# No Only God Play Dice: Philosophy of Quantum Nonlocality

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**ABSTRACT**

Quantum entanglement and non locality are the essence of quantum mechanics, in this paper, we argue from a philosophical point of view, the relationship between quantum entanglement and non-locality.

**Key Words:** Philosophy of Quantum Mechanics, Entanglement, Interpretations of Quantum Mechanics, Non-Locality

**DOI Number: 10.14704/nq.2018.16.9.1369** **NeuroQuantology 2018; 16(9):20-27**

## Introduction

### Quantum Nonlocality After Bell: Not only does God play dice, but he plays with nonlocal dice

From experimental point of view until 1990 no one paid much attention to quantum nonlocality. But in the 1990's two things changed. First, a conceptual breakthrough happened thanks to Ekert and to his adviser Deutsch (Deutsch, 1985). They showed that quantum nonlocality could be exploited to establish a cryptographic key between two distant partners and that the confidentiality of the key could be tested by means of Bell's inequality. This was the first time that someone suggested that quantum nonlocality is not only real, but that it could even be of some use. Today, according Gisin (Gisin,2005, 2015), we can say that "**not only does God play dice, but he plays with nonlocal dice!**". According Gisin, QM predicts the existence of a totally new kind of correlation that will never have any kind of mechanical explanation. And experiments confirm this: Nature is able to produce the same randomness at several locations, possibly space-like separated. The standard explanation is "entanglement", but this is just a word, with a precise technical definition. Still words are useful to name objects and concepts. However, it remains to understand the concept. Entanglement is a new explanation for correlations. Quantum correlations simply happen. Entanglement appears at the same conceptual level as local causes and effects. It is a primitive concept, not reducible to local causes and effects. Entanglement describes "correlations without "correlata" in a holistic view. In other worlds, **quantum correlation is not a correlation between 2 events, but a single event that manifests itself at 2 locations**. Historically this was part of the suspicion that entanglement was not really real, nothing more than some exotic particles that live for merely a tiny fraction of a second. But today we see a growing number of remarkable experiments mastering entanglement. In few words, entanglement exists and is going to affect future technology. **It is a radically new concept, requiring new words and a new conceptual category**.

From foundational point of view, years after Bell demonstrated the need for quantum nonlocality, theoreticians continued to ask about a relationship between the structures described by QM and local reality. Żukowski (Żukowski and Brukner 2002) and Brukner (Brukner *et al.*, 2004).

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**Relevant conflicts of interest/financial disclosures:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.
**Received:** 06 April 2018; **Accepted:** 31 July 2018

(Institute for Experimental Physics, Vienna) notes, "No local realistic theory agrees with all predictions of QM as quantitatively expressed by violation of Bell's inequalities. Local realism [...] is based on everyday experience and classical physics [...] and supposes that measurement results are predetermined by the properties the particles carry prior to and independent of observations. Locality supposes that these results are independent of any action at ßpacelike separations". After Bell, quantum nonlocality was the practical basis for quantum computing and quantum cryptography. In 1967, Simon Kochen and Ernst Specker (Kochen and Specker 1990) developed a strong position against Bohmian and similar hidden variable arguments for interpreting QM as deterministic. Kochen and Specker showed that the apparently QM equivalent statistical results of Bohmian hidden variables "do not take into account the algebraic structure of quantum observables. Kochen-Specker advanced the position that QM mathematics represented probabilities instead of physical reality. The Kochen-Specker proof demonstrates the impossibility of Einstein's assumption, made in the famous EPR paper, that quantum mechanical observables represent "elements of physical reality". More generally does the theorem exclude hidden variable theories requiring elements of physical reality to be noncontextual (i.e. independent of the measurement arrangement).

In 1982, Aspect (at the Institut d'Optique in Paris) and co-workers verified Bell's theory of inequalities. A pair of photons created as a single decay event was emitted by the source. They traveled in opposite directions for a distance until they hit variable polarizers, the results of their interaction with the polarizers was recorded at each end. When the outcome was analyzed, the results verified QM nonlocality and showed a correlation that could not be supported by hidden variables A few years later (1986), Ghiraldi, Rimini, and Weber (Ghirardi *et al*., 2005) proposed a solution to the collapse and nonlocality problem by changing QM. Their approach allows the quantum state of a QS to develop according to Schrodinger's equation. At random instants, development stops and the quantum state spontaneously collapses into a single local state. But like Bohm's formulation, GRW assumes instantaneity. Random collapses occurs faster superluminally, violating Special Relativity (SR).

In 1997, Zeilinger (at the University of Innsbruck in Austria) and collaborators conducted a "quantum teleportation." The essential information contained within one of two entangled photons was transmitted instantaneously over a distance, materializing in the form of a third photon identical to the first. At the same instant, the first photon disappeared. Again, the influence causing the nonlocal change occurred at a superluminal speed. Quantum nonlocality is now empirically verified.

## Interpretations of Non-Locality

Some theoreticians argue that property theory has a role in interpreting quantum phenomena. Others suggest that quantum nonlocality may be interpreted as a holistic, nonseparable relational issue.

Summarizing Einstein's famous objection to entanglement, in the EPR paper, Richard Healey (Healey, 1989) reminds us that he assumed a classical physics understanding of the state of a whole system as combining individual component states, not adding something. Fifty years after EPR, Howard (Howard, 2007) equivalently restates the EPR principle as "The real state of the pair AB consists precisely of the real state of A and the real state of B, which states have nothing in to do with one another". In this EPR-like perspective, there is no supervenience of the whole system upon its components. Because the EPR deduction of nonlocal entanglement implies supervenience and contradicts separability, the paper argued that some unknowns (Bohm's "hidden variables") are missing in QM. Healey finds convincing explanations of quantum nonlocality as either "metaphysical property holism" or ßpatiotemporal nonseparability." The former implies that an entangled system is more than the sum of its parts. As EPR stressed, the whole (quantum state) seems to determine values of some of its parts. This threat to state separability was öne reason why Einstein denied that a QS's real state is given by its quantum state. This leads, according to Healey, to "physical property holism." The composite determines the state of its components.

In Healey's view, "nonseparability" can be interpreted as possibly varying magnetic field values extending "between" theoretically separated points in spacetime. And, he notes that yet-to-be-proven string theory does not eliminate the quantum nonseparability problem. Esfeld (Esfeld 2004, 2015) develops a metaphysical interpretation of physical relations which significantly diminishes or eliminates a role for intrinsic properties in QM. For Esfeld, QM presents



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us with two alternatives: "either physical phenomenon have unknown intrinsic properties or they are only relations. QM inclines us to the second view. "Quantum theory supports metaphysics of relations by speaking against intrinsic properties on which the relations [...] supervene.

"Esfeld proposes a "metaphysics of relations that dismisses intrinsic properties of relata which are a supervenience basis for the relations." He points to Wheeler's "geometrodynamics" (1962) which described everything as configurations of the "four-dimensional continuum." Although, as Esfeld notes, Wheeler's scheme was later rejected as incomplete, it does demonstrate that we can have a relational model of objects such as particles and quantum states "without intrinsic properties."

A few theoreticians suggest that there is no space between apparently separated entangled particles. For example, Brian Greene (Greene, 2005) notes that:

"space cannot be thought of as [...] intervening space[....] (distance) does not ensure that two objects are separate [.. .][because of] entanglement."

Karakostas (Karakostas, 2006) interprets quantum nonlocality holistically. Although quantum level interaction produces entanglement, entanglement itself does not require interaction. According Karakistas, entanglement: "does occur in the absence of any interactions [...] entangled correlations among the states of various physical systems do not acquire the status of a causally dependent relation [...] their delineation is rather determined by the entangled quantum state itself which refers directly to the whole system. [This is] a genuine quantum mechanical instance of holism: there exist properties of entangled quantum systems which [...] characterize the whole system but are neither reducible to nor implied by or causally dependent on the local properties of its parts."

The parts of an entangled system depend upon the whole rather than the reverse. Karakostas additionally argues that: "physical systems are realized as context-dependent. Quantum entities are not "things-in-themselves." Their wholeness is mind-independent and "veiled" from perception. "Any discussion concerning [...] whole is necessarily [...] ontological, metaphysical[...] the only confirmatory element about it [is] the network of interrelations which connect its events."

Richard Healey finds that nonlocal entangled systems can be interpreted holistically: "When one performs measurements of spin or polarization on certain separated quantum systems. The results ... exhibit patterns of statistical correlation that resist traditional causal explanation."

These correlations suggest ßpatiotemporal non-separability.

Berkovitz-Hemmo (Berkovitz-Hemmo, 2005 ) argue that quantum phenomena can be interpreted from a "relational modal" perspective. They claim that this point of view enables them to ßolve the measurement problem and [...] reconciles QM with the special theory of relativity." In the process, they reject local properties and argue that entities should be viewed in **terms of relations**. The assumption of a local property was basic to the EPR argument for QM incompleteness. Esfeld argues that QE necessitates relational descriptions. The empirical verification of entanglement (for example, Aspect *et al*., 1982) **means that there are no individual intrinsic properties of entangled particles**, instead there are önly correlations between the conditional probability distributions of the state-dependent properties of the quantum systems." In addition, the relation of hidden variables to the components of an entangled system "requires intrinsic properties on which these correlations supervene. Relational quantum mechanics (RQM) restates several basic QM principles. From an RQM perspective, a statement about a quantum event such as "A has a value x" must be rephrased as "A has the value x for B." By itself, "A has a value x" is meaningless. Discussing the impact of Bell's Inequalities on a hidden variables interpretation, Esfeld finds that "Bell's theorem does not rule out hidden variables that satisfy separability[....] If (we postulate) hidden variables that establish a causal connection with any of these [explanations: superluminal, backwards causation, or a joint cause], then [these] hidden variables [...] provide for intrinsic properties which are a supervenience basis for the correlations Esfeld finds that David Mermin's interpretation of QM which presents a "world of correlations without describing intrinsic properties of the correlate" is reasonable but unempirical. Instead, Esfeld finally argues that we must accept the empirically given evidence of QM and not expect additional factors. Filk (Filk, 2006) tries to avoid the nonlocal implications of Bell's Inequalities and finds "hidden variable" explanations feasible. Arguing that QM



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entanglement may be interpreted as local, he points out that "the wave function itself is interpreted as encoding the 'nearest neighbor' local relations between a QS and spatial points." This means that spatial position is ä purely relational concept[...] a new perspective onto quantum mechanical formalism where many weird aspects, like particle-wave duality, nonlocality of entanglement, and the 'mystery' of the double-slit experiment, disappear. This perspective circumvents the restrictions set by Bell's inequalities [...] a possible (realistic) hidden variable theory based on these concepts can be local and at the same time reproduce the results of QM "

Similarly, we could say that accurate probabilistic predictions of measurement results for an entangled pair can be made without specifying the separating distance between the members of the pair. Focusing on the relations between the members of the pair, enables us to more acceptably express a hidden variable explanation for the now-local entanglement phenomena. This non-spatial or a-spatial perspective can be seen in another relational approach to quantum theory explained by Rovelli (Rovelli, 1998) and Laudisa (Laudisa and Rovelli 2010) and as one that "discards the notions of absolute state of a system, absolute value of its physical quantities, or absolute event[s] [...] [and] describes [...] the way systems affect each other [...] in physical interactions. The physical content of quantum theory is [...] the net of relations connecting all different physical systems. Bitbol (Bitbol, 1998) suggests that these theories could be naturalistic if they focus on relations as the collective probabilistic prediction several physical observers. However these relational QM views are held by a minority. Conventional interpretations (e.g., Copenhagen) of quantum theory accepted the predictions of EPR and welcomed the probabilistic verification of nonlocality in Bell's theorem. However, their explanations for QM nonlocality vary:

- Nonlocality is an integral feature of QM.
- Nonlocality indicates geometric relational acausality
- Nonlocal effects are atemporal
- Apparently nonlocal events are actually local
- There are superluminal causal links
- Nonlocal quantum events are relations between causal processes.

Each approach attempts to resolve philosophic questions raised by QM nonlocality. Some of these views are summarized above.

*Nonlocality is Integral to Quantum Reality*

Many theoreticians assume that entanglement involves no "hidden variables" and there are no undetected connections (e.g., no Bohmian "pilot wave") between distantly entangled particles." Bohr, Heisenberg, and many others accepted the predictions of EPR as consistent with QM.

*Nonlocal Events are Atemporal*

Recent articles by Suarez (Suarez, 2001, 2003, 2012) and others at the Center for Quantum Philosophy in Zurich (articles published in the Physical Letters) suggest that nonlocality necessitates timelessness. "Experiments with moving beam-splitters demonstrate that there is no real time ordering behind the nonlocal correlations. In Bell's world there is no 'before' or 'after.'" A few suggest that measurement notifications travel instantly across distances separating entangled particles. Entangled particles can be subject to a superluminal causal link. According to Ray-Murray, "It may be possible to avoid the [EPR] paradoxes [...] while accepting the existence of superluminal causal links [...] because we have no real control over the links. We cannot, for instance, use them to send superluminal signals of any kind." Mauldin (Rutgers University) also finds that "Superluminal signals must[...] propagate into the past: the signal is received before it is sent. The conditions required for the possibility of such paradoxes are more complex than merely the existence of superluminal signals. Accordingly, violations of Bell's inequality predicted by QM do not allow superluminal signals. [However] even though nature may not allow superluminal signally, it does employ, according to Bell, superluminal causation [...] this will pressure us to add more structure to space-time than Relativity says there is." Here, relativity theory is not challenged because no signal passes between the separated, entangled particles. However, Barbour interprets Aspect's experimental results as evidence of superluminal, causal contact. But a deeply troubled John Bell wrote the verified superluminal causal effect of nonlocal entanglement was "for me[.. .]the real problem of quantum theory.

## Entanglement vs non-locality?

**Despite these important advances, it was still only a handful of physicists who were deeply interested in entanglement. Philosophers of physics recognized the importance of entanglement and Bell's work, but many continued to think of entanglement as an äll or nothing" phenomenon and described entanglement as simply a spooky action-at-a-distance or mysterious holism.** In the last two decades new discoveries, many of which are associated with the investigation of quantum information, have shown that much philosophical and foundational work remains to be done to deepen our understanding of entanglement and non-locality.

Toward the end of the 1980s and the beginning of the 1990s a number of important transformations in our understanding of entanglement took place. First, it was recognized (e.g., Shimony,1995) **that entanglement can be quantified**; that is it comes in degrees ranging from "maximally entangled" to not entangled at all. Moreover, entanglement can be manipulated in all sorts of interesting ways. For example, Bennett *et al*. (Bennett, 1996) have shown that one can take a large number of electrons that are all partly (that is, ä little bit") entangled with each other, and concentrate that entanglement into a smaller number of maximally entangled electrons, leaving the other electrons unentangled (a process known as entanglement distillation). Conversely, one can take a pair of maximally entangled electrons and spread that entanglement out over a larger number of electrons (so that they are now only partly entangled) in such a way that the total entanglement is conserved (a process known as entanglement dilution). The notion of a "degree of entanglement" seems to have been first recognized through the related notion of a degree of violation of the Bell inequalities, indeed, this was used as the first measure of entanglement in the case of **pure states: the greater the degree of violation of the inequalities, the greater the amount of entanglement.** There are, however, limitations to using a violation of Bell's inequality as a general measure of entanglement. First, there are Bell-type inequalities whose largest violation is given by a non-maximally entangled state, so entanglement and non-locality do not always vary monotonically. Werner (Werner, 1989) showed that there are some mixed states (now referred to as Werner states) that, though entangled, do not violate Bell's inequality, so we can have entanglement without non-locality. Popescu (1995) has shown that even with these local Werner states one can perform a non-ideal measurement (or series of ideal measurements) that "distills" a non-local entanglement from the initially local state. The Horodecki family (Horodecki, 2009, 2015) subsequently showed that not all entanglement can be distilled in this way there are some entangled states that are "bound." These bound entangled states are ones that satisfy the Bell inequalities (i.e., they are local) and cannot have maximally entangled states violating Bell's inequalities extracted from them by means of local operations. **Not only can one have entanglement without non-locality**, but also, as Bennett *et al*. (1999) have shown, **one can have a kind of "non-locality without entanglement.**" There are systems that exhibit a type of non-local behavior even though entanglement is used neither in the preparation of the states nor in the joint measurement that discriminates the states (see Cerf and Cleve 1997). This work highlights another facet of the concept of non-locality, which, rather than involving correlations for space-like separated systems, involves instead a kind of indistinguishability based on local operations and classical communication. The relationship between this new notion of non-locality and the traditional one involving space-like separated systems remains to be worked out.

**These recent developments point to the need for a new, more adequate way of measuring and quantifying entanglement. They show that the concepts of entanglement and non-locality are much more subtle and multifaceted than earlier analyses based solely on Bell's theorem realized. Much philosophical and foundational work remains to be done on understanding precisely how the important notions of entanglement and non-locality are related.**

These questions of how to quantify entanglement and non-locality and the need to clarify the relationship between them are important not only conceptually, but also practically, insofar as entanglement and non-locality seem to be different resources for the performance of quantum information processing tasks. As Brunner (Viola, Brunner 2007) and colleagues have argued, it is important to ask "whether in a given quantum information protocol (cryptography, teleportation, and algorithm, it is better to look for the largest amount of



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entanglement or the largest amount of non-locality" (Brunner *et al.*, 2007).

## Entanglement and Information

Arguably it is this new emphasis on the exploitation of entanglement and non-locality for the performance of practical tasks that marks the most fundamental transformation in our understanding of these concepts. The newly formed field of quantum information theory is devoted to using the principles and laws of QM to aid in the acquisition, transmission, and processing of information. In particular, it seeks to harness the peculiarly quantum phenomena of entanglement, superposition, and non-locality to perform all sorts of novel tasks, such as enabling computations that operate exponentially faster or more efficiently than their classical counterparts (via quantum computers) and providing unconditionally secure cryptographic systems for the transfer of secret messages over public channels (via quantum key distribution). By contrast, classical information theory is concerned with the storage and transfer of information in classical systems. It uses the "bit" as the fundamental unit of information, where the system capable of representing a bit can take on one of two values (typically 0 or 1). Classical information theory is based largely on the concept of information formalized by Shannon in the late 1940s. Quantum information theory, which was later developed in analogy with classical information theory, is concerned with the storage and processing of information in quantum systems, such as the photon, electron, quantum dot, or atom. Instead of using the bit, however, it defines the fundamental unit of quantum information as the "qubit." What makes the qubit different from a classical bit is that the smallest system capable of storing a qubit, the two-level QS, not only can take on the two distinct values $|0\rangle$ and $|1\rangle$,but can also be in a state of superposition of these two states:

$$\psi = \alpha_0|0\rangle + \alpha_1|1\rangle. \quad (1)$$

Quantum information theory has opened up a whole new range of philosophical and foundational questions. The first cluster of questions concerns the nature of quantum information.A second cluster of important philosophical questions concerns how it is that quantum information protocols are able to achieve more than their classical counterparts. A third important cluster of philosophical questions concerns what new insights recent work in quantum information theory might provide into the foundations of QM. Some authors have argued that an information-theoretic approach may provide a new axiomatic basis for QM and provide deeper insight into what makes QM different from classical mechanics. Zeilinger (Zeilinger,1999) has proposed a new information-theoretic "foundational principle" which he believes can explain both the intrinsic randomness of quantum theory and the phenomenon of entanglement.In another approach, Fuchs (Fuchs,2002) has adopted a Bayesian approach and argued that QM just is quantum information theory a more sophisticated gloss on the old idea that a quantum state is just a catalogue of expectations. Bub (Bub, 2005) in particular has taken this ("CBH") theorem to show that quantum theory is best interpreted as a theory about the possibilities of information transfer rather than a theory about the non-classical mechanics of waves or particles. Much philosophical work remains to be done assessing these various claims that quantum information provides a new, more adequate way of conceiving quantum theory.



The second contribution in this thesis focuses on the concept of entanglement and how the notion of entanglement might be generalized for situations in which the overall system cannot be easily partitioned into separated subsystems A and B. The standard definition of entanglement for pure states depends on being able to define two or more subsystems for which the state cannot be factored into product states. For strongly interacting quantum systems, such as indistinguishable particles (bosons or fermions) that are close enough together for quantum statistics to be important, the entangled systems cannot easily be partitioned into subsystems in this way. In response to this problem, Viola and Barnum (Viola, 2007) have developed a notion of "generalized entanglement", **which depends on the expectation values of a preferred set of observables, rather than on a partitioning of the entangled system into subsystems**. The intuition behind their approach is that entangled pure states look mixed to local observers, and the corresponding reduced state provides expectation values for a set of distinguished observables. They define a pure state as "generalized unentangled" relative to the distinguished observables if the reduced state is pure and "generalized entangled" otherwise (Barnum *et al*., 2004). Similarly a mixed state is "generalized unentangled" if it can be written as a convex combination of unentangled pure states. Their hope is that this new approach will lead to a deeper understanding of entanglement by allowing it to be defined in more general contexts. Recent developments in quantum information theory have renewed interest in finding a new axiomatic formulation of QM. In his paper for this volume, D'Ariano takes up this challenge of finding a new axiomatization. D'Ariano argues that a more promising approach to an operational axiomatization involves situating QM within the broader context of probabilistic theories whose non-local correlations are stronger than QM and yet are still non-signaling.

Another way in which considerations of probability have been at the center of foundational debates in quantum information theory is in the analogy that has been drawn between Bayesian conditionalization and quantum state updating upon measurement (e.g., Bub and Fuchs (2002)). In the Bayesian approach, named for the eighteenth-century mathematician and theologian Thomas Bayes, probabilities are interpreted as subjective degrees of belief, rather than frequencies.

Speaking of information, it has been argued that quantum information (QI) theory may hold the key to solving the conceptual puzzles of QM. Timpson (Timpson, 2016) takes stock of such proposals, arguing that many are just the old interpretative positions of immaterialism and instrumentalism in new guise. Immaterialism is the philosophical view that the world at bottom consists not of physical objects but of immaterial ones, in this context, the immaterial stuff of the world is information. As Timpson shows, this immaterialist view can be seen underlying Wheeler's (1990) "It from bit" proposal and Zeilinger's "foundational principle" (1999). Similarly, instrumentalism is another philosophical approach that it has long been popular to invoke in the context of QM, and has found new life in the context of quantum information theory. Instrumentalism is the view that the task of scientific theories is simply to provide a tool for making predictions not to be a description of the fundamental objects and laws actually operating in the world. In this context instrumentalism argues that the quantum state is merely a representation of our information, one that allows us to make predictions about experiments, but which should not be thought of as a description of any objective features of the world. Timpson (Timpson, 2006) argues that merely re-dressing these well-worn philosophical positions in the new language of information theory does not in fact gain any interpretive ground. After providing a detailed critical analysis of Zeilinger's foundational approach, Timpson concludes that there is indeed great promise for gaining new insights into the structure and axiomatics of QM by focusing on information-theoretic phenomena, as long as one steers clear of the non-starters of immaterialism and instrumentalism.

As we have seen in this brief overview, quantum information science is in the process of transforming our understanding of both QM and information theory.

## References

Aspect A, Dalibard J, Roger G. Experimental test of Bell's inequalities using time-varying analyzers. Physical review letters 1982; 49(25): 1804-07.

Berkovitz J, Hemmo M. Modal interpretations of quantum mechanics and relativity: A reconsideration. Foundations of Physics 2005; 35(3): 373-97.

Bennett CH. Quantum information and computation. Physics Today, 1995.

Kochen S, Specker EP. Problem of hidden variables in quantum mechanics. Journal of Mathematics and Mechanics 1967; 17(1): 59-87.

Bitbol M. Schrodinger's Philosophy of Quantum Mechanics. Boston: Kluwer Academic, 1998.

Brukner C, Taylor S, Cheung S, Vedral V. Quantum entanglement in time. arXiv preprint quant-ph/0402127. 2004.

Bub J. Quantum mechanics is about quantum information. Foundations of Physics 2005; 35(4): 541-60.

Anisimov MA, Caponigro M, Mancini S, Man'ko VI. Tomograms and the quest for single particle nonlocality. Journal of Physics: Conference Series 2007; 70( 1): 012002.

Cerf NJ, Cleve R. Information-theoretic interpretation of quantum error-correcting codes. Physical Review A 1997; 56(3):1721-32

Christensen BG, Liang YC, Brunner N, Gisin N, Kwiat PG. Exploring the limits of quantum nonlocality with entangled photons. Physical Review X 2015; 5(4): 041052.

Esfeld M. Quantum entanglement and a metaphysics of relations. Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics 2004; 35(4): 601-17.

Esfeld M. Quantum physics and presentism. InRe-Thinking Time at the Interface of Physics and Philosophy 2015: 231-48.

Fuchs CA. Quantum mechanics as quantum information (and only a little more). arXiv preprint quant-ph/0205039. 2002.

Filk T. Relational interpretation of the wave function and a possible way around Bell's theorem. International Journal of Theoretical Physics 2006; 45(6): 1166-80.

Gisin N. Can relativity be considered complete? From Newtonian nonlocality to quantum nonlocality and beyond. arXiv preprint quant-ph/0512168. 2005.

Gisin N, Tanzilli S, Tittel W. Quantum light-The puzzling predictions of entanglement are coming of age. Europhysics News 2015; 46(5-6): 36-40.

Ghirardi G. Bucher und Software-Sneaking a Look at God's Cards. Physik Journal 2005; 4(10): 61.

Greene B. The Fabric of the Cosmos. New York: Vintage Books, 2005.

Healey R. The Philosophy of Quantum Mechanics: An Interactive Interpre- tation. Cambridge: Cambridge University Press, 1989.

Horodecki R, Horodecki P, Horodecki M, Horodecki K. Quantum entanglement. Reviews of Modern Physics 2009; 81(2): 865.

Horodecki R, Korbicz JK, Horodecki P. Quantum origins of objectivity. Physical Review A 2015; 91(3):032122.

Karakostas V. Forms of quantum nonseparability and related philosophical consequences. Journal for General Philosophy of Science 2004; 35(2): 283-312.

Kochen S, Specker EP. The problem of hidden variables in quantum mechanics. Ernst Specker Selecta 1990: 235-63.

Laudisa F, Rovelli C. Relational quantum mechanics. Stanford Encyclopedia of Philosophy 2010.

Maudlin T. Quantum Non-Locality and Relativity: Metaphysical Intima- tions of Modern Physics Oxford: Blackwell, 2002.

Rohrlich D, Popescu S. Nonlocality as an axiom for quantum theory. arXiv preprint quant-ph/9508009. 1995.

Rovelli C. Relational quantum mechanics. International Journal of Theoretical Physics 1996; 35(8): 1637-78.

Shimony A. Foundations of Quantum Mechanics in the Light of New Tech- nology, ed. S. Kamefuchi. Tokyo: Japan Physical Society, 1983.

Suarez A. Entanglement and time. arXiv preprint quant-ph/0311004. 2003.

Suarez A. Is there a real time ordering behind the nonlocal correlations?. arXiv preprint quant-ph/0110124. 2001.

Suarez A, Adams P, editors. Is science compatible with free will?: Exploring free will and consciousness in the light of quantum physics and neuroscience. Springer Science & Business Media, 2012.

Timpson C. Philosophical aspects of quantum information theory. The Ashgate companion to contemporary philosophy of physics 2016 : 203-67.

Werner RF. Quantum states with Einstein-Podolsky-Rosen correlations admitting a hidden-variable model. Physical Review A 1989; 40(8): 4277.

Wheeler JA. Information, physics, quantum: the search for links. In Feyman and Computation: Exploring the Limits of Computers, ed AJG Hey. Reading: Persus Books, 1999.

Żukowski M, Brukner Č. Bell's theorem for general N-qubit states. Physical Review Letters 2002;88(21):210401.

Zeilinger A. Dance of the photons: from Einstein to quantum teleportation. Farrar, Straus and Giroux; 2010.

Zeilinger A. On the Interpretation and Philosophical Foundation of Quantum Mechanics. InGrenzen menschlicher Existenz, Ed. Hans Daub, 184-201, Michael Imhof Verlag, 2008.