Science & Philosophy Volume 7(2), 2019, pp. 59-70

A model for the solution of the quantum measurement problem

Biswaranjan Dikshit[*]

Abstract

The basic idea of quantum mechanics is that the property of any system can be in a state of superposition of various possibilities (or eigen states). This state of superposition is also known as wave function and it evolves linearly with time in a deterministic way in accordance with the Schrodinger equation. However, when a measurement is carried out on the system to determine the value of that property (say position), the system instantaneously transforms to one of the eigen states and thus we get only a single value as an outcome of the measurement. Quantum measurement problem seeks to find the cause and exact mechanism governing this transformation. In an attempt to solve the above problem, in this paper, we will first define what the wave function represents in real-world and will identify the root cause behind the stochastic nature of events. Then, we will develop a model to explain the mechanism of collapse of the quantum mechanical wave function in response to a measurement. In the process of development of model, we will explain Schrodinger cat paradox and will show how Born's rule for probability becomes a natural consequence of the measurement process.

Keywords: Quantum measurement problem, Born's rule, Schrodinger cat paradox, Biased will theory.[†]

---

[*] Laser and Plasma Technology Division, Bhabha Atomic Research Centre, Mumbai-400085, India and Homi Bhabha National Institute, Mumbai, India; e-mail address: bdikshit73@yahoo.co.in

[†] Received on December 9th, 2019. Accepted on December 21st, 2019. Published on December 31st, 2019. doi:10.23756/sp.v7i2.482. ISSN 2282-7757; eISSN 2282-7765.

1. Introduction

As per modern physics, all processes in nature are governed by laws of quantum mechanics. Till date, no violation of quantum mechanical laws has been observed in experiments. Even for macroscopic bodies, each classical event can be explained as a consequence of a large number of quantum processes happening at the microlevel. The most interesting characteristic of quantum mechanics is that it permits a system to be in the state of superposition of all possible values represented by orthogonal vectors for any physically observable property. The vector space created by these possibilities (eigenvectors) is known as Hilbert space and the state vector of the system lies in this Hilbert space. For example, spin angular momentum of an electron can be in a mixed state of $+\frac{1}{2}\hbar$ (up) and $-\frac{1}{2}\hbar$ (down) spins although the measurement yields only a single value, either up or down. Similarly, the position of a particle in a box can be superposition all possible values although its measurement by an external body gives us only a single value for the position. The generalized superposition state of the quantum mechanical system is also known as a wave function. When we measure a physical property, the probability of finding a specific value is given by Born's rule which states that probability is proportional to the square of the component corresponding to that value in the state vector. Stated simply, the probability is proportional to the square of the wavefunction. Immediately after the measurement, the state of the system is found to be same as the eigen state of the value it exhibited. Thus, although the state vector, in general, evolves deterministically and linearly with time as per the Schrodinger equation, in response to the act of measurement, the state or wave function instantaneously collapses to one of the eigen states. Quantum measurement problem seeks to understand what is it in the measurement process that stimulates the wave function collapse and how does this wave function collapse exactly occur in nature. The Copenhagen interpretation (by Bohr and others), the oldest interpretation of quantum mechanics believes that certain '*something*' happens during the act of measurement which collapses the wave function. But, it is unable to find out what this "*something*" is. Rather, it takes up an often-quoted stand "shut up and calculate" [1].

Many-worlds theory [2-4] rejects altogether the phenomenon of wave function collapse. It suggests, at the time of measurement, the universe just makes many copies of itself in which all the possibilities happen. The question still remains, why we happen to be in the universe in which a specific value of the physical property was observed. In other words, this theory doesn't explain the mechanism for choosing one out of many possible options. In addition, methods of the derivation of Born’s rule for probability by many-worlds theories have been proved to be circular by many researchers [5-10].

Meanwhile, Einstein, Podolskey and Rosen [11] had suggested that some local hidden pre-existing variables in the system (which are not normally considered by quantum mechanics) might be responsible for observation of a particular value instead of other values. By assuming this local hidden variable theory to be the correct, Bell [12] derived an inequality expression for the spin correlation among entangled pairs of particles which was in contradiction with the quantum mechanical prediction. Consequently, a large number of experiments [13-21] have been carried out which demonstrate the violation of Bell’s inequality and thus explanations based on local hidden variable theory are ruled out for the solution of the measurement problem.

Recently, non-local (or global) hidden variable theories like deterministic Bohmian mechanics [22-23] for the solution of measurement problem have also been proved to be incompatible with quantum mechanics and relativity by Leggets [24] and Gisin [25]. Groblacher [26-27] has reported experimental results demonstrating the inconsistencies of non-local hidden variable theory. Groblacher stated [26], “Our result suggests that giving up the concept of locality is not sufficient to be consistent with quantum experiments unless certain intuitive features of realism are abandoned”.

The GRW theory [28-29] tries to explain only the collapse of the macroscopic measurement system and that too by assuming spontaneous collapse of the microscopic objects. This theory doesn’t provide any explanation for the spontaneous collapse of microscopic system. In this approach, an additional stochastic term is postulated in the quantum dynamical equation without the required logical reasoning. So, this approach for the solution of the measurement problem is not convincing.

Decoherence theory [30-31] identifies the environmental monitoring as the cause for the destruction of quantum coherence between classical pointer states and hence for expression of a single value of observable out of many possibilities. However, the quantum mechanical measurement problem is also applicable for a microscopic isolated system for which above theory doesn’t have any explanation. In addition, decoherence theory doesn’t explain the mechanism for choosing a specific eigenvalue by the system during measurement. That’s why even one of the proponents of decoherence theory, Joos [32] has stated “Does decoherence solve the measurement problem? Clearly not. What decoherence tells us is that certain objects appear classical when observed”. In another article titled “Why decoherence has not solved the measurement problem: a response to P. W. Anderson”, Adler [33] has given a mathematical treatment to justify the fact that decoherence theory doesn’t solve the measurement problem.

In this paper, we will propose a theoretical model for the solution of quantum mechanical measurement problem. We will explain the mechanism of collapse of the quantum mechanical wave function during measurement and will also identify the root cause behind the probabilistic nature of events. We will explain the Schrodinger cat paradox and will show how Born’s rule for probability becomes a natural consequence of the measurement process. The uniqueness of the present derivation of Born’s rule as compared to our purely mathematical approach [34] published earlier is that it identifies the exact mechanism in which Born’s rule comes into picture during the process of collapse of the quantum mechanical wave function.

2. Proposed model for the solution of the quantum measurement problem

To explain the stochastic nature of every particle, initially, Schrodinger [35] and then Coway and Kochen [36-37] proposed that every elementary particle in the universe might have *free will* which causes the uncertainty or randomness in events. In our recently published paper [38], we have proposed *biased will* theory which provides a theoretical justification for the form of the quantum mechanical wave function of a free particle so that quantum mechanical operators can be derived on which the whole of quantum mechanics stands. This theory was also able to derive the quantum mechanical probability distribution for the spin of a particle. The biased will theory assumes the existence of *will* in every inanimate object and states that quantum processes proceed in a direction so as to achieve collective goals of the universe or coherent assembly of particles. This explains the recently reported adaptive mutation in the DNA of bacteria [39-40]. In response to a changing environment, mutations in E. Coli bacteria (which are quantum processes) instead of being random were found to be biased in a direction such that the chance of survival of the bacteria is increased.

In the background of the above developments, we will assume that each fundamental particle or any coherent system has consciousness and has its own *thought* which decides its behavior in the physical world. What is known as the wave function or state vector is actually the *thought* of the particle. Because thought can contain mutually exclusive options at the same time, the wave function can also be the superposition of various physical possibilities. For example, suppose you enter a city and you are thinking of which hotel to stay in. You can think of many hotels simultaneously although your actual physical stay can only be in a single hotel. Similarly, an electron can be in a state of superposition of ‘up’ and ‘down’ spins until it is required to physically interact with the external world using one of the options. Since the position is just a property expressed by a particle during interaction with another body, it (i.e. position) can also be in a state of superposition which is commonly known as wave function in position space. Just like *thought* resides in our mind, wave function resides in the multidimensional space of possibilities technically known as Hilbert space. So, we can identify the Hilbert space to be same as the mind of particle.

Regarding evolution, the dynamics of our thought depends upon our own present state, environmental conditions and future objectives. For example, our thought to select a hotel in a new city will be guided by considerations such as our financial status, the information we have collected about nearby hotels, which hotel is nearer to our workplace and our goal such as whether we need to save money or have the luxury. Similarly, the position of interference maxima of a particle depends on its properties carried over from past (such as momentum, energy), environment (how many slits are there) and what is the ultimate goal (like conservation of momentum, energy and maintaining symmetry of space that gives rise to wave behavior [38]). So, dynamically, thought and quantum mechanical wave function (or state vector) behave in the same manner.

Since we have identified the state vector or wave function as the *thought* carried by the particle, we will now address the core question of why and how wave function collapses during measurement. Measurement of any observable is a two-step process. The first step is interaction and second is awareness about this interaction by some subject. It is the first step only i.e. *interaction* that causes the collapse of the wave function. Collapse has nothing to do whether this interaction is observed by some living being or not. So, ours is an objective interpretation. We support this idea as even when living beings were not created, this universe did exist and evolved in accordance with the laws of quantum mechanics. The interaction causes collapse of the wave function as in this nature two systems can physically interact with each other only if each of them has a specific value of the observable (not a superposition). Using this line of thought, we can explain the Schrodinger cat paradox as given below.

In Schrodinger cat problem, a cat along with a radioactive nucleus and a bottle filled with poisonous gas is kept in a box. As soon as the radioactive decay occurs, it triggers an electronic circuit which ultimately breaks the bottle and the poisonous gas comes out killing the cat. Conventionally, it is said that if the box is closed for a long time, the nucleus remains in a state of superposition of 'decayed' and 'un-decayed'. So, the cat also remains in a state of superposition of 'alive' and 'dead'. When the observer opens the box, he forces the system to take a stand and so, he is indirectly responsible for death or life of the cat. Of course, the conclusion here is paradoxical or flawed. This is because we have started from an un-decayed nucleus and just by closing the box so that no one observes it, it doesn't go into a state of superposition. An observation can certainly change the quantum state of a system from a superposition state to a specific eigen state as it is also an interaction. But the opposite is not true. *Non-observation of a system cannot bring it from an eigen state to superposition state.* So, Einstein correctly commented, "Isn't moon there in the sky when no one looks at it?". In case of Schrodinger cat problem, since we have started from a live cat and an undecayed nucleus, they remain so *till* the radioactive decay event. Radioactive decay occurs not by personal observation, but by physical interaction between quarks or nucleons. The quarks are in continuous motion inside the nucleus and constantly try to break the nucleus. Within a few minutes, they are subjected to a huge number of trials and they can succeed at any time. As soon as they succeed, the electronic circuit is triggered, the bottle breaks and the cat goes to the state of "dead". The cat doesn't wait for us to open the box (i.e. for our observation) to change its state. So, when we open the box, we only get to know about the state of the cat after possible interactions that have already happened inside the box and the observer opening the window is in no way responsible for the death of the cat.

So, after clarifying that it is only the interaction which causes the collapse of the wave function, let us now understand the mechanism of collapse. At first, we will consider the example of the spin of an electron as it is the simplest case in the sense that it has only two options i.e. +½$\hbar$ (up) and -½ $\hbar$ (down). As explained earlier, spin can be in a state of superposition of 'up' and 'down' spins until it is required to physically interact with the external world through magnetic moment generated by its one of the options. Using Dirac notation for vectors, let us represent the normalized system state vector by $|\psi\rangle$, 'up' spin by eigenvector $|A\rangle$ and 'down' spin by eigenvector $|B\rangle$ as shown in Fig. 1. Writing $|\psi\rangle$ as a vector sum of its components along eigenvectors,

$$|\psi\rangle = \overrightarrow{OP} + \overrightarrow{PS} \tag{1}$$

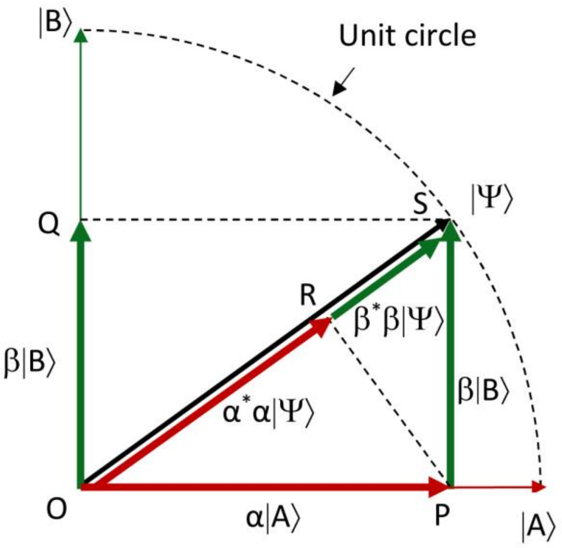

Fig. 1 Vectorial representation of superposition state and eigen states of a quantum system

Using the definition of projection operator and writing

$$\langle A|\psi\rangle=\alpha \quad and \quad \langle B|\psi\rangle=\beta \tag{2}$$

We get, $\overrightarrow{OP}$ = Projection of $|\psi\rangle$ along $|A\rangle = |A\rangle\langle A|\psi\rangle = |A\rangle\alpha$ (3)

And $\overrightarrow{PS}$ = Projection of $|\psi\rangle$ along $|B\rangle = |B\rangle\langle B|\psi\rangle = |B\rangle\beta$ (4)

We know, actions of any human being is generally decided by his or her own thought. Similarly, since state vector $|\psi\rangle$ is considered to be a kind of thought carried by the particle, the physical behavior of the particle is decided by the vector components ***collinear*** with state $|\psi\rangle$. In Fig.1, along $|\psi\rangle$, the collinear components contributed by eigen vectors are given by,

$\overrightarrow{OR}$ =Projection of $\overrightarrow{OP}$ along $|\psi\rangle$

$= |\psi\rangle\langle\psi|A\rangle\alpha = |\psi\rangle\alpha^*\alpha$ (Using Eq. (2))

$= |\alpha|^2|\psi\rangle$

Similarly,

$\overrightarrow{RS}$ =Projection of $\overrightarrow{PS}$ along $|\psi\rangle$

$= |\psi\rangle\langle\psi|B\rangle\beta = |\psi\rangle\beta^*\beta$ (Using Eq. (2))

$$= |\beta|^2 |\psi\rangle$$

Thus, we find that the magnitudes of collinear vectors contributed by eigen vectors $|A\rangle$ and $|B\rangle$ are $|\alpha|^2$ and $|\beta|^2$ respectively. When the system (or particle) encounters an external object (say measuring equipment) for possible interaction, it selects any point at random on line OS in Fig. 1. This is the step where the particle makes an acausal selection due to the virtue of its *creativity*. Whichever collinear component the selected point falls on, the system tends to expand that to acquire the full magnitude of unity by instantaneously rotating the state vector to coincide with the corresponding eigen vector (as only a single value for the observable is physically allowed). However, this rotation of state vector occurs only if the interaction of the particle with external body is possible with the help of selected eigen vector. This is how the collapse of the wave function occurs. As the probability of selecting a point on a collinear vector is equal to its magnitude $|\alpha|^2$ or $|\beta|^2$, probability of collapse of the state $|\psi\rangle$ to any eigen vector $|A\rangle$ or $|B\rangle$ is also $|\alpha|^2$ or $|\beta|^2$ respectively. Thus, the Born's rule for probability of interaction come into picture.

The mechanism for collapse of the wave function when there are many possible values for the observable (such as wave function for position) can similarly be explained. Like other properties of a quantum system, the position is just another physical property expressed by the particle. However, since the position is continuous, it has infinite possible values. So, position state vector (in our language, thought that decides the choice of position) lies in an infinite-dimensional Hilbert space. If x_i is any position of the particle in space, $|x_i\rangle$ is the corresponding eigenvector, $|\psi\rangle$ is position state vector and $\psi(x_i)$ is the wave function,

$$|\psi\rangle = \sum \psi(x_i)|x_i\rangle \qquad (5)$$

The projection of $|\psi\rangle$ on $|x_i\rangle$ is $\psi(x_i)|x_i\rangle$. As calculated earlier, the magnitude of the projection of $\psi(x_i)|x_i\rangle$ along the state vector $|\psi\rangle$ is given by,

$$M = \langle\psi| \left(\psi(x_i)|x_i\rangle\right) \qquad (6)$$

Using Eq. (5) in Eq. (6),

$$M = \left(\sum \psi(x_j)^* \langle x_j|\right) \left(\psi(x_i)|x_i\rangle\right) \qquad 7)$$

As all eigenvectors $|x_i\rangle$ are orthogonal to each other, the terms in Eq. (7) involving dot product of any two vectors with $i \neq j$ are zero. So, Eq. (7) becomes,

$$M = \psi(x_i)^* \langle x_i | \psi(x_i) | x_i \rangle$$

Or $$M = \psi(x_i)^* \psi(x_i) = |\psi(x_i)|^2 \tag{8}$$

Thus, the magnitude of the collinear component contributed by any eigenvector corresponding to a particular position is equal to the square of the wave function as given in Eq. (8). In response to a stimulus, the system randomly selects any point on the state vector using its own creativity and the collinear component on which this point falls instantaneously expands to become the complete eigenvector and other components die out (of course only if there is a scope of interaction). This is made possible by the state vector rotating instantaneously towards the eigenvector corresponding to the selected collinear component. Since the probability of selection of a collinear component is proportional to its magnitude which ultimately is proportional to the square of the wave function, probability of interaction is given by $|\psi(x)|^2$. That's why, when a single particle passes through a slit and encounters a detector, either it is detected with a probability of $|\psi(x)|^2$ or it moves forward unaffected in a superposed state.

3. Conclusions

In this paper, to solve the quantum mechanical measurement problem, we have developed a model to explain the mechanism of the collapse of the wave function in response to a measurement attempt. We have identified that the root cause behind the stochastic nature of events in nature is the thought process (or creativity) present in every inanimate particle or quantum system. The cause of the collapse is the physical interaction between two bodies (not the observation or awareness by conscious human beings). In this light, we have understood the Schrodinger cat paradox. Last but not the least, our analysis correctly reproduces the Born's rule for the probability of quantum interaction for which no convincing proof using other approaches exists.

References

[1] N. David Mermin. Could Feynman Have Said This?. Physics Today, 57 (5), 10. 2004.

[2] David Deutsch. Quantum theory of probability and decisions. Proc. R. Soc. Lond. A, **455**,3129-3137. 1999

[3] Edward Farhi, Jeffrey Goldstone and Sam Gutmann, How Probability Arises in Quantum Mechanics. Annals of Physics, **192**, 368-382. 1989.

[4] J B Hartle. Quantum mechanics of Individual systems. American Journal of Physics, **36**(8), 704-712. 1968

[5] Meir Hemmo and Itamar Pitowsky. Quantum probability and many worlds. Studies in History and Philosophy of Modern Physics, **38,** 333-350. 2007.

[6] David J. Baker. Measurement outcomes and probability in Everettian quantum mechanics. Studies in History and Philosophy of Modern Physics, **38**, 153-169. 2007.

[7] Adrian Kent. Against Many-Worlds Interpretations. Int. J. Mod. Phys. A, **5**, 1745-1762. 1990.

[8] Andres Cassinello and Jose Luis Sanchez-Gomez. On the probabilistic postulate of quantum mechanics. Foundations of Physics, **26** (10), 1357-1374. 1996.

[9] Carlton M. Caves and Rudiger Schack. Properties of the frequency operator do not imply the quantum probability postulate. Annals of Physics, **315**, 123–146. 2005.

[10] Euan J. Squires. On an alleged “proof” of the quantum probability law. Physics Letters A, **145** (2-3), 67-68. 1990.

[11] A Einstein, B Podolsky and N Rosen. Can Quantum-Mechanical Description of Physical reality be considered complete?. Physical Review, **47**, 777-780. 1935.

[12] J S Bell, “On the Einstein Podolsky Rosen paradox”, Physics, **1** (3), 195-200 (1964)

[13] Alain Aspect, Philippe Grangier and Gerard Roger. Experimental realization of Einstein-Podolsky-Rosen-Bohm Gedanken experiment: A new violation of Bell’s inequalities. Physical Review Letters, **49** (2), 91-94. 1982.

[14] Alain Aspect, Jean Dalibard and Gerard Roger. Experimental test of Bell’s inequalities using time varying analyzers. Physical Review Letters, **49** (25), 1804-1807. 1982.

[15] Alain Aspect. Bell’s inequality test: more ideal than ever. Nature, **398**, 189-190. 1999.

[16] W Tittel, J Brendel, H Zbinden and N Gisin. Violation of Bell inequalities by photons more than 10 km apart. Physical Review Letters, **81** (17), 3563-3566. 1998.

[17] Z Y Ou and L Mandel. Violation of Bell’s inequality and classical probability in a two-photon correlation experiment. Physical Review Letters, **61** (1), 50-53. 1988.

[18] Y H Shih and C O Alley. New type of Einstein-Podolsky-Rosen-Bohm experiment using pairs of light quanta produced by optical parametric down conversion. Physical Review Letters, **61** (26), 2921-2924. 1988.

[19] Gregor Weihs, Thomas Jennewein, Christoph Simon, Harald Weinfurter and Anton Zeilinger. Violation of Bell’s inequality under strict Einstein Locality conditions. Physical Review Letters, **81** (23), 5039-5043. 1998.

[20] Roger Colbeck and Renato Renner, “No extension of quantum theory can have improved predictive power”, Nature communications, **2**:411, 1-5 (2011)

[21] Zeeya Merali. Quantum Mechanics Braces for the ultimate test. Science, **331**, 1380-1382. 2011.

[22] David Bohm. A Suggested Interpretation of the Quantum theory in terms of “Hidden” variables. I. Physical Review, **85** (2), 166-179. 1952.

[23] Marco Genovese. Research on hidden variable theories: A review of recent progresses. Physics Reports, **413**, 319-396. 2005.

[24] A J Leggett. Nonlocal Hidden-Variable Theories and Quantum mechanics: An incompatibility theorem. Foundations of Physics, **33** (10), 1469-1493. 2003.

[25] Nicolas Gisin. Impossibility of covariant deterministic nonlocal hidden-variable extensions of quantum theory. Physical Review A, **83**, 020102(R). 2011.

[26] Simon Groblacher, Tomasz Paterek, Rainer Kaltenbaek, Caslav Brikner, Marek Zukowski, Markus Aspelmeyer and Anton Zeilinger. An experimental test of non-local realism. Nature, **446**, 871-875. 2007.

[27] Tomasz Paterek, Alessandro Fedrizz, Simon Groblacher, Thomas Jennewein, Marek Zukowski, Markus Aspelmeyer and Anton Zeilinger. Experimental test of Nonlocal Realistic theories without the Rotational Symmetry assumption. Physical Review Letters, **99**, 210406, 1-4. 2007.

[28] G C Ghirardi, A Rimini and T weber. Unified dynamics for microscopic and macroscopic systems. Physical Review D, **34** (2), 470-491. 1986.

[29] Gian Carlo Ghirardi, Philip Pearle and Alberto Rimini. Markov processes in Hilbert space and continuous spontaneous localization of systems of identical particles. Physical Review A, **42** (1), 78-89. 1990.

[30] Wojciech Hubert Zurek. Decoherence, einselection, and the quantum origins of the classical. Reviews of Modern Physics, **75** (3), 715-775. 2003.

[31] Wojciech H. Zurek. Decoherence and the transition from quantum to classical. Physics Today, **44** (10), 36-44. 1991.

[32] E. Joos. Elements of environmental decoherence. In P. Blanchard, D. Giulini, E. Joos, C. Kiefer, I.-O. Stamatescu (Eds.), Decoherence: Theoretical, experimental, and conceptual problems (pp. 1–17). New York: Springer, 1999

[33] Stephen L Adler. Why decoherence has not solved the measurement problem: a response to P. W. Anderson. Studies in history and Philosophy of Modern physics, 34, 135-142. 2003.

[34] Biswaranjan Dikshit. A simple proof of Born’s rule for statistical interpretation of quantum mechanics. Journal for Foundations and Applications of Physics, **4** (1), 24-30. 2017.

[35] E Schrodinger. Indeterminism and Free will. Nature, **138**, 13-14. 1936.

[36] John Conway and Simon Kochen. The free will theorem. Foundations of Physics, **36** (10), 1441-1473. 2006.

[37] John H. Conway and Simon Kochen. The strong free will theorem. Notices of the AMS, **56** (2), 226-232. 2009.

[38] Biswaranjan Dikshit. Origin of Quantum Mechanical Results and Life: A Clue from Quantum Biology. NeuroQuantology, **16** (4), 26-33. 2018.

[39] Zeeya Merali. Solving Biology's Mysteries Using Quantum Mechanics. Discover, December 29. 2014 (http://discovermagazine.com/2014/dec/17-this-quantum-life)

[40] Johnjoe McFadden and Jim Al-Khalili. A quantum mechanical model of adaptive mutation. Biosystems, **50**, 203 – 211. 1999.