# 10.4: Interpretations of Quantum Mechanics

The fact that quantum mechanics is incompatible with local reality, makes it reconciliation with our (classically-bred) "common sense" rather challenging. Here is a brief list of the major interpretations of quantum mechanics, that try to provide at least a partial reconciliation of this kind.

(i) The so-called Copenhagen interpretation - to which most physicists adhere. This "interpretation" does not really interpret anything; it just accepts the intrinsic stochasticity of measurement results in quantum mechanics, and the absence of local reality, essentially saying: "Do not worry; this is just how it is; live with it". I generally subscribe to this school of thought, with the following qualification. While the Copenhagen interpretation implies statistical ensembles (otherwise, how would you define the probability? - see Sec. 1.3), its most frequently stated formulations [34] do not put a sufficient emphasis on their role, in particular on the ensemble re-definition as the only point of human observer's involvement in a nearly-perfect measurement process - see Sec. 1 above. The most famous objection to the Copenhagen interpretation belongs to A. Einstein: "God does not play dice." OK, when Einstein speaks, we all should listen, but perhaps when God speaks (through experimental results), we have to pay even more attention.

(ii) Non-local reality. After the dismissal of J. von Neumann's "proof" by J. Bell, to the best of my knowledge, there has been no proof that hidden parameters could not be introduced, provided that they do not imply the local reality. Of constructive approaches, perhaps the most notable contribution was made by David Joseph Bohm, [35] who developed the initial Louis de Broglie's interpretation of the wavefunction as a "pilot wave", making it quantitative. In the wave-mechanics version of this concept, the wavefunction governed by the Schrödinger equation, just guides a "real", point-like classical particle whose coordinates serve as hidden variables. However, this concept does not satisfy the notion of local reality. For example, the measurement of the particle's coordinate at a certain point $\mathbf{r}_1$ has to instantly change the wavefunction everywhere in space, including the points $\mathbf{r}_2$ in the superluminal range (27). After A. Einstein's private criticism, D. Bohm essentially abandoned his theory. [36]

(iii) The many-world interpretation, introduced in 1957 by Hugh Everitt and popularized in the $1960$ s and $1970$ s by Bruce de Witt. In this interpretation, all possible measurement outcomes do happen, splitting the Universe into the corresponding number of "parallel multiverses", so that from one of them, other multiverses and hence other outcomes cannot be observed. Let me leave to the reader an estimate of the rate at which the parallel multiverses have to be constantly generated (say, per second), taking into account that such generation should take place not only at explicit lab experiments but at every irreversible process - such as fission of every atomic nucleus or an absorption/emission of every photon, everywhere in each multiverse - whether its result is formally recorded or not. Nicolaas van Kampen has called this a "mind-boggling fantasy". [37] Even the main proponent of this interpretation, B. de Witt has confessed: "The idea is not easy to reconcile with common sense." I agree.

(iv) Quantum logic. In desperation, some physicists turned philosophers have decided to dismiss the formal logic we are using - in science and elsewhere. From what (admittedly, very little) I have read about this school of thought, it seems that from its point of view, definite statements like "the SG detector has found the spin to be directed along the magnetic field" should not necessarily be either true or false. OK, if we dismiss the formal logic, I do not know how we can use any scientific theory to make any predictions - until the quantum logic experts tell us what to replace it with. To the best of my knowledge, so far they have not done that. I personally trust the opinion by J. Bell, who certainly gave more thought to these issues: "It is my impression that the whole vast subject of Quantum Logic has arisen $[\ldots]$ from the misuse of a word."

As far as I know, neither of these interpretations has yet provided a suggestion on how it might be tested experimentally to exclude other ones. On the positive side, there is a virtual consensus that quantum mechanics makes correct (if sometimes probabilistic) predictions, which do not contradict any reliable experimental results we are aware of. Maybe, this is not that bad for a scientific theory. [38]

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[34] With certain pleasant exceptions - see, e.g. L. Ballentine, Rev. Mod. Phys. 42, 358 (1970).

[35] D. Bohm, Phys. Rev. $\mathbf{85}, 165; 180$(1952).

[36] See, e.g., Sec. $22.19$ of his (generally very good) textbook D. Bohm, Quantum Theory, Dover, $1979$.

[37] $\mathrm{N}.$ van Kampen, Physica $A153, 97(1988)$ By the way, I highly recommend the very reasonable summary of the quantum measurement issues, given in this paper, though believe that the quantitative theory of dephasing, discussed in Chapter 7 of this course, might give additional clarity to some of van Kampen's statements.

[38] For the reader who is not satisfied with this "positivistic" approach, and wants to improve the situation, my earnest advice is to start not from square one, but from reading what other (including some very clever!) people thought about it. The review collection by J. Wheeler and W. Zurek, cited above, may be a good starting point.

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