Summary of common interpretations of quantum mechanics

Classification adopted by Einstein

An interpretation (i.e. a semantic explanation of the formal mathematics of quantum mechanics) can be characterized by its treatment of certain matters addressed by Einstein, such as:

- Realism
- Completeness
- Local realism
- Determinism

To explain these properties, we need to be more explicit about the kind of picture an interpretation provides. To that end we will regard an interpretation as a correspondence between the elements of the mathematical formalism **M** and the elements of an interpreting structure **I**, where:

- The *mathematical formalism* **M** consists of the Hilbert space machinery of ket-vectors, self-adjoint operators acting on the space of ket-vectors, unitary time dependence of the ket-vectors, and measurement operations. In this context a measurement operation is a transformation which turns a ket-vector into a probability distribution (for a formalization of this concept see quantum operations).
- The *interpreting structure* **I** includes states, transitions between states, measurement operations, and possibly information about spatial extension of these elements. A measurement operation refers to an operation which returns a value and might result in a system state change. Spatial information would be exhibited by states represented as functions on configuration space. The transitions may be non-deterministic or probabilistic or there may be infinitely many states.

The crucial aspect of an interpretation is whether the elements of **I** are regarded as physically real. Hence the bare instrumentalist view of quantum mechanics outlined in the previous section is not an interpretation at all, for it makes no claims about elements of physical reality.

The current usage of realism and completeness originated in the 1935 paper in which Einstein and others proposed the EPR paradox.[12] In that paper the authors proposed the concepts *element of reality* and the *completeness of a physical theory*. They characterised element of reality as a quantity whose value can be predicted with certainty before measuring or otherwise disturbing it, and defined a complete physical theory as one in which every element of physical reality is accounted for by the theory. In a semantic view of interpretation, an interpretation is complete if every element of the interpreting structure is present in the mathematics. Realism is also a property of each of the elements of the maths; an element is real if it corresponds to something in the interpreting structure. For example, in some interpretations of quantum mechanics (such as the many-worlds interpretation) the ket vector associated to the system state is said to correspond to an element of physical reality, while in other interpretations it is not.

Determinism is a property characterizing state changes due to the passage of time, namely that the state at a future instant is a function of the state in the present (see time evolution). It may not always be clear whether a particular interpretation is deterministic or not, as there may not be a clear choice of a time parameter. Moreover, a given theory may have two interpretations, one of which is deterministic and the other not.

Local realism has two aspects:

- The value returned by a measurement corresponds to the value of some function in the state space. In other words, that value is an element of reality;
- The effects of measurement have a propagation speed not exceeding some universal limit (e.g. the speed of light). In order for this to make sense, measurement operations in the interpreting structure must be localized.

A precise formulation of local realism in terms of a local hidden variable theory was proposed by John Bell.

Bell's theorem, combined with experimental testing, restricts the kinds of properties a quantum theory can have, the primary implication being that quantum mechanics cannot satisfy both the principle of locality and counterfactual definiteness.

The Copenhagen interpretation

Main article: Copenhagen interpretation

The Copenhagen interpretation is the "standard" interpretation of quantum mechanics formulated by Niels Bohr and Werner Heisenberg while collaborating in Copenhagen around 1927. Bohr and Heisenberg extended the probabilistic interpretation of the wavefunction proposed originally by Max Born. The Copenhagen interpretation rejects questions like "where was the particle before I measured its position?" as meaningless. The measurement process randomly picks out exactly one of the many possibilities allowed for by the state's wave function in a manner consistent with the well-defined probabilities that are assigned to each possible state. According to the interpretation, the interaction of an observer or apparatus that is external to the quantum system is the cause of wave function collapse, thus according to Paul Davies, "reality is in the observations, not in the electron".[13] What collapses in this interpretation is the knowledge of the observer and not an "objective" wavefunction.

Many worlds

Main article: Many-worlds interpretation

The many-worlds interpretation is an interpretation of quantum mechanics in which a universal wavefunction obeys the same deterministic, reversible laws at all times; in particular there is no (indeterministic and irreversible) wavefunction collapse associated with measurement. The phenomena associated with measurement are claimed to be explained by decoherence, which occurs when states interact with the environment producing entanglement, repeatedly "splitting" the universe into mutually unobservable alternate histories—effectively distinct universes within a greater multiverse. In this interpretation the wavefunction has objective reality.

Consistent histories

Main article: Consistent histories

The consistent histories interpretation generalizes the conventional Copenhagen interpretation and attempts to provide a natural interpretation of quantum cosmology. The theory is based on a consistency criterion that allows the history of a system to be described so that the probabilities for each history obey the additive rules of classical probability. It is claimed to be consistent with the Schrödinger equation.

According to this interpretation, the purpose of a quantum-mechanical theory is to predict the relative probabilities of various alternative histories (for example, of a particle).

Ensemble interpretation, or statistical interpretation

Main article: Ensemble interpretation

The ensemble interpretation, also called the statistical interpretation, can be viewed as a minimalist interpretation. That is, it claims to make the fewest assumptions associated with the standard mathematics. It takes the statistical interpretation of Born to the fullest extent. The interpretation states that the wave function does not apply to an individual system – for example, a single particle – but is an abstract statistical quantity that only applies to an ensemble (a vast multitude) of similarly prepared systems or particles. Probably the most notable supporter of such an interpretation was Einstein:

> The attempt to conceive the quantum-theoretical description as the complete description of the individual systems leads to unnatural theoretical interpretations, which become immediately unnecessary if one accepts the interpretation that the description refers to ensembles of systems and not to individual systems.
>
> — *Einstein in Albert Einstein: Philosopher-Scientist, ed. P.A. Schilpp (Harper & Row, New York)*

The most prominent current advocate of the ensemble interpretation is Leslie E. Ballentine, professor at Simon Fraser University, author of the graduate level text book *Quantum Mechanics, A Modern Development*. An experiment illustrating the ensemble interpretation is provided in Akira Tonomura's Video clip 1.[14] It is evident from this double-slit experiment with an ensemble of individual electrons that, since the quantum mechanical wave function (absolutely squared) describes the *completed* interference pattern, it must describe an ensemble. A new version of the ensemble interpretation that relies on a reformulation of probability theory was introduced by Raed Shaiia.[15][16]

De Broglie–Bohm theory

Main article: De Broglie–Bohm theory

The de Broglie–Bohm theory of quantum mechanics is a theory by Louis de Broglie and extended later by David Bohm to include measurements. Particles, which always have positions, are guided by the wavefunction. The wavefunction evolves according to the Schrödinger wave equation, and the wavefunction never collapses. The theory takes place in a single space-time, is non-local, and is deterministic. The simultaneous determination of a particle's position and velocity is subject to the usual uncertainty principle constraint. The theory is considered to be a hidden variable theory, and by embracing non-locality it satisfies Bell's inequality. The measurement problem is resolved, since the particles have definite positions at all times.[17] Collapse is explained as phenomenological.[18]

Relational quantum mechanics

Main article: Relational quantum mechanics

The essential idea behind relational quantum mechanics, following the precedent of special relativity, is that different observers may give different accounts of the same series of events: for example, to one observer at a given point in time, a system may be in a single, "collapsed" eigenstate, while to another observer at the same time, it may be in a superposition of two or more states. Consequently, if quantum mechanics is to be a complete theory, relational quantum mechanics argues that the notion of "state" describes not the observed system itself, but the relationship, or correlation, between the system and its observer(s). The state vector of conventional quantum mechanics becomes a description of the correlation of some *degrees of freedom* in the observer, with respect to the observed system. However, it is held by relational quantum mechanics that this applies to all physical objects, whether or not they are conscious or macroscopic. Any "measurement event" is seen simply as an ordinary physical interaction, an establishment of the sort of correlation discussed above. Thus the physical content of the theory has to do not with objects themselves, but the relations between them.[19][20]

An independent relational approach to quantum mechanics was developed in analogy with David Bohm's elucidation of special relativity,[21] in which a detection event is regarded as establishing a relationship between the quantized field and the detector. The inherent ambiguity associated with applying Heisenberg's uncertainty principle is subsequently avoided.[22]

Transactional interpretation

Main article: Transactional interpretation

The transactional interpretation of quantum mechanics (TIQM) by John G. Cramer is an interpretation of quantum mechanics inspired by the Wheeler–Feynman absorber theory.[23] It describes a quantum interaction in terms of a standing wave formed by the sum of a retarded (forward-in-time) and an advanced (backward-in-time) wave. The author argues that it avoids the philosophical problems with the Copenhagen interpretation and the role of the observer, and resolves various quantum paradoxes.

Stochastic mechanics

Main article: Stochastic interpretation

An entirely classical derivation and interpretation of Schrödinger's wave equation by analogy with Brownian motion was suggested by Princeton University professor Edward Nelson in 1966.[24] Similar considerations had previously been published, for example by R. Fürth (1933), I. Fényes (1952), and Walter Weizel (1953), and are referenced in Nelson's paper. More recent work on the stochastic interpretation has been done by M. Pavon.[25] An alternative stochastic interpretation[26] was developed by Roumen Tsekov.

Objective collapse theories

Main article: Objective collapse theory

Objective collapse theories differ from the Copenhagen interpretation in regarding both the wavefunction and the process of collapse as ontologically objective. In objective theories, collapse occurs randomly ("spontaneous localization"), or when some physical threshold is reached, with observers having no special role. Thus, they are realistic, indeterministic, no-hidden-variables theories. The mechanism of collapse is not specified by standard quantum mechanics, which needs to be extended if this approach is correct, meaning that Objective Collapse is more of a theory than an interpretation. Examples include the Ghirardi-Rimini-Weber theory[27] and the Penrose interpretation.[28]

Consciousness causes collapse

Main article: Consciousness causes collapse

In his treatise *The Mathematical Foundations of Quantum Mechanics*, John von Neumann deeply analyzed the so-called measurement problem. He concluded that the entire physical universe could be made subject to the Schrödinger equation (the universal wave function). He also described how measurement could cause a collapse of the wave function.[29] This point of view was prominently expanded on by Eugene Wigner, who argued that human experimenter consciousness (or maybe even dog consciousness) was critical for the collapse, but he later abandoned this interpretation.[30][31]

Variations of the consciousness causes collapse interpretation include:

Subjective reduction research

This principle, that consciousness causes the collapse, is the point of intersection between quantum mechanics and the mind/body problem; and researchers are working to detect conscious events correlated with physical events that, according to quantum theory, should involve a wave function collapse; but, thus far, results are inconclusive.[32][33]

Participatory anthropic principle (PAP)

Main article: Anthropic principle

John Archibald Wheeler's participatory anthropic principle says that consciousness plays some role in bringing the universe into existence.[34]

Other physicists have elaborated their own variations of the consciousness causes collapse interpretation; including:

- Henry P. Stapp (*Mindful Universe: Quantum Mechanics and the Participating Observer*)
- Bruce Rosenblum and Fred Kuttner (*Quantum Enigma: Physics Encounters Consciousness*)
- Amit Goswami (*The Self-Aware Universe*)

Many minds

Main article: Many-minds interpretation

The many-minds interpretation of quantum mechanics extends the many-worlds interpretation by proposing that the distinction between worlds should be made at the level of the mind of an individual observer.

Quantum logic

Main article: Quantum logic

Quantum logic can be regarded as a kind of propositional logic suitable for understanding the apparent anomalies regarding quantum measurement, most notably those concerning composition of measurement operations of complementary variables. This research area and its name originated in the 1936 paper by Garrett Birkhoff and John von Neumann, who attempted to reconcile some of the apparent inconsistencies of classical boolean logic with the facts related to measurement and observation in quantum mechanics.

Quantum information theories

Quantum informational approaches[35] have attracted growing support.[36][5] They subdivide into two kinds[37]

- Information ontologies, such as J. A. Wheeler's "it from bit". These approaches have been described as a revival of immaterialism[38]
- Interpretations where quantum mechanics is said to describe an observer's knowledge of the world, rather than the world itself. This approach has some similarity with Bohr's thinking.[39] Collapse (also known as reduction) is often interpreted as an observer acquiring information from a measurement, rather than as an objective event. These approaches have been appraised as similar to instrumentalism.

> The state is not an objective property of an individual system but is that information, obtained from a knowledge of how a system was prepared, which can be used for making predictions about future measurements. ...A quantum mechanical state being a summary of the observer's information about an individual physical system changes both by dynamical laws, and whenever the observer acquires new information about the system through the process of measurement. The existence of two laws for the evolution of the state vector...becomes problematical only if it is believed that the state vector is an objective property of the system...The "reduction of the wavepacket" does take place in the consciousness of the observer, not because of any unique physical process which takes place there, but only because the state is a construct of the observer and not an objective property of the physical system[40]

Modal interpretations of quantum theory

Modal interpretations of quantum mechanics were first conceived of in 1972 by B. van Fraassen, in his paper "A formal approach to the philosophy of science." However, this term now is used to describe a larger set of models that grew out of this approach. The Stanford Encyclopedia of Philosophy describes several versions:[41]

- The Copenhagen variant
- Kochen-Dieks-Healey Interpretations
- Motivating Early Modal Interpretations, based on the work of R. Clifton, M. Dickson and J. Bub.

Time-symmetric theories

Several theories have been proposed which modify the equations of quantum mechanics to be symmetric with respect to time reversal.[42][43][44][45][46][47] (E.g. see Wheeler-Feynman time-symmetric theory). This creates retrocausality: events in the future can affect ones in the past, exactly as events in the past can affect ones in the future. In these theories, a single measurement cannot fully determine the state of a system (making them a type of hidden variables theory), but given two measurements performed at different times, it is possible to calculate the exact state of the system at all intermediate times. The collapse of the wavefunction is therefore not a physical change to the system, just a change in our knowledge of it due to the second measurement. Similarly, they explain entanglement as not being a true physical state but just an illusion created by ignoring retrocausality. The point where two particles appear to "become entangled" is simply a point where each particle is being influenced by events that occur to the other particle in the future.

Not all advocates of time-symmetric causality favour modifying the unitary dynamics of standard quantum mechanics. Thus a leading exponent of the two-state vector formalism, Lev Vaidman, highlights how well the two-state vector formalism dovetails with Hugh Everett's many-worlds interpretation.[48]

Branching space-time theories

BST theories resemble the many worlds interpretation; however, "the main difference is that the BST interpretation takes the branching of history to be a feature of the topology of the set of events with their causal relationships... rather than a consequence of the separate evolution of different components of a state vector."[49] In MWI, it is the wave functions that branches, whereas in BST, the space-time topology itself branches. BST has applications to Bell's theorem, quantum computation and quantum gravity. It also has some resemblance to hidden variable theories and the ensemble interpretation: particles in BST have multiple well defined trajectories at the microscopic level. These can only be treated stochastically at a coarse grained level, in line with the ensemble interpretation.[49]

Other interpretations

Main article: Minority interpretations of quantum mechanics

As well as the mainstream interpretations discussed above, a number of other interpretations have been proposed which have not made a significant scientific impact for whatever reason. These range from proposals by mainstream physicists to the more occult ideas of quantum mysticism.

Comparison of interpretations

The most common interpretations are summarized in the table below. The values shown in the cells of the table are not without controversy, for the precise meanings of some of the concepts involved are unclear and, in fact, are themselves at the center of the controversy surrounding the given interpretation. For another table comparing interpretations of quantum theory, see reference.[50]

No experimental evidence exists that distinguishes among these interpretations. To that extent, the physical theory stands, and is consistent with itself and with reality; difficulties arise only when one attempts to "interpret" the theory. Nevertheless, designing experiments which would test the various interpretations is the subject of active research.

Most of these interpretations have variants. For example, it is difficult to get a precise definition of the Copenhagen interpretation as it was developed and argued about by many people.

Interpretation	Author(s)	Deterministic?	Wavefunction real?	Unique history?	Hidden variables?	Collapsing wavefunctions?	Obs ro
Ensemble interpretation	Max Born, 1926	Agnostic	No	Yes	Agnostic	No	N
Copenhagen interpretation	Niels Bohr, Werner Heisenberg, 1927	No	No1	Yes	No	Yes2	Ca
de Broglie–Bohm theory	Louis de Broglie, 1927, David Bohm, 1952	Yes	Yes3	Yes4	Yes	No	N
Quantum logic	Garrett Birkhoff, 1936	Agnostic	Agnostic	Yes5	No	No	Interpre
Time-symmetric theories	Satosi Watanabe, 1955	Yes	Yes	Yes	Yes	No	N
Many-worlds interpretation	Hugh Everett, 1957	Yes	Yes	No	No	No	N
Consciousness causes collapse	Eugene Wigner, 1961	No	Yes	Yes	No	Yes	Ca
Stochastic interpretation	Edward Nelson, 1966	No	No	Yes	Yes14	No	N
Many-minds interpretation	H. Dieter Zeh, 1970	Yes	Yes	No	No	No	Interpre
Consistent	Robert B.	No	No	No	No	No	N

Interpretation	Author(s)	Deterministic?	Wavefunction real?	Unique history?	Hidden variables?	Collapsing wavefunctions?	Obs ro
histories	Griffiths, 1984						
Transactional interpretation	John G. Cramer, 1986	No	Yes	Yes	No	Yes8	N
Objective collapse theories	Ghirardi–Rimini–Weber, 1986, Penrose interpretation, 1989	No	Yes	Yes	No	Yes	N
Relational interpretation	Carlo Rovelli, 1994	Agnostic	No	Agnostic9	No	Yes10	Intri
QBism	Christopher Fuchs, Ruediger Schack, 2010	No	No16	Agnostic17	No	Yes18	Intri

- [1] According to Bohr, the concept of a physical state independent of the conditions of its experimental observation does not have a well-defined meaning. According to Heisenberg the wavefunction represents a probability, but not an objective reality itself in space and time.
- [2] According to the Copenhagen interpretation, the wavefunction collapses when a measurement is performed.
- [3] Both particle AND guiding wavefunction are real.
- [4] Unique particle history, but multiple wave histories.
- [5] But quantum logic is more limited in applicability than Coherent Histories.
- [6] Quantum mechanics is regarded as a way of predicting observations, or a theory of measurement.
- [7] Observers separate the universal wavefunction into orthogonal sets of experiences.
- [8] In the TI the collapse of the state vector is interpreted as the completion of the transaction between emitter and absorber.
- [9] Comparing histories between systems in this interpretation has no well-defined meaning.
- [10] Any physical interaction is treated as a collapse event relative to the systems involved, not just macroscopic or conscious observers.
- [11] The state of the system is observer-dependent, i.e., the state is specific to the reference frame of the observer.
- [12] The transactional interpretation is explicitly non-local.
- [13] The assumption of intrinsic periodicity is an element of non-locality consistent with relativity as the periodicity varies in a causal way.
- [14] In the stochastic interpretation is not possible to define velocities for particles, i.e. the paths are not smooth. Moreover, to know the motion of the particles at any moment, you

have to know what the Markov process is. However, once we know the exactly initial conditions and the Markov process, the theory is in fact a realistic interpretation of quantum mechanics.

- [15] The kind of non-locality required by the theory, sufficient to violate the Bell inequalities, is weaker than that assumed in EPR. In particular, this kind non-locality is compatible with no signaling theorem and Lorentz invariance.
- [16] A wavefunction merely encodes an agent's expectations for future experiences. It is no more real than a probability distribution is in subjective Bayesianism.
- [17] Quantum theory is a tool any agent may use to help manage their expectations. The past comes into play only insofar as an agent's individual experiences and temperament influence their priors.
- [18] Although QBism would eschew this terminology. A change in the wavefunction that an agent ascribes to a system as a result of having an experience represents a change in his or her beliefs about further experiences they may have. See Doxastic logic.
- [19] Observers, or more properly, participants, are as essential to the formalism as the systems they interact with.

See also

- Afshar experiment
- Bohr–Einstein debates
- Glossary of quantum philosophy
- Macroscopic quantum phenomena
- Path integral formulation
- Philosophical interpretation of classical physics
- Quantum gravity
- Quantum Zeno effect

References

1.

- Vaidman, L. (2002, March 24). Many-Worlds Interpretation of Quantum Mechanics. Retrieved March 19, 2010, from Stanford Encyclopedia of Philosophy: http://plato.stanford.edu/entries/qm-manyworlds/#Teg98
- *Frank J. Tipler (1994). The Physics of Immortality: Modern Cosmology, God, and the Resurrection of the Dead. Anchor Books. ISBN 978-0-385-46799-5*. A controversial poll mentioned in found that of 72 "leading cosmologists and other quantum field theorists", 58% including Stephen Hawking, Murray Gell-Mann, and Richard Feynman supported a many-worlds interpretation ["Who believes in many-worlds?", *Hedweb.com*, Accessed online: 24 Jan 2011].
- *Quantum theory as a universal physical theory*, by David Deutsch, International Journal of Theoretical Physics, Vol 24 #1 (1985)
- *Three connections between Everett's interpretation and experiment Quantum Concepts of Space and Time*, by David Deutsch, Oxford University Press (1986)

- *Schlosshauer, Maximilian; Kofler, Johannes; Zeilinger, Anton (2013-01-06). "A Snapshot of Foundational Attitudes Toward Quantum Mechanics". Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics. **44** (3): 222–230. arXiv:1301.1069. doi:10.1016/j.shpsb.2013.04.004.*
- For a discussion of the provenance of the phrase "shut up and calculate", see *Mermin, N. David (2004). "Could feynman have said this?". Physics Today. **57** (5): 10. doi:10.1063/1.1768652.*
- Dirac, P.A.M. (1987). 'The inadequacies of quantum field theory', pp. 194–198 in *Paul Adrien Maurice Dirac*, edited by B. N. Kursunoglu and E. P. Wigner, Cambridge University Press, Cambridge UK
- F. J. Duarte, *Quantum Optics for Engineers* (CRC, New York, 2014).
- Meinard Kuhlmann, "Physicists debate whether the world is made of particles or fields—or something else entirely", *Scientific American*, 24 Jul 2013.
- Guido Bacciagaluppi, "The role of decoherence in quantum mechanics", *The Stanford Encyclopedia of Philosophy* (Winter 2012), Edward N Zalta, ed.
- *La nouvelle cuisine*, by John S Bell, last article of Speakable and Unspeakable in Quantum Mechanics, second edition.
- *Einstein, A.; Podolsky, B.; Rosen, N. (1935). "Can quantum-mechanical description of physical reality be considered complete?". Phys. Rev. **47**: 777–780. doi:10.1103/physrev.47.777.*
- http://www.naturalthinker.net/trl/texts/Heisenberg,Werner/Heisenberg,%20Werner%20-%20Physics%20and%20philosophy.pdf
- *"An experiment illustrating the ensemble interpretation". Hitachi.com. Retrieved 2011-01-24.*
- *Shaiia, Raed M. (9 February 2015). "On the Measurement Problem". International Journal of Theoretical and Mathematical Physics. **4**: 202–219. doi:10.5923/j.ijtmp.20140405.04.*
- https://sites.google.com/site/physicsraedshaiia/publications
- *Maudlin, T. (1995). "Why Bohm's Theory Solves the Measurement Problem". Philosophy of Science. **62**: 479–483. doi:10.1086/289879.*
- *Durr, D.; Zanghi, N.; Goldstein, S. (Nov 14, 1995). "Bohmian Mechanics as the Foundation of Quantum Mechanics ". arXiv:quant-ph/9511016.* Also published in *J.T. Cushing; Arthur Fine; S. Goldstein (17 April 2013). Bohmian Mechanics and Quantum Theory: An Appraisal. Springer Science & Business Media. pp. 21–43. ISBN 978-94-015-8715-0.*
- *"Relational Quantum Mechanics (Stanford Encyclopedia of Philosophy)". Plato.stanford.edu. Retrieved 2011-01-24.*
- For more information, see *Carlo Rovelli (1996). "Relational Quantum Mechanics". International Journal of Theoretical Physics. **35** (8): 1637–1678. arXiv:quant-ph/9609002. Bibcode:1996IJTP...35.1637R. doi:10.1007/BF02302261.*
- David Bohm, *The Special Theory of Relativity*, Benjamin, New York, 1965
- See relational approach to wave-particle duality. For a full account see *Zheng, Qianbing; Kobayashi, Takayoshi (1996). "Quantum Optics as a Relativistic Theory of Light"* (PDF).

Physics Essays. **9** (3): 447. doi:10.4006/1.3029255. Also, see Annual Report, Department of Physics, School of Science, University of Tokyo (1992) 240.

- *"Quantum Nocality – Cramer". Npl.washington.edu. Retrieved 2011-01-24.*
- *Nelson, E (1966). "Derivation of the Schrödinger Equation from Newtonian Mechanics". Phys. Rev.* ***150****: 1079–1085. doi:10.1103/physrev.150.1079.*
- *Pavon, M. (2000). "Stochastic mechanics and the Feynman integral". J. Math. Phys.* ***41****: 6060–6078. doi:10.1063/1.1286880.*
- *Roumen Tsekov (2012). "Bohmian Mechanics versus Madelung Quantum Hydrodynamics". Ann. Univ. Sofia, Fac. Phys.* ***SE****: 112–119. arXiv:0904.0723. Bibcode:2012AUSFP..SE..112T.*
- *"Frigg, R. GRW theory" (PDF). Retrieved 2011-01-24.*
- *"Review of Penrose's Shadows of the Mind". Thymos.com. 1999. Archived from the original on 2001-02-09. Retrieved 2011-01-24.*
- von Neumann, John. (1932/1955). *Mathematical Foundations of Quantum Mechanics*. Princeton: Princeton University Press. Translated by Robert T. Beyer.
- [Michael Esfeld, (1999), "Essay Review: Wigner's View of Physical Reality", published in *Studies in History and Philosophy of Modern Physics*, 30B, pp. 145–154, Elsevier Science Ltd.]
- *Zvi Schreiber (1995). "The Nine Lives of Schrödinger's Cat". arXiv:quant-ph/9501014.*
- Dick J. Bierman and Stephen Whitmarsh. (2006). *Consciousness and Quantum Physics: Empirical Research on the Subjective Reduction of the State Vector.* in Jack A. Tuszynski (Ed). **The Emerging Physics of Consciousness**. p. 27-48.
- *Nunn, C. M. H.; et al. (1994). "Collapse of a Quantum Field may Affect Brain Function. '". Journal of Consciousness Studies'.* ***1*** *(1): 127–139.*
- *"- The anthropic universe". Abc.net.au. 2006-02-18. Retrieved 2011-01-24.*
- *"In the beginning was the bit". New Scientist. 2001-02-17. Retrieved 2013-01-25.*
- *Kate Becker (2013-01-25). "Quantum physics has been rankling scientists for decades". Boulder Daily Camera. Retrieved 2013-01-25.*
- Information, Immaterialism, Instrumentalism: Old and New in Quantum Information. Christopher G. Timpson
- Timpson,Op. Cit.: "Let us call the thought that information might be the basic category from which all else flows informational immaterialism."
- "Physics concerns what we can say about nature". (Niels Bohr, quoted in Petersen, A. (1963). The philosophy of Niels Bohr. *Bulletin of the Atomic Scientists*, 19(7):8–14.)
- *Hartle, J. B. (1968). "Quantum mechanics of individual systems". Am. J. Phys.* ***36*** *(8): 704–712. doi:10.1119/1.1975096.*
- *"Modal Interpretations of Quantum Mechanics". Stanford Encyclopedia of Philosophy. Science.uva.nl. Retrieved 2011-01-24.*
- *Watanabe, Satosi (1955). "Symmetry of physical laws. Part III. Prediction and retrodiction". Reviews of Modern Physics.* ***27*** *(2): 179–186. doi:10.1103/revmodphys.27.179.*

- *Aharonov, Y.; et al. (1964). "Time Symmetry in the Quantum Process of Measurement". Phys. Rev. **134**: B1410–1416. doi:10.1103/physrev.134.b1410.*
- Aharonov, Y. and Vaidman, L. "On the Two-State Vector Reformulation of Quantum Mechanics." *Physica Scripta*, Volume T76, pp. 85-92 (1998).
- *Wharton, K. B. (2007). "Time-Symmetric Quantum Mechanics". Foundations of Physics. **37** (1): 159–168. doi:10.1007/s10701-006-9089-1.*
- *Wharton, K. B. (2010). "A Novel Interpretation of the Klein–Gordon Equation". Foundations of Physics. **40** (3): 313–332. doi:10.1007/s10701-009-9398-2.*
- *Heaney, M. B. (2013). "A Symmetrical Interpretation of the Klein–Gordon Equation". Foundations of Physics. **43**: 733–746. doi:10.1007/s10701-013-9713-9.*
- Yakir Aharonov, Lev Vaidman: *The Two-State Vector Formalism of Quantum Mechanics: an Updated Review.* In: Juan Gonzalo Muga, Rafael Sala Mayato, Íñigo Egusquiza (eds.): *Time in Quantum Mechanics*, Volume 1, Lecture Notes in Physics 734, pp. 399–447, 2nd ed., Springer, 2008, ISBN 978-3-540-73472-7, DOI 10.1007/978-3-540-73473-4_13, arXiv:quant-ph/0105101v2 (submitted 21 May 2001, version of 10 June 2007), p. 443
- Sharlow, Mark; "What Branching Spacetime might do for Physics" p.2
- *Olimpia,, Lombardi,; 1979-, Fortin, Sebastian,; Federico,, Holik,; Cristian,, López,. What is quantum information? (PDF). ISBN 9781107142114. OCLC 965759965.*

51. *Smerlak, Matteo; Rovelli, Carlo (2007-03-01). "Relational EPR". Foundations of Physics. **37** (3): 427–445. doi:10.1007/s10701-007-9105-0. ISSN 0015-9018.*

https://en.wikipedia.org/wiki/Interpretations_of_quantum_mechanics