Seminar | Interpretations of Quantum Mechanics

Interpretations of probability

A great deal of confusion about quantum mechanics originates from confusion about probability itself. Unbeknownst to most physicists, a great deal has been written by the philosophers about interpretations of probability [1]. Are probabilities just relative frequencies? Then one must explain how to connect that with the usual probability calculus. Or are probabilities better understood as subjective degrees of belief [2]? Then one must explain why probabilistic events like Chernobyl seem pretty much objective. Or maybe objective chances exist after all [3]? Maybe they do, but one must do better than simply postulating that this is the case.

[1] A. Hájek. *Stanford Encyclopedia of Philosophy: Interpretations of Probability*. 2011. URL: `https://plato.stanford.edu/entries/probability-interpret/`.

[2] C. Caves. *Notes on the Dutch Book Argument*. 2000. URL: `http://info.phys.unm.edu/~caves/reports/dutchbook.pdf`.

[3] D. Lewis. "A Subjectivist's Guide to Objective Chance". *Studies in Inductive Logic and Probability*. Ed. by R. Carnap and R. Jeffrey. v. 2. University of California Press, 1980, p. 293. URL: `http://www.andrewmbailey.com/dkl/Subjectivist_Guide.pdf`.

The measurement problem

The central problem in the interpretation of quantum mechanics is the measurement problem [1, 2]: how does one describe physically what happens during a measurement? Does the quantum state evolve according to the projection postulate, in a non-linear, irreversible, non-deterministic way [3], or does it obey the Schrödinger equation, evolving linearly, reversibly, and deterministically [4]? If it is the projection postulate, what is special about measurement apparata, apparently made of atoms, that allows them to escape the domain of the Schrödinger equation? If it is the Schrödinger equation, how do we make sense of quantum states that include superpositions of dead and alive cats, and how do we explain seeing only one measurement outcome? Or maybe none of them is true, and we need new physics to reconcile them [5]?

[1] W. Myrvold. *Stanford Encyclopedia of Philosophy: Philosophical Issues in Quantum Theory*. 2016. URL: `https://plato.stanford.edu/entries/qt-issues/#MeasProb`.

[2] P. Ball. *Quantum common sense*. 2017. URL: `https://aeon.co/essays/the-quantum-view-of-reality-might-not-be-so-weird-after-all`.

[3] W. Heisenberg. "The Copenhagen Interpretation of Quantum Theory". *Physics & Philosophy: the revolution in modern science*. unwin university books, 1955, p. 46. URL: `https://archive.org/download/PhysicsPhilosophy/Heisenberg-PhysicsPhilosophy.pdf`.

[4] H. Everett. “"Relative State" Formulation of Quantum Mechanics”. *Rev. Mod. Phys.* **29** 454–462 (1957).

[5] T. Maudlin. “Three measurement problems”. *Topoi* **14** 7–15 (1995).

Decoherence

Decoherence is not a philosophical problem, it is rather closer to a philosophical solution. It was introduced by Zeh in 1970 in order to explain why we don’t observe superpositions of macroscopically different states [1], and later developed and popularised by Żurek [2]. The reason for the suppression of quantum effects at macroscopic scales is the nigh-unavoidable interaction of large quantum systems with the environment, which effectively erases the *coherence* of the quantum states and thus makes interference impossible [3]. Contrary to popular misconception it is not a complete solution to the measurement problem, as it does not explain why we see a single outcome.

[1] H. D. Zeh. “On the interpretation of measurement in quantum theory”. *Foundations of Physics* **1** 69–76 (1970).

[2] W. H. Zurek. “Pointer basis of quantum apparatus: Into what mixture does the wave packet collapse?” *Phys. Rev. D* **24** 1516–1525 (1981).

[3] C. Kiefer and E. Joos. “Decoherence: Concepts and Examples”. *Quantum Future: From Volta and Como to the Present and Beyond*. Ed. by P. Blanchard and A. Jadczyk. Vol. 517. Lecture Notes in Physics, Berlin Springer Verlag. 1999, p. 105. arXiv:`quant-ph/9803052`.

Bell’s theorem

Intimately related to the measurement problem is the problem of nonlocality, the apparent faster-than-light influence that the collapse of the wavefunction has on distant events. It was noted already at the birth of modern quantum theory in the Solvay conference in 1927, and gained prominence in 1935 when it was formalised by Einstein, Podolsky, and Rosen as the famous EPR paradox [1]. Until 1964, however, it was regarded as a strictly philosophical problem of little physical consequence, until John Bell showed that local theories were in fact in contradiction with the predictions of quantum mechanics [2], which have been since then confirmed experimentally, making nonlocality inescapable. Or is it? A huge amount of literature has developed to examine the assumptions behind Bell’s theorem and so avoid its fateful conclusion. It is so large that I had to write myself a manageable summary in Ref. [3].

[1] A. Einstein, B. Podolsky, and N. Rosen. “Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?” *Phys. Rev.* **47** 777–780 (1935).

[2] J. S. Bell. “On the Einstein-Poldolsky-Rosen paradox”. *Physics* **1** 195–200 (1964). URL: `https://cds.cern.ch/record/111654/files/vol1p195-200_001.pdf`.

[3] M. Araújo. *Understanding Bell’s theorem*. 2016. URL: `http://mateusaraujo.info/2016/07/15/understanding-bells-theorem-part-1-the-simple-version/`.

The Copenhagen interpretation

The Copenhagen interpretation of quantum mechanics is not a single interpretation, but rather an amalgam of ideas developed mainly by Bohr and Heisenberg in the 1920s that for a long time formed the core of the "orthodox" interpretation of quantum mechanics. It was first systematized only in 1955 by Heisenberg in Ref. [1] as a reaction to the introduction of alternative interpretations. More confusingly, it changed a lot since then as the most controversial ideas of the founding fathers lost favour in the scientific community, and its current form is often called neo-Copenhagen interpration, of which a good exposition can be found in Ref. [2].

Here we are, however, interested in the historical Copenhagen interpretation with its main concepts such as Bohr's complementarity, Heisenberg's cut, and von Neumann's wavefunction collapse.

Here we are interested in understanding the ideas that were historically defended by the Copenhageners and their flaws, so modern contributions that reject the most controversial ideas but still call themselves Copenhageners are explicitly off-topic.

[1] W. Heisenberg. "The Copenhagen Interpretation of Quantum Theory". *Physics & Philosophy: the revolution in modern science*. unwin university books, 1955, p. 46. URL: `https://archive.org/download/PhysicsPhilosophy/Heisenberg-PhysicsPhilosophy.pdf`.

[2] Č. Brukner. "On the quantum measurement problem" (2015). arXiv:`1507.05255 [quant-ph]`.

Collapse models

Collapse models take seriously the idea that a wavefunction collapse happens in the measurement process, and tries to model this physically, by modifying the Schrödinger equation so that macroscopic systems spontaneously collapse [1]. Because of this they have the dubious honour of being the only interpretations of quantum mechanics which actually have empirical consequences which are different from the standard theory [2]. Independently of the issue of experimental falsification (which might conceivably go in favour of collapse models, with Earth-shattering consequences), collapse models have internal problems such as the problem of tails, which is the fact that the collapse cannot make the wavefunction be identically zero outside a given region.

[1] G. Ghirardi. *Stanford Encyclopedia of Philosophy: Collapse Theories*. 2016. URL: `https://plato.stanford.edu/entries/qm-collapse/`.

[2] A. Bassi, K. Lochan, S. Satin, T. P. Singh, and H. Ulbricht. "Models of wave-function collapse, underlying theories, and experimental tests". *Rev. Mod. Phys.* **85** 471–527 (2013). arXiv:`1204.4325 [quant-ph]`.

Bohmian mechanics

Introduced in 1952, Bohmian mechanics was the first fully fleshed-out example of a *hidden-variable* theory: a theory that supplements quantum theory with additional variables that makes its dynamics deterministic even in the measurement process [1]. Previously thought to be an impossibility (due to a foolish theorem proved by von Neumann), this development came as a shock and caused a flurry of activity in developing other interpretations. Arguably its greatest success was not to restore determinism, but to solve the measurement problem and thus provide a theory capable in principle of describing the whole Universe. This success comes, though, at a high price: the values of the hidden variables cannot be usefully discovered, and their (hidden) dynamics grossly violate locality [2]. More recently, the theory was subject to criticism that the dynamics of the hidden variables have no physical consequence, and thus that Bohmian mechanics is just the Many-Worlds interpretation in disguise [3, 4].

[1] D. Bohm. “A Suggested Interpretation of the Quantum Theory in Terms of “Hidden” Variables. I”. *Phys. Rev.* **85** 166–179 (1952).

[2] J. S. Bell. “On the problem of hidden variables in quantum mechanics”. *Rev. Mod. Phys.* **38** 447–452 (1966).

[3] H. R. Brown and D. Wallace. “Solving the Measurement Problem: De Broglie–Bohm Loses Out to Everett”. *Found. Phys.* **35** 517–540 (2005). arXiv:`quant-ph/0403094`.

[4] A. Valentini. “De Broglie-Bohm Pilot-Wave Theory: Many Worlds in Denial?” (2008). arXiv:`0811.0810 [quant-ph]`.

The Many-Worlds interpretation

The Many-Worlds interpretation of quantum mechanics, introduced in 1957 by Hugh Everett in his PhD thesis [1, 2], proposed a radical solution to the measurement problem: the superposition of macroscopic states predicted by the Schrödinger equation to occur after a measurement was simply reality. Each member of the superposition corresponded to a equally-real world, and thus the Universe was in a process of never-ending branching [3]. His proposal was met with open derision by the scientific community and Everett quit physics after a disastrous meeting with Bohr.

There is, nevertheless, legitimate criticism to be made against the Many-Worlds interpretation. Historically the most important one, which pretty much killed the interpretation until the 1980s, was the preferred basis problem: given the universal wave function, in which basis do we write it so that the members of the superposition correspond to the many quasi-classical worlds? The way originally done by Everett was essentially by fiat, saying that this was the basis in which measurements were done. This is rather unsatisfactory, as a measurement is a high-level object that should have no place in the fundamental physics. The current view is that decoherence picks out such a preferred basis [4].

Another problem, of a more psychological taste, is of how to make sense of probabilities in a deterministically branching world [5]. It was controversially claimed to be solved by the Deutsch-Wallace theorem [6–9].

[1] H. Everett. “"Relative State" Formulation of Quantum Mechanics”. *Rev. Mod. Phys.* **29** 454–462 (1957).

[2] H. Everett. “The Theory of the Universal Wavefunction”. PhD thesis. (1956,1973). URL: `https://www.pbs.org/wgbh/nova/manyworlds/pdf/dissertation.pdf`.

[3] D. Wallace. *The Emergent Multiverse: Quantum Theory According to the Everett Interpretation*. Oxford University Press, 2012. ISBN: 9780199546961.

[4] D. Wallace. “Decoherence and Ontology, or: How I Learned To Stop Worrying And Love FAPP” (2011). arXiv:`1111.2189`.

[5] S. Saunders. “Chance in the Everett interpretation” (2016). arXiv:`1609.04720 [quant-ph]`.

[6] D. Deutsch. “Quantum theory of probability and decisions”. *Proc. R. Soc. Lond. A* **455** 3129 (1999). arXiv:`quant-ph/9906015`.

[7] D. Wallace. “Everettian Rationality: defending Deutsch’s approach to probability in the Everett interpretation”. *Stud. Hist. Phil. Sci. B* **34** 415–439 (2003). arXiv:`quant-ph/0303050`.

[8] D. Wallace. “Quantum probability from subjective likelihood: Improving on Deutsch’s proof of the probability rule”. *Stud. Hist. Phil. Sci. B* **38** 311–332 (2007). arXiv:`quant-ph/0312157`.

[9] A. Kent. “One world versus many: the inadequacy of Everettian accounts of evolution, probability, and scientific confirmation” (2009). arXiv:`0905.0624 [quant-ph]`.

Quantum Bayesianism

The new kid on the block of interpretations is Quantum Bayesianism, introduced in 2002 by Caves, Fuchs, and Schack [1], and given a more well-rounded presentation by Fuchs, Mermim, and Schack in 2014 [2]. It is based on the idea that probabilities only make sense if taken as subjective degrees of belief, and since a quantum state is nothing but a collection of probabilities, it must itself be a subjective degree of belief. In this way it allows different agents to assign incompatible quantum states to the same physical system, as it is ok for subjective degrees of belief to differ. As a consequence, however, it cannot talk about an objective reality shared by different agents.

[1] C. M. Caves, C. A. Fuchs, and R. Schack. “Quantum probabilities as Bayesian probabilities”. *Phys. Rev. A* **65,** 022305 022305 (2002). arXiv:`quant-ph/0106133`.

[2] C. A. Fuchs, N. D. Mermin, and R. Schack. “An introduction to QBism with an application to the locality of quantum mechanics”. *Am. J. Phys.* **82** 749–754 (2014). arXiv:`1311.5253 [quant-ph]`.