Is the Many Worlds Interpretation of Quantum Mechanics consistent?

Vijay Shankar[1*] and Narayanankutty Karuppath[2†]
[1] *Center for Computational Engineering and Networking (CEN), Amrita School of Engineering, Amrita Vishwa Vidyapeetham, Coimbatore, India and*
[2*] *Department of Physics, Amrita Vishwa Vidyapeetham, Amritapuri, India*
(Dated: Submitted May 27, 2021)

Duality in quantum mechanical wave functions is manifest through the famous measurement problem. There have been several interpretations to explain this duality, but none have seen full consensus among physicists. The Copenhagen interpretation, which is at least to some extent the most widely accepted interpretation has the 'collapse' of the wave function (or state vector reduction) during measurement, does not attribute a physical reality to the wave function. Moreover, the idea of measurement having a role in defining reality shakes the very foundation of classical physics. On the other hand, the Many worlds interpretation proposed by Everett is a very brave attempt to attribute physical significance to the wave function. Though mathematically sound and elegant, 'the splitting of the universe' in the Many Worlds Interpretation completely redefines reality as we know it. We test Everett's original thought experiment in the presence of a super observer and for sequential measurements as well. We observe that the no-clone theorem helps the Many Worlds Interpretation, yet it does not provide a consistent picture for sequential measurements, unlike the Copenhagen Interpretation.

Keywords: Many Worlds Interpretation, Copenhagen Interpretation, duality, completeness,no-clone theorem

I. INTRODUCTION

The classical Rutherford atomic model proposes that the electron revolves around the nucleus in elliptical orbits. In the pre-quantum era it was believed that the electron must emit light as per the electrodynamics of the system. But Quantum mechanics shows that the state of the atom does not change with time, unless there is an external intervention (with the exception of spontaneous emission) (Bohr 1913; Lim 1998). When you measure an attribute of the electron, say a component of the spin in a particular direction, you get a value with certain probability for the electron having that spin and it will evolve in that state continuously, if you leave it as it is. Subsequent measurement for spin in a different direction would reveal different probabilities with the spin changing its state. Leave it undisturbed, it will evolve in the new state. Each act of measurement takes it to a new state. Thus quantum reality is almost akin to saying that the moon exists only when you look at it (Mermin 1985). This duality has historically resulted in a lot of debates, that led not just to key understanding of quantum mechanics, but which raised questions on the concept of reality as we perceive it.

The major common schools of thought can be categorized into three when it comes to interpretations of this duality (Einstein, Podolsky, and Rosen 1935; d'Espagnat 1979; Lewis 2016; Stapp 1972; Darby 2010; Griffiths and Schroeter 2018)- the realist, the orthodox and the metaphysical. The realist argument is the classical physicist's favorite one. The indeterminacy is due to the presence of a hidden variable which we are unaware of (Einstein, Podolsky, and Rosen 1935). In the metaphysical interpretation, this and other quantum paradoxes ("The uses of paradox" 2005; Franco Selleri 1990) are considered to be a consequence of human consciousness by certain physicists (Achuthan et al. 2009; Lewis 2016; Abner Shimony and Philosophy Documentation Center 1978; Darby 2010).

But as per one of the most commonly accepted interpretations(orthodox), the Copenhagen interpretation (Stapp 1972). A quantum state exists in its most general form as a superposition of several other sub-states and the wave function 'collapses' to a particular state when measured. The probability is a measure of the proportion of the measured sub-state contained in the 'complete' state. The main criticism against the Copenhagen Interpretation is that it reduces physical reality into an observer created one, thus smuggling in subjectivity or consciousness into physics (Achuthan et al. 2009; N. Karuppath 2010; N. K. Karuppath and Panajikunnath 2010; Pálffy 2012; Popper 1967). Subjectivity in physics, at any level becomes untenable as it goes against the basic tenets of physics or or the age old concept reality, in general. An inevitable logical conclusion is that quantum mechanical wave function function is only a mathematical construct and not a physically realizable one.

Such conundrums are not limited to the Copenhagen Interpretation alone, but almost all the interpretations are associated with some type of 'weirdness' in a classical sense (Pesic 2002; Mullin 2017). In addition, a good number of the interpretations fail to keep intervention of an observer and hence, the role of consciousness or subjectivity at bay (N. Karuppath 2010). Even after years of research, the physics world has not come to a consensus on the exact interpretation of quantum mechanics. The

* vijaynebula@gmail.com
† corresponding author: narayanankuttyk@am.amrita.edu

most compelling reason for the study of the interpretations of quantum mechanics is mainly the understanding of quantum mechanics itself through the resolution of its paradoxes, is mainly the understanding of quantum reality itself (N. Karuppath 2010). Insights, leading to modern applications of quantum physics, including quantum computing, are just some of the spin offs (Lini 2015; Santanam et al. 2011)

Among the prominent interpretations which attempt to restore the classical concept of physical reality is the Many Worlds Interpretation (DeWitt, Everett, and Graham 1973). The Many Worlds Interpretation tries to reconcile the probabilistic outcome resulting from the 'state vector reduction' upon measurement and the deterministic evolution of Schrodinger equation in a completely novel way. Imagine *Alice* is in possession of an atom with 'electron orbits'. Her picture is that of a continuous evolution of the electron wave function. Then, her friend *Bob* serendipitously makes a measurement and obtains an outcome (with a particular probability value for one of its states). Thus splitting the world, as per the Many Worlds Interpretation, into two or more parallel universes (or branching of the universal wave function) with each measurement. This splitting was proposed as a supposed alternative to the collapse of wave function or state vector reduction. Instead of the wave function 'collapsing' into one of the many possibilities, each measurement splits the world into two or multiple worlds. Each of those worlds is associated with a 'Universal Wave function/state vector', thus the MWI tries to espouse a clear physical state rather than a mere mathematical record in contrast with the Copenhagen Interpretation. Thus the 'problem of causeless choice of a particular outcome' associated with indeterminacy is circumvented.

In addition, the Copenhagen Interpretation or other 'single world models' (generic term for non many world interpretations) (Saunders et al. 2010) in the context of quantum non locality fails to give any viable explanation for quantum entanglement, while the Many Worlds Interpretation provides a potential answer to understanding quantum entanglement. In single world models, quantum non locality is suggested as one of the basic axioms of quantum mechanics (Popescu 2014) , but in general, the very idea of classical physics is local in nature. Quantum non local entanglement experiments in the past were restricted to the laboratory (Aspect, Dalibard, and Roger 1982; Clauser and Shimony 1978; Franco Selleri 1988; Home and F. Selleri 1991). The most recent ground breaking experiment confirms quantum entanglement at a much larger scale (Liao et al. 2018). The assumption of transmission of signals faster than light between entangled quantum states is explicitly forbidden by special relativity (Popescu and Rohrlich 1994). Though it is proved that such transmissions cannot be faster than light there is a tension between the special theory of relativity and quantum mechanics. Special relativity is local and quantum entanglement is not. Quantum non locality may be an evidence to MWI (Frank J. Tipler 2012; F. J. Tipler 2014). Corresponding to the measurement of each of the correlated pairs of spins of entangled quantum particles the universe splits into separate ones, where each of the spins are local in their own respective universes (Frank J. Tipler 2012). In this case there is no explicit contradiction with special relativity, which makes the MWI an interesting case indeed.

In this paper our main focus is to examine Everett's original thought experiment (DeWitt, Everett, and Graham 1973) and bring out the nuances in his basic argument. We revisit it in Sec. II and present different scenarios for the same in Sec. III and Sec. IV. Finally we conclude in Sec. V critically examining the Many Worlds Interpretation in contrast with the state of the art Copenhagen Interpretation.

II. MANY WORLDS INTERPRETATION'S ORIGINAL THOUGHT EXPERIMENT: A REVISIT

Since we will be developing our own thought experiments which are inspired by the original thought experiment of Everett in Ref.(ibid.), let us reproduce his original thought experiment. There are quite a few modified versions of the Many Worlds Interpretation (Kent 1990; Saunders et al. 2010), all of them basically derived from this thought experiment given at the very beginning of (DeWitt, Everett, and Graham 1973).

Consider two quantum mechanics experts A and B and A is inside the room carrying out his measurements on a quantum mechanical state Ψ as in Eqn.1 (Where E_i represents the eigenvalue or observable of the measurement), which exists as a super position of several sub states ψ_i, with a total of n sub states. On each measurement A gets a probability $|c_i|^2$ of the quantum state living in one of the sub states.

$$\Psi(t) = \sum_{n=1}^{n} c_i \psi_i e^{\frac{-iE_i t}{\hbar}} \tag{1}$$

$$\sum_{n=1}^{n} |c_i|^2 = 1 \tag{2}$$

Imagine A notes his measurements and the probabilities. On the other hand B who is standing outside, is in full possession of the entire system. Entire system refers to the room, A and his experiment. In concrete mathematical sense, B is in possession of the time dependent solution to the Schrodinger equation $\Psi(t)$ (as in Eqn.1) and the wave function evolves in time. Unlike A, B does not disturb the system in any way. B records its behaviour, for say a week.

The only logical conclusion is that the total amplitude of the complete wave function that B possesses the complete picture is the sum of the amplitudes of the of the discrete probabilistic measurements made by A (This part is validated if you consider the concept of *A's* sum of probabilistic amplitudes Eqn.2 and *B's* normalization of the wave function which are both 1).

But, B possesses the complete wave function only until the current measurement of A. When B opens the door (dramatically) B sees that A gives a probabilistic result $|c_i|^2$ of Ψ being in some ψ_i. Thus the existence of A is due to the 'mercy' of B, that is if B had not opened the door *A's* result would not exist. Until B opened the door he had a deterministic view of the wave function. When B opens the door, the probabilistic measurement of A comes into existence, thereby creating a new world. Thus there are now two worlds, one where the wave function is deterministic and another one where it is probabilistic in nature. If B had chosen to open the door on a different occasion, there would have been a different probabilistic result which A would have measured and thus each of *As* measurements constitute a separate world.

Everett mentions that the complete wave function is in possession with B includes the room, A himself and the apparatus. If he had mentioned instead that he only had the wave function Eqn.1) alone, that would have been a violation of the no-clone theorem (Wootters and Zurek 1982). Instead Everett assumes that the room, the observer etc are quantum mechanical. The probability in the Many Worlds Interpretation is a measure of the number of worlds which represent the given sub state associated with the probability under consideration (Vaidman 2012; Deutsch 1999), known as the 'counting worlds model'.

The above thought experiment and the conclusion is based on the physical duality already forming the basic tenet of quantum mechanics as it is existent today. The Many Worlds Interpretation is only a manifestation of this duality. If the above thought experiment were to be taken for a an explicit splitting of the universe, then you and I will not exist unless some person doing a quantum mechanics experiment opens his door. But the idea may not be about splitting of the universes so explicitly, rather that space and time may exist in a superposition of several versions of itself (Tegmark 1998). In physics, theories are to be accepted only on the basis of experimental validity - or the argument that the splitting of the universe or reality must have some observable effect on the current reality we live in. An acceptable theory must be falsifiable (Popper 1969). Every time when a quantum experiment is carried out or an observation is made, the reality splits into many and that we have never had any observational is indeed strange.

III. THE SUPEROBSERVER IMPOSSIBILITY THOUGHT EXPERIMENT

Let us modify Everett's thought experiment. Instead of B being outside the room, let B be inside the room itself. Let us consider the room having two floors. Let B be the super observer *(S)* looking from above. At the floor below, the quantum state as in Eqn.3, which is the inital state at time t=0.

$$\Psi = \sum_{n=1}^{n} c_i \psi_i \tag{3}$$

But instead of just A, let us consider a large number of observers who are making measurements . Let there be a number of observers $A_1, A_2..A_n$ *(As)* who are making observations on the quantum system represented by Eqn.3. Each of them have a copy of the same system, which is a gross violation of the no-clone theorem (Wootters and Zurek 1982). Each of those observers simultaneously measure the system to be in $\psi_1, \psi_2..\psi_n$ with probabilities $|c_1|^2, |c_2|^2..|c_n|^2$ which follow initially. But, after a small amount of time t, for each of those observers, the system will evolve in a unitary way : $\psi_1(t) = \psi_1 e^{\frac{-iE_1 t}{\hbar}}, \psi_2(t) = \psi_2 e^{\frac{-iE_2 t}{\hbar}}..\psi_n(t) = \psi_n e^{\frac{-iE_n t}{\hbar}}$. Now, for each of those observers, their own quantum wavefunction should represent the full picture of the system and according to the Many Worlds Interpretation constitutes one distinct reality each.

But S is watching all this from above. The super observer (as the name suggests), will observe all of the observers below making their respective measurements. The super observer collects the initial probabilistic measurements of the observers below and thus the initial wave function at time t=0 is as in Eqn.3. At a later time t, S collects the wave functions $\psi_1(t), \psi_2(t)..\psi_n(t)$, which the observers below possess, each of which only represent a part of the complete picture (according to S). Which means all of them are only a part of the total wave function $\Psi(t)$, which have probabilities $|c_1|^2, |c_2|^2..|c_n|^2$ as in Eqn.1. That is at a later time t, the probability to find the system in any one of $\psi_1, \psi_2..\psi_n$ is going to be $|c_1|^2, |c_2|^2..|c_n|^2$. This is like the weighted sum total of the wave functions of the observer below. We assume the time elapsed t, as the same for everyone, for every increase in t and *As* update S with the wave functions.

If not for the no-clone theorem, the results would be in direct contradiction of the world splitting as assumed by Everett. If each of the observers in the bottom floor were to split into separate worlds according to the Many Worlds Interpretation, then according to S, all their worlds or realities will split. But one more thing, S needs the time-evolved wave functions continuously from the observers below him to construct his full wave function as in Eqn.1, thus all those observers are very much part of his world, hence the world can not split by the logic of Many Worlds Interpretation. So one can observe that the no-clone theorem may be one of the factors helping the Many Worlds Interpretation. If not for the no-clone theorem this thought experiment could have violated the Many Worlds Interpretation, but the no-clone theorem comes to the rescue.

IV. COMPOSITE SYSTEMS THOUGHT EXPERIMENT

In this 'gedanken' experiment, let us closely follow the footsteps of Everett, but let us consider a simple yet composite system. This thought experiment is inspired by problem 3.32 in Ref.(Griffiths and Schroeter 2018). Instead of following the 'Shut up and calculate' recipe (Tegmark 1998; Baily and Finkelstein 2010) as is common in most quantum mechanics text books, we will take into consideration the interpretational consequence of such a system.

Let us start with A, who is inside a room and B who is outside the room. B is in possession of the simplest superposed wave function, at a time t equal to zero.

$$\Psi = \frac{1}{\sqrt{2}}\psi_1 + \frac{1}{\sqrt{2}}\psi_2 \tag{4}$$

For B the wave function will evolve as

$$\Psi = \frac{1}{\sqrt{2}}\psi_1 e^{\frac{-iE_1 t}{\hbar}} + \frac{1}{\sqrt{2}}\psi_2 e^{\frac{-iE_2 t}{\hbar}} \tag{5}$$

With a probability of 0.5 of being in either one of the sub states. Here E_1 and E_2 are the eigenvalues or observables associated with the measurements.

But in the most general form a quantum mechanical state can be expressed as a linear combination or superposition of other states. This goes not just for Ψ in Eqn. 5 but for ψ_1 and ψ_2 as well, as in Equations 6 and 7.

$$\psi_1 = \frac{3}{5}\phi_1 + \frac{4}{5}\phi_2 \tag{6}$$

$$\psi_2 = \frac{4}{5}\phi_1 - \frac{3}{5}\phi_2 \tag{7}$$

This same formulation can also be written as

$$\phi_1 = \frac{3}{5}\psi_1 + \frac{4}{5}\psi_2 \tag{8}$$

$$\phi_2 = \frac{4}{5}\psi_1 - \frac{3}{5}\psi_2 \tag{9}$$

If A were to measure ψ_1 and ψ_2 A will get a probability of 0.5 for either of them. For B who is standing outside, the system evolves according to Eqn.5, where the probabilities of being in either ψ_1 or ψ_2 as 0.5. Until now the system is very much similar to Sec. II.

But, further considerations will show that *A's* picture is much more interesting. Let A measure for ψ_1, he gets ψ_1 with a probability 0.5. Now after this measurement the wave function is expected to live as in Eqn. 6. Now A measures ϕ_1 and the total probability of the system to be in ϕ_1 is $P(\frac{\phi_1}{\psi_1}) = (\frac{1}{2})(\frac{9}{25})$. The system after this measurement lives in the state ϕ_1. Now the probability of finding the state in ψ_1 and ψ_2 will be.

$$P(\frac{\psi_1}{\psi_1, \phi_1}) = (\frac{1}{2})(\frac{9}{25})(\frac{9}{25}) = 0.065 \tag{10}$$

$$P(\frac{\psi_2}{\psi_1, \phi_1}) = (\frac{1}{2})(\frac{9}{25})(\frac{16}{25}) = 0.125 \tag{11}$$

The probabilities measured are considerably different from what A measured for ψ_1 and ψ_2 initially, before he measured ϕ_1. This is a typical case of conditional probability. In addition, the other probabilities that can be associated with *A's* measurement of ψ_1 and ψ_2 are $P(\frac{\psi_1}{\psi_1,\phi_2}), P(\frac{\psi_2}{\psi_1,\phi_2}), P(\frac{\psi_1}{\psi_2,\phi_1}), P(\frac{\psi_2}{\psi_2,\phi_1}), P(\frac{\psi_1}{\psi_2,\phi_2})$ and $P(\frac{\psi_2}{\psi_2,\phi_2})$, depending upon the sequential order of *A's* choice. These probabilities are all completely oblivious to B who is outside, all he is aware of is ψ_1 and ψ_2 both at 0.5.

The implicit relation between ψ_1 and ψ_2 and ϕ_1 and ϕ_2 is better explained by the Copenhagen interpretation than the Many worlds interpretation. If we go by the Many worlds interpretation when A measures ψ_1, that will be one version of him making that measurement. Next, if he measures ϕ_1 after that, there will be a version of him corresponding to that world within the world where he measured ψ_1 initially . Now if he again measures ψ_1 there will be another world within that world. Thus we have a complex superposition of several worlds within worlds all of which contain a different version of the measurer and the measured. The probability associated with ψ_1 initially will be different from the probabilities for ψ_1 measured after ϕ_1. The probability in the Many Worlds Interpretation does not take into consideration the interdependence between wave functions for sequential measurements. The Copenhagen Interpretation narrates the collapse of the wave function during measurement to explain the interdependence between wave functions during sequential measurements. The Many Worlds Interpretation's probability is only a measure of the number of worlds having a particular possibility or wave function (Vaidman 2012; Deutsch 1999), it does not explain the interdependence between wave functions for sequential measurements. Indeed, there are other many other models of probability for the Many Worlds Interpretation (Vaidman 2018), none of them provide anything as intuitive and conclusive as the counting worlds model.

A much better narrative is given by the Copenhagen interpretation where the measurer, the measurement or the experimental arrangement causes the change in probabilities (Bohr 1935). The Many worlds interpretation thus fails to give a consistent picture for sequential measurements.

V. CONCLUSIONS

Reductionism is the notion wherein everything in the world when decomposed into smaller parts, the constituents will follow the same laws as does the object itself. Reductionism has a very deep roots in physics (Gentile 2006). Quantum mechanics grossly violates the principles of reductionism. In every interpretation of quantum mechanics there is a considerable amount of controversial weirdness. No matter what interpretation one takes there is an element of subjectivity, which makes quantum mechanics so disturbing and intriguing at the same time. A metaphor 'the moon exists only when you look at it', that can be associated with quantum mechanical measurements, makes the whole subject queer.

The main problem with the Copenhagen Interpretation is the concept of observer created reality (Bohr 1935). Hence, the narrative is treated as a mere mathematical construct. The beauty of the Many Worlds Interpretation lies in its elegant narrative of physical duality as two different worlds of reality. The destructive nature of quantum measurements manifests in the form of the no-clone theorem, which is a very fundamental aspect of the experimental nature of quantum mechanical measurements. This helps the Many Worlds Interpretation as we have seen in Sec.III. But for sequential measurements as in Sec.IV, the probability picture of the Many Worlds Interpretation does not provide consistency here especially with reference to the sequential interdependence of probabilities between the wave functions.

Both the Copenhagen Interpretation and Many Worlds interpretation fail to keep subjectivity at bay. While the Copenhagen Interpretation gives an explanation for the dynamic nature of the probabilities, which is poignant in the case of sequential measurements, the Many worlds Interpretation does not succeed there. At the end of both our thought experiments we must conclude, that the Many Worlds Interpretation is a very strong argument, which needs to be substantiated with a conclusive, intuitive and concise version of probability, to explain sequential measurements.

VI. ACKNOWLEDGEMENT

The authors wish to express their gratitude to the Chancellor of Amrita Vishwa Vidyapeetham, H.H. Mata Amritanandamayi Devi (Amma) for her inspiration to do the work. We would also like to thank Dr.E.A. Goapalakrishnan the chairman of the project committee of the Center for Computational Engineering and Networking (CEN), Amrita Vishwa Vidyapeetham, Coimbatore for having supported this work by understanding its interdisciplinary nature.

REFERENCES

Achuthan, P. et al. (2009). "On mathematical modeling of quantum systems". en. In: *AIP Conference Proceedings*. Agra (India): AIP, pp. 105–112. DOI: `10.1063/1.3183535`. URL: `http://aip.scitation.org/doi/abs/10.1063/1.3183535`.

Aspect, Alain, Jean Dalibard, and Gérard Roger (Dec. 1982). "Experimental test of bell's inequalities using time- varying analyzers". en. In: *Physical Review Letters* 49.25, pp. 1804–1807. ISSN: 0031-9007. DOI: `10.1103/PhysRevLett.49.1804`. URL: `https://link.aps.org/doi/10.1103/PhysRevLett.49.1804`.

Baily, Charles and Noah D. Finkelstein (Jan. 2010). "Teaching and understanding of quantum interpretations in modern physics courses". en. In: *Physical Review Special Topics - Physics Education Research* 6.1, p. 010101. ISSN: 1554-9178. DOI: `10.1103/PhysRevSTPER.6.010101`. URL: `https://link.aps.org/doi/10.1103/PhysRevSTPER.6.010101` (visited on 05/25/2021).

Bohr, N. (July 1913). "I. *On the constitution of atoms and molecules*". en. In: *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 26.151, pp. 1–25. ISSN: 1941-5982, 1941-5990. DOI: `10.1080/14786441308634955`. URL: `https://www.tandfonline.com/doi/full/10.1080/14786441308634955`.

– (July 1935). "Quantum mechanics and physical reality". en. In: *Nature* 136.3428, pp. 65–65. ISSN: 0028-0836, 1476-4687. DOI: `10.1038/136065a0`. URL: `http://www.nature.com/articles/136065a0`.

Clauser, J F and A Shimony (Dec. 1978). "Bell's theorem. Experimental tests and implications". In: *Reports on Progress in Physics* 41.12, pp. 1881–1927. ISSN: 0034-4885, 1361-6633. DOI: `10.1088/0034-4885/41/12/002`. URL: `https://iopscience.iop.org/article/10.1088/0034-4885/41/12/002`.

d'Espagnat, Bernard (Nov. 1979). "The quantum theory and reality". In: *Scientific American* 241.5, pp. 158–181. ISSN: 0036-8733. DOI: `10.1038/scientificamerican1179-158`. URL: `https://www.scientificamerican.com/article/the-quantum-theory-and-reality`.

Darby, George (June 2010). "Quantum mechanics and metaphysical indeterminacy". en. In: *Australasian Journal of Philosophy* 88.2, pp. 227–245. ISSN: 0004-8402, 1471-6828. DOI: `10.1080/00048400903097786`. URL: `http://www.tandfonline.com/doi/abs/10.1080/00048400903097786`.

Deutsch, David (Aug. 1999). "Quantum theory of probability and decisions". en. In: *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 455.1988, pp. 3129–3137. ISSN: 1364-5021, 1471-2946. DOI: `10.1098/rspa.1999.0443`. URL: `https://royalsocietypublishing.org/doi/10.1098/rspa.1999.0443` (visited on 05/26/2021).

DeWitt, Bryce S., Hugh Everett, and Neill Graham (1973). *The many-worlds interpretation of quantum mechanics: a fundamental exposition*. Princeton series in physics. Princeton, N.J: Princeton University Press. ISBN: 9780691081267 9780691081311.

Einstein, A., B. Podolsky, and N. Rosen (May 1935). "Can quantum-mechanical description of physical reality be considered complete?" en. In: *Physical Review* 47.10, pp. 777–780. ISSN: 0031-899X. DOI: `10.1103/PhysRev.47.777`. URL: `https://link.aps.org/doi/10.1103/PhysRev.47.777`.

Gentile, David (Mar. 2006). "Physics, reductionism, and the real world". en. In: *Physics Today* 59.3, pp. 12–12. ISSN: 0031-9228, 1945-0699. DOI: 10.1063/1.2195298. URL: http://physicstoday.scitation.org/doi/10.1063/1.2195298.

Griffiths, David J. and Darrell F. Schroeter (Aug. 2018). *Introduction to quantum mechanics*. 3rd ed. Cambridge University Press. ISBN: 9781316995433 9781107189638. DOI: 10.1017/9781316995433. URL: https://www.cambridge.org/core/product/identifier/9781316995433/type/book.

Home, D. and F. Selleri (Sept. 1991). "Bell's theorem and the EPR paradox". en. In: *La Rivista del Nuovo Cimento* 14.9, pp. 1–95. ISSN: 1826-9850. DOI: 10.1007/BF02811227. URL: http://link.springer.com/10.1007/BF02811227.

Karuppath, Narayanan Kutty and Achuthan Panajikunnath (2010). "Quantum nonlocality, einstein–podolsky–rosen argument, and consciousness". English. In: *An Interdisciplinary Journal of Neuroscience and Quantum Physics* Volume 8.No 2, pp. 231–236. ISSN: 1943-023X. DOI: 10.14704/nq.2010.8.2.289. URL: http://neuroquantology.com/article.php?id=1895.

Karuppath, Narayanankutty (2010). "Critical studies in aspects of quantum reality, time and some applications". English. In: *INFLIBNET*. URL: http://shodhganga.inflibnet.ac.in:8080/jspui/handle/10603/2360.

Kent, Adrian (May 1990). "Against many-worlds interpretations". en. In: *International Journal of Modern Physics A* 05.09, pp. 1745–1762. ISSN: 0217-751X, 1793-656X. DOI: 10.1142/S0217751X90000805. URL: https://www.worldscientific.com/doi/abs/10.1142/S0217751X90000805.

Lewis, Peter J. (Aug. 2016). *Quantum ontology: a guide to the metaphysics of quantum mechanics*. Oxford University Press. ISBN: 9780190469825. DOI: 10.1093/acprof:oso/9780190469825.001.0001. URL: https://oxford.universitypressscholarship.com/view/10.1093/acprof:oso/9780190469825.001.0001/acprof-9780190469825.

Liao, Sheng-Kai et al. (Jan. 2018). "Satellite-relayed intercontinental quantum network". en. In: *Physical Review Letters* 120.3, p. 030501. ISSN: 0031-9007, 1079-7114. DOI: 10.1103/PhysRevLett.120.030501. URL: https://link.aps.org/doi/10.1103/PhysRevLett.120.030501.

Lim, Yung-Kuo (Sept. 1998). *Problems and solutions on quantum mechanics*. en. Major American Universities Ph.D. Qualifying Questions and Solutions - Physics. WORLD SCIENTIFIC. ISBN: 9789810231323 9789810248161. DOI: 10.1142/3471. URL: https://www.worldscientific.com/worldscibooks/10.1142/3471.

Lini, Giacomo (Dec. 2015). "Quantum parallelism thesis, many world interpretation and physical information thesis". en. In: *Philosophies* 1.1, pp. 102–110. ISSN: 2409-9287. DOI: 10.3390/philosophies1010102. URL: http://www.mdpi.com/2409-9287/1/1/102.

Mermin, N. David (Apr. 1985). "Is the moon there when nobody looks? Reality and the quantum theory". en. In: *Physics Today* 38.4, pp. 38–47. ISSN: 0031-9228, 1945-0699. DOI: 10.1063/1.880968. URL: http://physicstoday.scitation.org/doi/10.1063/1.880968.

Mullin, William J. (Mar. 2017). *Quantum weirdness*. Oxford University Press. ISBN: 9780198795131. DOI: 10.1093/acprof:oso/9780198795131.001.0001. URL: https://oxford.universitypressscholarship.com/view/10.1093/acprof:oso/9780198795131.001.0001/acprof-9780198795131.

Pálffy, Adriana (May 2012). "Quantum enigma: physics encounters consciousness, 2nd edn. , by bruce rosenblum and fred kuttner: scope: general interest. Level: general readership". en. In: *Contemporary Physics* 53.3, pp. 282–283. ISSN: 0010-7514, 1366-5812. DOI: 10.1080/00107514.2012.661786. URL: http://www.tandfonline.com/doi/abs/10.1080/00107514.2012.661786.

Pesic, Peter (2002). "Quantum Identity: Physicists have long struggled with the weirdness of quantum mechanics—a consequence of like particles being completely indistinguishable from one another". In: *American Scientist* 90.3, pp. 262–267. ISSN: 0003-0996. URL: https://www.jstor.org/stable/27857662.

Popescu, Sandu (Apr. 2014). "Nonlocality beyond quantum mechanics". en. In: *Nature Physics* 10.4, pp. 264–270. ISSN: 1745-2473, 1745-2481. DOI: 10.1038/nphys2916. URL: http://www.nature.com/articles/nphys2916.

Popescu, Sandu and Daniel Rohrlich (Mar. 1994). "Quantum nonlocality as an axiom". en. In: *Foundations of Physics* 24.3, pp. 379–385. ISSN: 0015-9018, 1572-9516. DOI: 10.1007/BF02058098. URL: http://link.springer.com/10.1007/BF02058098.

Popper, Karl R. (1967). "Quantum mechanics without "the observer"". en. In: *Quantum Theory and Reality*. Ed. by Mario Bunge. Studies in the Foundations Methodology and Philosophy of Science. Berlin, Heidelberg: Springer, pp. 7–44. ISBN: 9783642880261. DOI: 10.1007/978-3-642-88026-1_2.

– (1969). *Conjectures and refutations: the growth of scientific knowledge*. 3rd ed. (revised). London: Routledge & K. Paul. ISBN: 9780710065070.

Santanam, Raghu et al., eds. (2011). *Cyber security, cyber crime and cyber forensics: applications and perspectives*. Advances in Digital Crime, Forensics, and Cyber Terrorism. IGI Global. ISBN: 9781609601232 9781609601256. DOI: 10.4018/978-1-60960-123-2. URL: http://services.igi-global.com/resolvedoi/resolve.aspx?doi=10.4018/978-1-60960-123-2.

Saunders, Simon et al. (June 2010). *Many worlds?* Oxford University Press. ISBN: 9780199560561. DOI: 10.1093/acprof:oso/9780199560561.001.0001. URL: https://oxford.universitypressscholarship.com/view/10.1093/acprof:oso/9780199560561.001.0001/acprof-9780199560561.

Selleri, Franco, ed. (1988). *Quantum mechanics versus local realism: the einstein-podolsky-rosen paradox*. en. Boston, MA: Springer US. ISBN: 9781468487763 9781468487749. DOI: 10.1007/978-1-4684-8774-9. URL: http://link.springer.com/10.1007/978-1-4684-8774-9.

– (1990). *Quantum paradoxes and physical reality*. en. Ed. by Alwyn van der Merwe. Dordrecht: Springer Netherlands. ISBN: 9789401073301 9789400918627. DOI: 10.1007/978-94-009-1862-7. URL: http://link.springer.com/10.1007/978-94-009-1862-7.

Shimony, Abner and Philosophy Documentation Center (1978). "Metaphysical problems in the foundations of quantum mechanics:" in: *International Philosophical Quarterly* 18.1, pp. 3–17. ISSN: 0019-0365. DOI: 10.5840/ipq19781818. URL: http://www.pdcnet.org/oom/service?url_ver=Z39.88-2004&rft_val_fmt=&rft.imuse_id=ipq_1978_0018_0001_0003_0017&svc_id=info:www.pdcnet.org/collection.

Stapp, Henry Pierce (Aug. 1972). "The copenhagen interpretation". en. In: *American Journal of Physics* 40.8, pp. 1098–1116. ISSN: 0002-9505, 1943-2909. DOI: 10.1119/1.1986768.

URL: http://aapt.scitation.org/doi/10.1119/1.1986768.

Tegmark, Max (1998). "The interpretation of quantum mechanics: many worlds or many words?" de. In: *Fortschritte der Physik* 46.6-8, pp. 855–862. ISSN: 1521-3978. DOI: https://doi.org/10.1002/(SICI)1521-3978(199811)46:6/8<855::AID-PROP855>3.0.CO;2-Q. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/%28SICI%291521-3978%28199811%2946%3A6/8%3C855%3A%3AAID-PROP855%3E3.0.CO%3B2-Q.

"The uses of paradox" (2005). en. In: *Quantum Paradoxes*. John Wiley & Sons, Ltd, pp. 1–9. ISBN: 9783527619115. DOI: 10.1002/9783527619115.ch1. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/9783527619115.ch1.

Tipler, F. J. (Aug. 2014). "Quantum nonlocality does not exist". en. In: *Proceedings of the National Academy of Sciences* 111.31, pp. 11281–11286. ISSN: 0027-8424, 1091-6490. DOI: 10.1073/pnas.1324238111. URL: http://www.pnas.org/cgi/doi/10.1073/pnas.1324238111.

Tipler, Frank J. (Feb. 2012). "Nonlocality as evidence for a multiverse cosmology". en. In: *Modern Physics Letters A* 27.04, p. 1250019. ISSN: 0217-7323, 1793-6632. DOI: 10.1142/S0217732312500198. URL: https://www.worldscientific.com/doi/abs/10.1142/S0217732312500198.

Vaidman, Lev (2012). "Probability in the many-worlds interpretation of quantum mechanics". In: *Probability in Physics*. Ed. by Yemima Ben-Menahem and Meir Hemmo. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 299–311. ISBN: 9783642213281 9783642213298. DOI: 10.1007/978-3-642-21329-8_18. URL: http://link.springer.com/10.1007/978-3-642-21329-8_18 (visited on 05/26/2021).

– (2018). "Many-worlds interpretation of quantum mechanics". In: *The Stanford Encyclopedia of Philosophy*. Ed. by Edward N. Zalta. Fall 2018. Metaphysics Research Lab, Stanford University. URL: https://plato.stanford.edu/archives/fall2018/entries/qm-manyworlds/ (visited on 05/26/2021).

Wootters, W. K. and W. H. Zurek (Oct. 1982). "A single quantum cannot be cloned". en. In: *Nature* 299.5886, pp. 802–803. ISSN: 0028-0836, 1476-4687. DOI: 10.1038/299802a0. URL: http://www.nature.com/articles/299802a0 (visited on 05/25/2021).