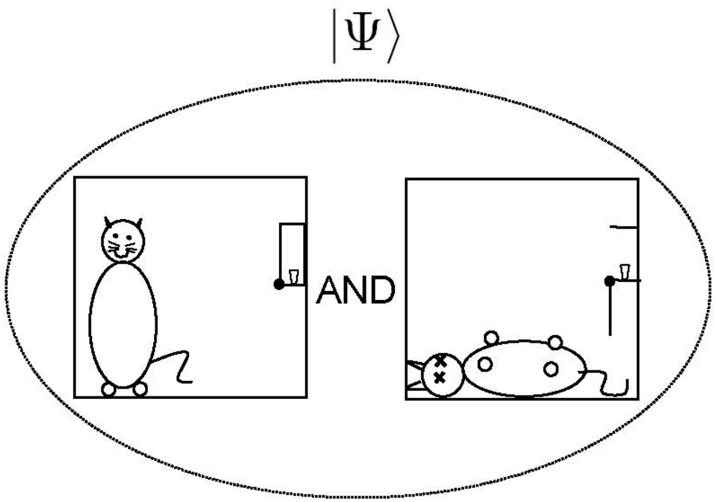
The basic equations of time evolution can take various (equivalent) forms:

- the Schrödinger/von Neumann/ Heisenberg differential equations
- path integral method (Feynman)

They are very nice and useful, even if sometimes they may be extremely difficult to solve (in condensted matter physics for instance). But this is not a fundamental problem, but a challenge: mathematicians and physicists are used to develop approximation methods.

The equations are deterministic. Macroscopic uniqueness does is not a natural consequence of quantum mechanics.

The famous parable of the Schrödinger cat



Schrödinger calls this a « ridiculous case ». To what extent should be take the Schrödinger equation seriously?

Other famous paradoxes: Wigner’s friend, Einstein’s bomb, negative measurements, etc.

The « measurement problem »

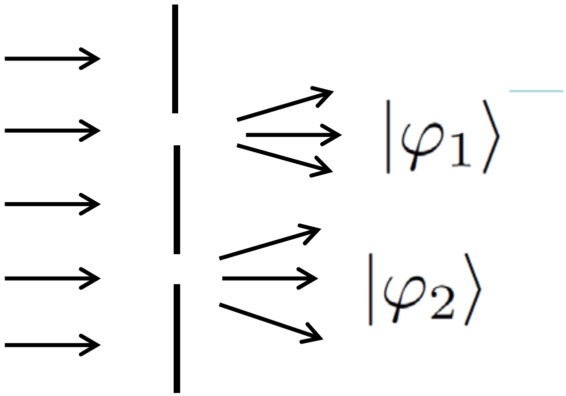
The Schrödinger equations predicts that, at the end of a measurement, the « pointer » may be simultaneously at different locations of space, indicating several results at the same time!

Physics can deal with stochastic noise perturbing the measurements; moreover, fundamentally stochastic dynamical equations are not a problem per se. But if any experiment can give all possible results at the same time, how can we apply the scientific experimental method (Claude Bernard, Francis Bacon, Popper, etc.)?

The observation of (reasonably) well defined position of macroscopic objects seems to be a routine observation. Could it really be that the moon is at the same time at all positions on its orbit around the earth?

So, a general feeling is that something has to be added to the dynamical equations of quantum mechanics, in order to ensure macroscopic uniqueness (or, alternatively, explain why it does not exist).

DECOHERENCE



$$|\Psi\rangle = \alpha\,|\varphi_1\rangle + \beta\,|\varphi_2\rangle$$

$$|\Psi'\rangle = \alpha\,|\varphi_1\rangle\,|\chi_1\rangle + \beta\,|\varphi_2\rangle\,|\chi_2\rangle$$

$$|\Psi''\rangle = \alpha\,|\varphi_1\rangle\,|\chi_1\rangle\,|\theta_1\rangle + \beta\,|\varphi_2\rangle\,|\chi_2\rangle\,|\theta_2\rangle$$

Monogamy of entanglement: if A is completely entangled with B, then B cannot be entangled with C

1. BOHR

The state vector (wave function) alone does not describe physical reality. We can speak of physical reality at our scale, so that it can only be defined in terms of the whole macroscopic experimental apparatus used in the experiment (preparation and measurement).

It has no meaning (it is forbidden!) to try and consider separate physical elements in the whole system (as for instance Einstein, Podolsky and Rosen did).

Wholeness

Contextuality

Non-locality

Consistent history interpretation (Griffiths, Gell-Mann, Omnès, Hohenberg): same general scheme, but more precise than Bohr’s (more descriptions are possible).

VON NEUMANN

Von Neumann treats the measurement as a quantum process (as opposed to Bohr). When S is measured by M1, both get entangled, no definite outcome is obtained. So a second measurement apparatus M2 is used to measure S+M1. But the three just get entangled, and no definite outcome is obtained. etc. One obtains an infinite regress (chain) where macrosocpic uniqueness never appears.

“It is inherently entirely correct that the measurement or the related process of the subjective perception is a new entity relative to the physical environment and is not reducible to the latter”.

“Translation” by Jammer: “It is not possible to formulate the laws of quantum mechanics in a complete and consistent way without a reference to human consciousness”.

An information is gained in a measurement: one must update the information contained in the state vector: $\Longrightarrow$ state vector projection postulate. Often called « collapse of the state vector ».

2. PRAGMATISM IN LABORATORIES

Practicing physicists in laboratories do not really care about the interpretations of quantum mechanics! They have no problem at all using if.

They just apply a combination of quantum mechanics + common sense.

-- Most experiments measure only an average over many individual systems; this average is considered as a classical object, as is the rest of the measurement apparatus. Then the use of the projection postulate is not necessary. In the other cases:

-- When decoherence has propagated sufficiently far in the environement, and when it becomes clear that restoring coherent interference effects has become impossible in practice, one « breaks the von Neumann chain by hand and applies the projection postulate.

This works perfectly well, at least for the moment. The « distance » between the microscopic and macroscopic worlds is so large that the precise point where the projection is made does not matter.

3. STATISTICAL INTERPRETATIONS

- Statistical interpretation (Einstein, Ballentine, etc.)
- Correlation interpretation (Wigner formula, Mermin, etc.)
- Informational (Peres, Parisi, Zeilinger, etc.)

4. OTHER INTERPRETATIONS

- Relational (Rovelli)
- Modal (van Fraassen, Healey)
- Transactional (Cramer)
- Veiled reality (d'Espagnat)
- Logical, algebraic, formal, constructive, etc. (von Neumann, Hilbert, Jauch, Kastler, etc.); Gleason theorem
- Embedded density operators (Balian et al.)
- Contextual (Grangier et al.)
- Propagation of intricacy and incoherence (Omnès)
- etc.

5. DE BROGLIE-BOHM (dBB) INTERPRETATION

The standard wave function is:

$$\Psi\left(\mathbf{r}_1,\mathbf{r}_2,....,\mathbf{r}_N\right)=R\left(\mathbf{r}_1,\mathbf{r}_2,....,\mathbf{r}_N\right)\ e^{i\xi\left(\mathbf{r}_1,\mathbf{r}_2,....,\mathbf{r}_N\right)}$$

It evolves according to the standard Schrödinger equation.

Additional variables are introduced, the dBB positions $\mathbf{q}_i\left(t\right)$

The positions are « guided » by the wave function according to:

$$\frac{d}{dt}\mathbf{q}_i\left(t\right)=\frac{\hbar}{m}\ \overrightarrow{\nabla}_{\mathbf{r}_i}\xi\left(\mathbf{q}_1,\mathbf{q}_2,.,\mathbf{r}_i,...,\mathbf{q}_N\right)\Big|_{\mathbf{r}_i=\mathbf{q}_i}$$

The positions are considered as real physical quantities, which evolve in ordinary 3D space; but they are driven by a wave that propagates in configuration space (hence non-local effects in ordinary space).

DBB INTERPRETATION (2)

The initial distribution at t=0 of the dBB positions is random; in configuration space, it is defined by a probability distribution standard wave function is:

$$D_{dBB} = \left| R\left(\mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_N\right) \right|^2$$

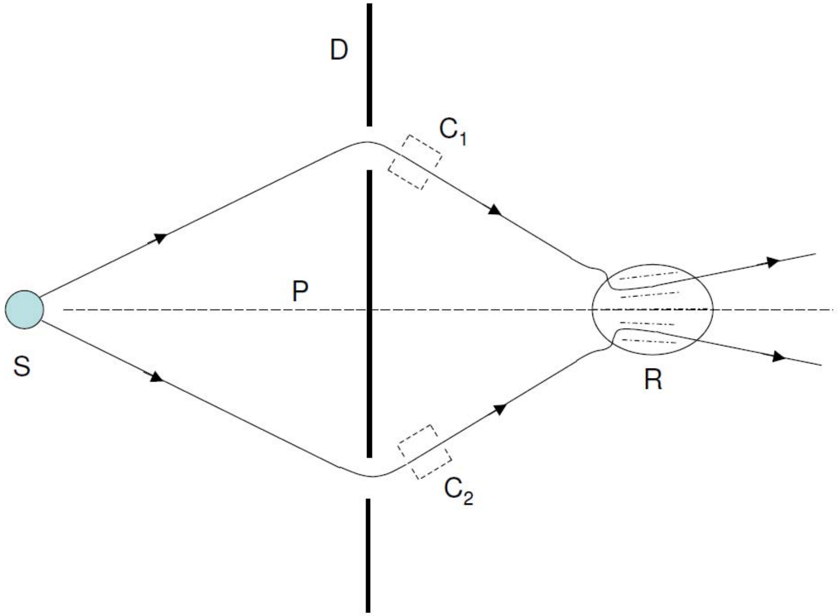
This distribution is equal to the quantum distribution at t=0. One can then show that the two distributions remain equal at all times.

Measurements always end up with a measurement of position (position of the pointer for instance). For all these measurements, the predictions of the dBB theory coincide exactly with those of standard quantum mechanics.

The dBB time evolution is completely deterministic (but starts with completely random positions). The dBB positions can be considered as directly representing physical reality.

DBB INTERPRETATION (3)

An interference experiment



The quantum interference pattern is recovered perfectly. For other cases, see P. Holland, « The quantum theory of motion », Cambridge Univ. Press (1993).

The dBB positions of free particles do not go on straight lines. They follow the diffraction and interference effects of the pilot wave.

6. MODIFIED SCHRÖDINGER DYNAMICS

GRW (Ghirardi, Rimini, Weber)

The wave function is subject to randoms « hits » at all points of space:

$$\left|\Psi'(t)\right\rangle = \frac{F_j\,|\Psi(t)\rangle}{\langle\Psi(t)|\left(F_j\right)^2|\Psi(t)\rangle} \qquad\qquad F_j = c\; e^{-\alpha\left(\mathbf{R}-\mathbf{r}_j\right)^2/2}$$

The probability P per unit time of a hit obeys the « probability rule »:

P= $\lambda\,\langle\Psi(t)|\left(F_j\right)^2|\Psi(t)\rangle$

The Schrödinger wave propagating in configuration space is considered as a field that is physically real. The theory depends on two parameters, a rate λ and a localization length $\alpha^{-1/2}$

MODIFIED SCHRÖDINGER DYNAMICS (2)

CSL (Continuous Spontaneous Localization); P. Pearle

The evolution of the wave function is continuous, but contains random additional terms (Wiener processes) :

$$|\psi(t)\rangle_w = \mathcal{T} e^{-i\int_0^t dt' H(t') - \frac{1}{4\lambda}\int_0^t dt' \int d\mathbf{x}' [w(\mathbf{x}',t') - 2\lambda G(\mathbf{x}')]^2} |\psi(0)\rangle$$

$$G(\mathbf{x}) \equiv \sum_n \frac{m_n}{M} \frac{1}{(\pi a^2)^{3/4}} \int d\mathbf{z} e^{-\frac{1}{2a^2}[\mathbf{x}-\mathbf{z}]^2} \xi_n^\dagger(\mathbf{z}) \xi_n(\mathbf{z})$$

A probability rule is also postulated.

MODIFIED SCHRÖDINGER DYNAMICS (3)

The rate constant λ and localization length $\alpha^{-1/2}$ are chosen in way that ensures that:

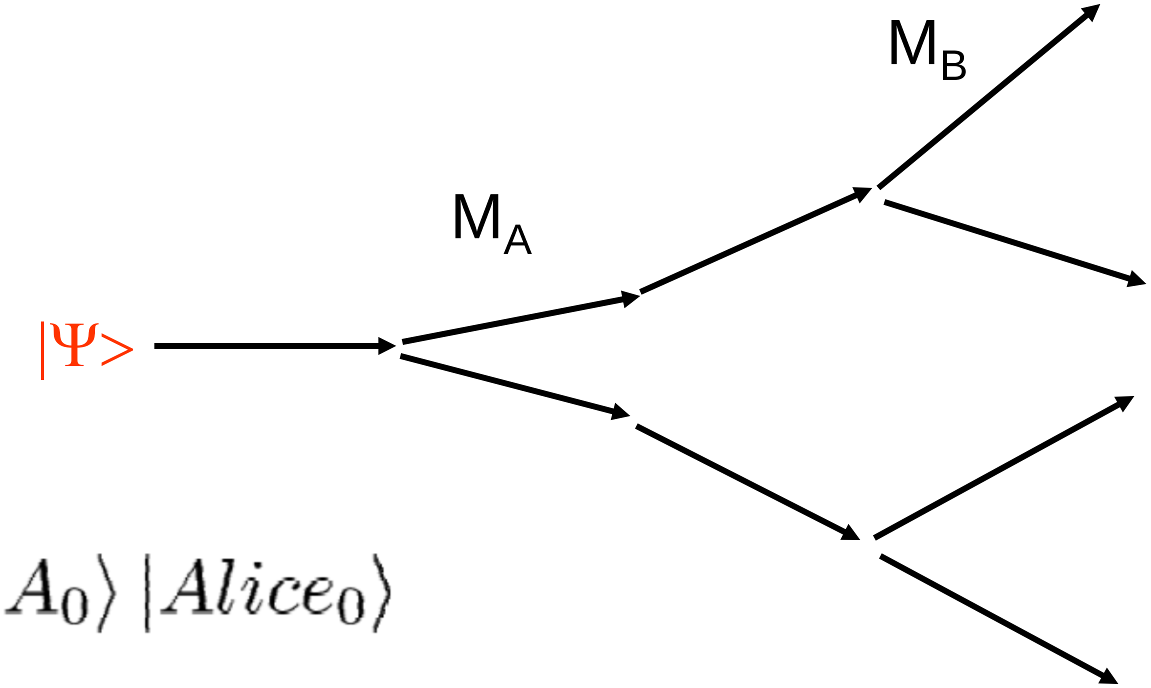
* the evolution of microscopic systems is practically not affected
* superpositions of macroscopically different densities in space are randomly resolved into one of their components.

These theories are not strictly equivalent to standard quantum mechanics. New effects are predicted. For instance, the evolution of mesoscopic systems should be different. Experiments are possible to test these theories.

One can combine the ideas of dBB with those of modified Schrödinger dynamics to obtain a rather nice (and simple) collapse equation.

7. EVERETT INTERPRETATION

(de Witt: « many world interpretation »)



$$|\Psi\rangle = |\varphi_0\rangle\,|A_0\rangle\,|Alice_0\rangle$$

$$|\Psi'\rangle = \alpha'\,|\varphi'_1\rangle\,|A'_1\rangle\,|Alice'_1\rangle + \beta'\,|\varphi'_2\rangle\,|A'_2\rangle\,|Alice'_2\rangle$$

$$|\Psi''\rangle = \sum_{i=1}^{4} \alpha_i\,|\varphi''_i\rangle\,|A''_i\rangle\,|Alice''_i\rangle\,|Bob''_i\rangle$$

CONCLUSION

Yes, we understand how to use quantum mechanics pretty well! It is a fantastic tool that never stops proving its usefulness. It predicts even more than what the founding fathers had in mind (exemple: Bose-Einstein condensates).

No, we are not sure of the best way to interpret it. Many points of view have been proposed, none has really emerged as THE best one.

Those among us who like the idea of a complete change of the notion of physical reality induced by quantum mechanics (in Bohr's line) may adhere to this point of view. The others who prefer a more intuitive point of view may also use it, since none of the many « impossibility theorems » has proved applicable.

It is also possible to remain agnostic. For the moment, the choice of one interpretation or the other remains a matter of personal preference,