Chapter 2
A Brief Survey of Main Interpretations of Quantum Mechanics

Since descriptions and comments on the plethora of various interpretations of quantum mechanics are widely accessible (see, e.g., [1, 2]), we give in this chapter only a very brief survey of the most popular of them. We stress that our presentation and evaluation of various interpretations is highly subjective. In particular, in our opinion ontic determinism precludes the existence of free will, which we treasure, therefore indeterminism is in our opinion a virtue, not a drawback of an interpretation.

The other difficulty in presenting such a brief survey of various interpretations of QM is caused by the fact that most of them are not uniquely defined. We tried in each case to extract a bunch of ideas that could be treated as a “common denominator” by various adherents of an interpretation, but in many cases this occurred to be a difficult task.

It should be also noticed that not all “interpretations of QM” presented in the literature are interpretations in the strict sense of this word, i.e., interpretations of the “bare” mathematical (Hilbert space) formalism of the orthodox quantum theory. In many cases an “interpretation” introduces or at least foresees various modifications of the usual mathematical formalism of QM, so it should be rather called a “theory”. Since in this brief survey we decided to confine to “interpretations of QM” in the strict sense of this word, we do not mention here such important proposals as Ghirardi et al. [3], or other “Objective Collapse Theories”, or “Hidden Variables Interpretations”.

The simplest test that allows to distinguish between an *interpretation* and a *theory* is the existence or nonexistence of experimental proposals that could, at least theoretically, distinguish it from the other ones, since no two interpretations of QM, by the very definition of this notion, could be distinguished in this way. Therefore, if a set of ideas pertaining to QM allows for its experimental discrimination from the other ones, it should be rather called a *theory*, not an *interpretation*. However, in many cases this issue is not settled even among various proponents of a specific interpretation, which causes the issue of filtering out *interpretations* from *theories* an extremely difficult task.

J. Pykacz, *Quantum Physics, Fuzzy Sets and Logic*,
SpringerBriefs in Physics, DOI 10.1007/978-3-319-19384-7_2

2.1 Ensemble Interpretation

Ensemble Interpretation (EI), called also Statistical Interpretation, takes literally Born's probabilistic interpretation of squared modulus of the wave function. Therefore, it assumes that the wave function does not refer to an individual quantum object, but to a statistical ensemble of such "identically prepared" objects. This ensemble can be either meant literally, as it is in the case of myriads of identically prepared photons emitted by a source, or it can be meant "abstractly" as an "imaginary collection" of multiple copies of an individual object. It seems that this interpretation of QM was supported by Einstein who, however, went further and inferred from it that the "orthodox" QM should be supplemented by hidden variables, while in general there is no such assumption in contemporary expositions of the EI. More recently EI was promoted vigorously by Ballentine [4, 5] (see also extensive bibliography at Ulf Klein's website [6]).

Main idea:

- Wave function is an abstract concept that refers to an ensemble of quantum systems. In particular, there does not exist anything like "wave function of an individual quantum system".

Virtues:

- EI is "minimal" in the sense that it does not make use of any metaphysical assumptions.
- No problems with measurements, collapse, Schrödinger's cats, etc.

Drawbacks:

- EI does not satisfy our deep desire for "final answers".
- Impossibility to explain "quantum Zeno effect".

2.2 Copenhagen Interpretation

Out of all interpretations of quantum mechanics proposed up to now, the Copenhagen Interpretation (CI), in spite of being still the most popular (see the results of a poll executed by Schlosshauer et al. [7]), is the worst-defined one. According to Peres [8]: "There seems to be at least as many different Copenhagen Interpretations as people who use that term, probably there are more".

CI has its roots in Bohr's and Heisenberg's ideas elaborated in the town of Copenhagen in the late twenties of the XX century. Nevertheless, the very name "Copenhagen Interpretation" was attached to this bunch of ideas not before than in the fifties. It should be also noticed that ideas usually presented in textbooks as CI are not entirely identical with original ideas of Bohr and Heisenberg which, moreover, were also different from each other in some details.

Main ideas:

- Quantum objects display either wave-like or particle-like properties. It is an experimental arrangement that defines which properties can be observed.
- Quantum mechanics is fundamentally about observations or results of measurements.
- It is meaningless to talk about properties of quantum objects before they are measured.
- Wave function is a mathematical concept. Physical meaning has its squared modulus which, according to Born's rule, defines probabilities of obtaining various experimental results.
- Wave functions evolve in two ways:

  1. Deterministically, according to Schrödinger equation, when no measurement is made.
  2. Indeterministically ("collapse" or "reduction") when measurement is made.

- Hilbert space description of quantum phenomena is the ultimate one. In particular, there are no hidden variables that could explain random behaviour of quantum objects. Therefore, quantum probabilities are ontic, not epistemic.

Virtues:

- Fundamental indeterminism of the quantum world.

Drawbacks:

- Artificial division of the physical world into the quantum world and the classical world.
- The "objectification problem", i.e., a problem how "potential" properties become "actual" in the course of a measurement.

2.3 Pilot-Wave Interpretation

The Pilot-Wave Interpretation (PWI), known also as Causal or Ontological Interpretation, de Broglie–Bohm theory, or Bohmian mechanics, is based on the ideas presented by de Broglie in 1927 in a paper [9] published in *Le Journal de Physique et le Radium* and also presented at the 5th Solvay Conference, and later on rediscovered by Bohm [10]. It seems that the majority of advocates of this interpretation (although not all) maintain that all experimental predictions of the de Broglie–Bohm theory are exactly the same as predictions of the "orthodox" QM, therefore according to them, it is really an *interpretation* of QM in the narrow sense of this word.

Main ideas:

- Both "wave-like" and "particle-like" aspects of quantum objects have simultaneous reality: quantum particles move along definite trajectories guided by their pilot waves. In particular, in a two-slit experiment a particle goes through one slit only but its pilot wave goes through both slits, interferes with itself, and attracts the particle to the areas of constructive interference.

- Pilot waves are represented mathematically by solutions of Schrödinger equation. They never collapse.
- The actual positions of particles are "hidden variables".

Virtues:

- PWI provides a "classical-like", visible and easy to comprehend image of the microworld.
- No measurement problem.

Drawbacks:

- Manifest nonlocality.
- Determinism.

2.4 Many-Worlds Interpretation

The cornerstone of the Many Worlds Interpretation (MWI) was laid down by Hugh Everett III in his PhD thesis [11] (reprinted in [12], see also paper [13] based on this thesis). Nevertheless, it should be noticed that Everett himself never jumped into far-reaching ontological conclusions drawn by his followers, and only stated enigmatically: "*From the present viewpoint all elements of superposition are equally 'real*'" ([12], pp. 116–117).

Actually, the very name MWI and explicit formulation of the idea that "*every quantum transition taking place on every star, in every galaxy, in every remote corner of the universe is splitting our local world on earth into myriads of copies of itself*" is due to DeWitt [14].

Among other distinguished advocates of the MWI are Deutsch [15, 16] and Vaidman [17]. It should be noticed that according to the results of a poll executed by Schlosshauer et al. [7]), the MWI occurred to be the second w.r.t. popularity after the Copenhagen Interpretation.

Main ideas:

- There exists the "basic physical entity": the universal wave function, that never collapses.
- At every "moment of choice": a photon either passes through a semi-transparent mirror or is reflected, Schrödinger's cat is either poisoned or not, a universe that we witness (which is only one copy of myriads of its copies that form the *Multiverse*) splits into separate, equally real copies in which either this or that course of events takes place. Adherents of the MWI are not unanimous whether these different copies can somehow "influence" or "feel the existence" of the others or not.

Virtues:

- Observers and measurements play no special role.
- No problems with collapse.
- According to Vaidman [17] "*The MWI resolves most*, *if not all*, *paradoxes of quantum mechanics*."

Drawbacks:

- Extremely weird ontology.
- The very idea of replacing the unique Universe by myriads of its copies that form the *Multiverse* seems to be in deep contradiction to the idea of the Ockham Razor that successfully guides Western Philosophy for centuries.
- Indeterminism observed in the microworld is only apparent since the universal wave function evolves deterministically.

2.5 Consistent Histories Interpretation

The Consistent Histories Interpretation (CHI) is sometimes proclaimed by its advocates as "Copenhagen done right". It was originated by Griffiths [18, 19], followed by Omnès [20, 21], and by Gell-Mann and Hartle [22] who used the term "decoherent histories". It is based on the notion of a *history* which is thought of as a time-sequence of properties actually possessed by a quantum object in consecutive instants of time. This sequence is mathematically represented by a tensor product of projection operators. Boundles of such histories, called *frameworks* are analogs of sample spaces in classical probability theory, and allow to define on them probabilities that coincide with probabilities yielded by Born's rule. However, it should be stressed that to a specific *framework* belong only histories that are *consistent* in the sense that at any instant of time they do not contain properties represented by non-commuting projectors.

Main ideas:

- Wave function is a tool for calculating probabilities, not a representation of reality.
- Time development of a quantum system is a stochastic process.
- All frameworks are equally "real".
- The *single framework rule*: Any discussion about properties of quantum objects has to be confined to a single framework. Using in the discussion properties that belong to incompatible frameworks is the source of paradoxes.
- Measurements reveal actually existing properties of quantum objects, however a property that exists in some frameworks may not exist in others.

Virtues:

- No measurement problem, no superluminal influences, no paradoxes.
- Fundamental indeterminism.

Drawbacks:

- Highly unclear ontology.
- Actuality of properties depends on the chosen framework (“relativity of reality”).

2.6 Modal Interpretations

The name of this class of interpretations refers to modal logic, i.e., logic capable of taking into consideration sentences expressing necessity, possibility and contingency.

Originally there was a single modal interpretation (MI) of non-relativistic quantum mechanics proposed by van Fraassen [23]. Later on various researchers involved in this line of investigation developed slightly different approaches which, however, are usually collectively called “modal interpretations”.

Characteristic to all MIs is a distinction between the *dynamical state* of a quantum system, which determines what *may* be the case and is just the quantum state of the orthodox QM, and the *value state* which represents all properties that the system actually possesses at a given instant. In various versions of MIs various observables are chosen as “privileged”, i.e., always possessing definite values.

Main ideas:

- The standard formalism of QM, however without the projection postulate, is accepted.
- Quantum systems possess all the time definite properties that define their value states.
- The dynamical state that always evolves according to Schrödinger equation and never collapses defines what the possible properties of a system and their corresponding probabilities are.

Virtues:

- No measurement problem.
- Indeterminism.

Drawbacks:

- Unclear ontology which is, moreover, different in different versions of MIs.

2.7 Relational Quantum Mechanics

The main assumption of Relational Quantum Mechanics (RQM), originated by Rovelli [24], states that QM is not an “absolute” description of reality but rather deals with relations between various objects. Consequently, the notion of “observer-independent” description of the world is declared as being unphysical. Different observers may give different descriptions of the same event. However, it should be noticed that this refers only to "hierarchical" sets of observers: the "prime" observer is O that observes what's going on in an observed system S, the "secondary" observer is P that observes what's going on in a system $S + O$, and so on...

Main ideas:

- All physical systems are, fundamentally, quantum systems.
- QM is a "complete" theory: there are no hidden variables or other items that should be added to it.
- QM is not about properties of objects, but about relations between objects.
- Measurement is an ordinary physical interaction.
- "Absolute" or "observer-independent" state of a quantum system has no meaning.

Virtues:

- Ontological parsimony.
- It is claimed [25] that RQM allows for such reformulation of the original EPR conditions, that apparent conflict between QM and special relativity disappears.

Drawbacks:

- Relativity of properties of physical objects (even if only w.r.t. "hierarchical" set of observers).
- Not clearly stated position w.r.t. the determinism/indeterminism issue.

2.8 Other, Less Popular Interpretations

Seven main interpretations outlined above definitely do not exhaust the list of up to now proposed interpretations of QM. Among the other ones we can mention the following:

- "*Consciousness Causes Collapse*": a rather extreme point of view ascribed to von Neumann [26] and Wigner [27, 28].
- *Many Minds Interpretation* [29, 30]: a "subjective offspring" of MWI, in which the multitude of "parallel universes" is replaced by the multitude of "minds" associated with each sentient being.
- *Transactional Interpretation* [31] in which a quantum event is a result of a "transaction" between advanced (backward-in-time) and retarded (forward-in-time) waves.
- *Information Interpretation* which assumes that "the QM-formalism describes information about micro systems extracted by means of macroscopic measurement devices" [32]. This relatively new interpretation quickly gains popularity and most probably will be considered as belonging to the mainstream soon (see, e.g., [33, 34]).

2.9 Summary

All interpretations of QM presented in this Chapter are based on 2-valued logic.[1] This is not a surprise, taking into account that 2-valued logic successfully guided Western Science for centuries. Actually, till Łukasiewicz there were no alternatives, and even later on many-valued logics wandered on the fringes of the mainstream of Science, and were regarded as a mathematical curiosity with no relation to the physical world.

Most probably to the majority of scientists the idea of going beyond the 2-valued logic in the description of the physical reality is as aberrant as it would be the idea of abandoning Ptolemaic system before the Copernicus or leaving the domain of Euclidean flat geometry before Einstein.

However, the accumulation of "paradoxes" and development of more and more weird interpretations of QM is maybe a sign that this Gordian knot should be cut by transgressing the boundaries encircled by the 2-valued logic. The rest of this work is devoted to the presentation and justification of this proposal.

References

1. *The Stanford Encyclopedia of Philosophy* (Winter 2014 Edition), Edward N. Zalta (ed.), http://plato.stanford.edu/search/searcher.py?query=Interpretation+of+quantum+mechanics.
2. Wikipedia contributors, "Interpretations of quantum mechanics," *Wikipedia, The Free Encyclopedia*, http://en.wikipedia.org/w/index.php?title=Interpretations_of_quantum_mechanics&oldid=623968383 (accessed June 5, 2014).
3. Ghirardi, G. C., A. Rimini, and T. Weber, "A Model for a Unified Quantum Description of Macroscopic and Microscopic Systems", in: L. Accardi et al. (eds) *Quantum Probability and Applications* (Springer, Berlin, 1985).
4. Ballentine, L. E. "The statistical interpretation of quantum mechanics", *Reviews of Modern Physics*, **42** (1970) 358–381.
5. Ballentine, L. E. *Quantum Mechanics: A Modern Development* (World Scientific., Singapore, 1998).
6. Klein, U. *The Statistical Interpretation of Quantum Theory*, version 02, 11. 12. 2012, statintquant.net/siq.html#siqli1.html.
7. Schlosshauer, M., J. Kofler, and A. Zeilinger, "A snapshot of foundational attitudes toward quantum mechanics", arXiv: 1301.1069 [quant-ph].
8. Peres, A. "Karl Popper and the Copenhagen interpretation", *Studies in History and Philosophy of Modern Physics*, **33** (2002) 23–34.
9. de Broglie, L. "Wave mechanics and the atomic structure of matter and of radiation", *Le Journal de Physique et le Radium*, **8** (1927) 225.
10. Bohm, D. "A suggested interpretation of the quantum theory in terms of hidden variables, I" *Physical Review*, **85** (1952) 166–179; and II, **85** (1952) 180–193.
11. Everett, H. *On the Foundations of Quantum Mechanics* (PhD Thesis, Princeton University, 1957). Available online as "The Theory of the Universal Wavefunction" at http://www-tc.pbs.org/wgbh/nova/manyworlds/pdf/dissertation.pdf

[1]Even modal logic, which is a base of modal interpretations, although non-classical and sometimes regarded as a "coarse graining" of many-valued logics, is generally considered as 2-valued logic.

12. DeWitt, B., and R. N. Graham (eds), *The Many-Worlds Interpretation of Quantum Mechanics* (Princeton University Press, Princeton, 1973).
13. Everett, H "Relative state formulation of quantum mechanics". *Reviews of Modern Physics*, **29** (1957) 454–462.
14. DeWitt, B. "Quantum mechanics and reality: Could the solution to the dilemma of indeterminism be a universe in which all possible outcomes of an experiment actually occur?", *Physics Today*, **23** (1970) 30–40.
15. Deutsch, D. "Three experimental implications of the Everett interpretation", in: R. Penrose and C. J. Isham (eds) *Quantum Concepts of Space and Time* (Clarendon Press, Oxford, 1986) 204–214.
16. Deutsch, D. *The Fabric of Reality: The Science of Parallel Universes and Its Implications* (Penguin Books, London, 1998).
17. Vaidman, L. "Many-Worlds Interpretation of Quantum Mechanics", *The Stanford Encyclopedia of Philosophy* (Winter 2014 Edition), Edward N. Zalta (ed.), http://plato.stanford.edu/archives/win2014/entries/qm-manyworlds/.
18. Griffiths, R. "Consistent histories and the interpretation of quantum mechanics", *Journal of Statistical Physics*, **36** (1984) 219–272.
19. Griffiths, R. *Consistent Quantum Theory* (Cambridge University Press, Cambridge, 2002).
20. Omnès, R. "Logical reformulation of quantum mechanics I. Foundations", *Journal of Statistical Physics*, **53** (1988) 893–932.
21. Omnès, R. *Understanding Quantum Mechanics* (Princeton University Press, Princeton, 1999).
22. Gell-Mann, M. and J. Hartle, "Quantum mechanics in the light of quantum cosmology", in: W. Zurek (ed) *Complexity, Entropy, and the Physics of Information* (Addison-Wesley, Reading, Mass., 1990) 425–458.
23. van Fraassen, B. C. "A formal approach to the philosophy of science", in: R. Colodny (ed) *Paradigms and Paradoxes: The Philosophical Challenge of the Quantum Domain* (University of Pittsburgh Press, Pittsburgh, 1972) 303–366.
24. Rovelli, C. "Relational quantum mechanics", *International Journal of Theoretical Physics*, **35** (1996) 1637–1678.
25. Laudisa, F. "The EPR argument in a relational interpretation of quantum mechanics", *Foundations of Physics Letters*, **14** (2001) 119–132.
26. von Neuman, J. *Mathematical Foundations of Quantum Mechanics* (Princeton University Press, Princeton, 1955).
27. Wigner, E. and H. Margenau, "Remarks on the mind body question", *American Journal of Physics*, **35** (1967) 1169–1170.
28. Esfeld, M. "Essay review. Wigner's view of physical reality", *Studies in History and Philosophy of Modern Physics*, **30B** (1999) 145–154.
29. Zeh, H. D. "On the interpretation of measurements in quantum theory", *Foundations of Physics*, **1** (1970) 69–76.
30. Albert, D. and B. Loewer, "Interpreting the many worlds interpretation", *Synthese*, **77** (1988) 195–213.
31. Cramer, J. "The transactional interpretation of quantum mechanics", *Reviews of Modern Physics*, **58** (1986) 647–688.
32. Khrennikov, A. "Växjö interpretation of wave function: 2012", in: A. Khrennikov et al. (eds) *Quantum Theory: Reconsiderations of Foundations 6,* AIP Conference Proceedings **1508** (2012) 244–252.
33. Fuchs, C. "Quantum mechanics as quantum information (and only a little more)" in: A. Khrennikov (ed) *Quantum Theory: Reconsideration of Foundations* (Växjö University Press, Växjö, 2002) 463–543.
34. Zeilinger, A. *Dance of the Photons: From Einstein to Quantum Teleportation* (Farrar, Straus and Giroux, New York, 2010).

Springer

http://www.springer.com/978-3-319-19383-0

Quantum Physics, Fuzzy Sets and Logic
Steps Towards a Many-Valued Interpretation of Quantum Mechanics
Pykacz, J.
2015, VI, 70 p., Softcover
ISBN: 978-3-319-19383-0