Zagadnienia Filozoficzne
w Nauce
XXXVII (2005), 119–139

Wojciech P. Grygiel
Pontifical Academy of Theology,
Faculty of Philosophy
Kraków

IS SCHRÖDINGER'S CAT DEAD OR ALIVE?

1. INTRODUCTORY REMARKS

Quantum mechanics is a contemporary physical theory that involves high level of mathematical complexity and abstraction. Classical mechanics easily associates values of physical quantities with properties of the objects of its study whereby it makes its method transparent for human common sense. The predominance of abstract structures made its mark already in the 19$^{\text{th}}$ century in the theory of electromagnetism where Maxwell applied the notion of a vector field. Defined by the use of strict mathematical language, this notion remains outside of the reach of human intuition. The problem escalates in case of quantum mechanics and the theory of relativity insofar as their spectacular results are achieved exclusively by means of complex mathematical apparatus. Since quantum mechanics utilizes the notions of a wave function and probability, it is necessary to develop a transitory basis to specify how these notions are refracted in the world of physical experiment, namely, where the output of a measurement is a number. The translation of the mathematical language into what may be intuitively perceptible is achieved by means of an *interpretation.* A prominent French theoretical physicist, Roland

Omnes maintains that the advent of abstractness and formalness that penetrates into the very heart of reality defeats the common sense together with its philosophical principles so that a new way of understanding may need to be invented.[1] Although it remains within the realm of speculation whether such radical means have to be resorted to, Omnes' assertion well illustrates how a philosophical (precisely epistemological) problem may arise in the context of natural sciences.

Inasmuch as the theory of relativity has found a consistent language of non–euclidean geometries, the framework of quantum mechanics is still seeking a meaningful way to correlate its inherent probabilism with a single experimental fact obtained through a measurement. For early masters such as Niels Bohr, quantum mechanics did not describe physical reality but offered only a formal means to accumulate the entire knowledge about a system under study (*quantum completedness*).[2] Technically speaking, in such instance one does not compute the values of physical quantities but the probabilities wherewith these values will occur. This approach, known as the Copenhagen Interpretation, resulted in the bifurcation of reality into the realm of the observer (measuring device) and the system under study thereby giving rise to the famous *measurement problem*. As an upshot, this interpretation did not equip quantum mechanics with the precise conditions of its experimental verification.[3] Bohr's standpoint was opposed by the great proponent of physical realism, Albert Einstein. He demanded that what is obtained in a measurement must correspond to an existing reality within a system. Also, he stipulated

[1] R. Omnes, *Quantum Philosophy: Understanding and Interpreting Contemporary Science*, Princeton and Oxford: Princeton University Press 1999, 82.

[2] N. Bohr, Quantum Mechanics and Physical Reality, *Nature* 136 (1935) 1025.

[3] R. Omnes, Consistent Interpretations of Quantum Mechanics, *Reviews of Modern Physics* 64 (2), April 1992, 340.

that since quantum mechanics does not fully correlate with reality (non–localities), it must be *incomplete*.[4]

The most virulent concerns of quantum mechanics prompted advancements in its mathematical framework as well. German mathematician, Johann von Neumann ranks among the most prominent in this matter especially in regards to his systematic treatment of multistate quantum systems within Hilbert spaces.[5] Also, he coined out the idea of the *wave function collapse* as an attempt to resolve the measurement problem. Aside from their physical significance, these developments generated a number of conceptual problems that found their expression in the paradox of the **Schrödinger's Cat** proposed by one of the founders of quantum mechanics, Edwin Schrödinger in 1935.[6] The gist of the paradox consists in the question whether a macro–physical system such as a cat can exist in a superposition of states as demanded by the general expression for the wave function of a multistate system. Moreover, it must be addressed whether the measurement that effects the collapse of the wave function decides about the fate of the cat. In short, whether it is the observer who kills or saves the cat. Within the Copenhagen paradigm, the paradox emphasizes the specificity of quantum mechanics in its insistence on the radical separation of the observer and the system under study.

The aim of this article is to demonstrate the solution of the Schrödinger's Cat paradox based on several newer developments in quantum mechanics. These developments seek to provide a larger interpretational framework in which the measurement problem can be treated in a consistent way so as to eliminate

[4] A. Einstein, B. Podolski, N. Rosen, Can Quantum Mechanical Description of Physical Reality Be Considered Complete?, *Physical Review* 47 (1935) 777–780.

[5] J. von Neumann, *Mathematical Foundations of Quantum Mechanics*, trans. R.T. Geyer, Princeton: Princeton University Press 1955.

[6] E. Schrödinger, Die gegenwärtige Situation in der Quantenmechanik, *Die Naturwissenschaften* 23 (1935) 807 sq.

the observer/observed dichotomy. This framework is referred to as *consistent histories* interpretation that was first proposed by Robert Griffiths in 1984.[7] One of its main ideas follows the intuition of von Neumann who insisted on the use of the quantum mechanical formalism in the description of both the measuring device as well as the measured system contrary to what was postulated by Niels Bohr. In particular, the phenomenon of *decoherence* that is responsible for the ultra fast quenching of quantum superposition states explains the emergence of the classical world out of the quantum realm and has been already confirmed experimentally.[8] Consequently, decoherence comes to the rescue of the Schrödinger's Cat paradox insofar as it stipulates the instantaneous disappearance of its 'quantum suspension state' to yield *either* a dead *or* an alive cat. This result bears philosophical significance because it not only accents the reality of the quantum micro–world but it also characterizes the process of transition (emergence) into the macro–world perceived 'classically' by human common sense. Lastly, it alleviates the torments of a poor cat oscillating between life and death in the clutches of a multistate wave function.

2. BACK TO BASICS

The accomplishment of the task of precise deciphering the nuances of the Schrödinger's Cat paradox with the aid of the phenomenon of decoherence demands a brief detour into the specifics of quantum mechanics alone. Although history of science rightly dates the beginnings of quantum mechanics to the quantum of

[7] R.B. Griffiths, Consistent Histories and the Interpretation of Quantum Mechanics, *Journal of Statistical Physics* 36 (1984) 219–272. See also: R. Omnes, *Understanding Quantum Mechanics*, Princeton: Princeton University Press 1999, 157–168.

[8] R. Omnes, *Understanding Quantum Mechanics*, Princeton: Princeton University Press 1999, 197–207.

hypothesis of Max Planck in 1900, the road to strict quantum formalism was paved by the wave–corpuscular dualism expressed in the matter wave hypothesis proposed by Louis de Broglie (1925). Since a mass can be correlated with a wave, the mathematical formalism used in wave mechanics will now apply to the description of moving particles. In other words, the state of a particle will be characterized by a wave function Ψ. As a result, the location of a particle in space is governed by the spatial indeterminacy of a wave for distances smaller than $\lambda/2$. This gives rise to the famous Heisenberg uncertainty principle.[9] Unlike in classical mechanics, each physical property is assigned an operator $\hat{\mathbf{A}}$ so that the only observable values corresponding to this property are the eigenvalues of the operator[10]:

$$\hat{\mathbf{A}}|\Psi>= a|\Psi> .$$

The quantum mechanical wave functions belong to the Hilbert space (a linear vector space with a scalar product). The operators are Hermitian resulting in their eigenvectors being orthogonal and eigenvalues real. This best suits the treatment of physical systems. The time evolution of a wave function is described by the time dependent Schrödinger equation that is entirely deterministic and reversible:

$$i\hbar\frac{\partial}{\partial t}|\psi>= \hat{\mathbf{H}}|\psi> .$$

$\hat{\mathbf{H}}$ is the quantum analogue of the Hamilton energy operator (Hamiltonian) where momentum is replaced by an appropriate momentum operator. Due to the fact that $\hat{\mathbf{H}}$ is a unitary operator, the above evolution will be further referred to as the unitary

[9] A good account of the historical development of quantum mechanics can be found in: W. Heisenberg, *Physics and Philosophy*, New York: Harper & Brothers Publishers 1958, 30–75.

[10] For standard exposition of the principles of quantum mechanics see for example: Ch. Isham, *Lectures on Quantum Theory: Mathematical and Structural Foundations*, London: Imperial College Press 1995.

procedure **U**. For a multistate system, the expression for the total wave function Ψ involves the linear superposition of all contributing single state eigenfunctions ψ_i in the Hilbert space:

$$|\Psi> = \sum_i c_i |\psi_i> .$$

According to the interpretation of wave functions proposed by Max Born (1925), the probability density of finding the particle described by $|\Psi>$ in a particular eigenstate $|\psi_i>$ is $|\psi_i|^2$. At this point it is worthwhile to stress that while in classical mechanics these are the values of measured properties that evolve, quantum mechanics considers the evolution of wave functions in time and, consequently, the time evolution of the distribution of probabilities to obtain respective observables in a measurement. However, nothing is stated whether a system has any real values related to the physical quantities concerned before the measurements are made. This assertion led to a prolonged discussion on the ontological status of quantum mechanics, namely, whether there is a correspondence between quantum description of measured systems and reality (the famous Bohr/Einstein controversy mentioned in the opening paragraphs).[11] Presently, the so called EPR experiments confirm the predictions of quantum theory suggesting that the reality of the micro–world obeys the quantum laws. The most precise and most convincing results were obtained in the experiments with photons performed in 1986 by Alain Aspect and his colleagues.[12]

In 1930's, John von Neumann, mentioned already in a previous paragraph, embedded quantum mechanics within the abstract theory of Hilbert spaces and developed a formal approach to the measurement problem by introducing the notion of the reduction

[11] M. Jammer, *The Philosophy of Quantum Mechanics*, New York: Wiley 1974.

[12] A. Aspect, P. Grangier, Experiments on Einstein–Podolsky–Rosen–Type Correlations with Pairs of Visible Photons, in: R. Penrose, C.I. Isham (ed.), *Quantum Concepts in Space and Time*, Oxford: Oxford University Press 1986.

of the wave vector, known otherwise as the "quantum leap". In the nomenclature used by Penrose, this process is denoted as procedure **R** in order to emphasize its radical irreversibility and discontinuity in distinction to the reversible and continuous unitary evolution **U** of the wave function according to the Schrödinger equation.[13] In short, the measurement process that effects the reduction of the vector selects out a single value of a measured quantity from among all those that contribute to the multistate wave function $|\Psi>$:

$$|\Psi>= \sum_i c_i|\psi_i> \Rightarrow |\psi_i> \Rightarrow a_i$$

where a_i is the eigenvalue corresponding to $|\psi_i>$. The discontinuity of this transition causes the radical incompatibility of procedures **U** and **R**. It is precisely this discontinuity that underlies most conceptual and interpretational problems of quantum mechanics. It finds no resolution within the context of the classical Copenhagen interpretation insofar as this interpretation does not account for the **U**/**R** leap and thus provides no context for experimental verification of quantum mechanics. Also, it gives rise to the Schrödinger's Cat paradox.

3. THE PARADOX REVISITED

The Schrödinger's Cat Paradox is an ingenious thought experiment conjured up by one of the leading founders of quantum mechanics, Edwin Schrödinger in 1935. In Schrödinger's own words, the details are as follows:

> One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following diabolical device (which must be secured against direct interference

[13] R. Penrose, *The Road to Reality: A Complete Guide to the Laws of the Universe*, New York: Alfred A. Knopf 2005, 527 et sq.

> by the cat): in a Geiger counter there is a tiny bit of radioactive substance, so small that perhaps in the course of one hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The first atomic decay would have poisoned it. The Psi function for the entire system would express this by having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts.[14]

Although much ink has been spilled about possible physical as well as philosophical consequences of this experiment, it is still haunted by a number of misconceptions. The one proposed with least caution states that it is the conscious observer who by the very act of opening the box determines the fate of the cat otherwise suspended in a superposition state between life and death as expressed by the wave function:

$$|\Psi> = c_a|\psi_a> + c_d|\psi_d>$$

where subscripts a and d refer to an alive and a dead cat, respectively.

Such an assertion involves much of a reductionist attitude for it bypasses several conceptual issues involved in the paradox. First of all, it does not corroborate with the Copenhagen Interpretation. This interpretation stipulates that quantum mechanics is a theory that accumulates our knowledge about the system under study and permits calculations of probabilities of obtaining certain values of physical properties in an experiment. By expressing the state of a system in a form of a superposition of wave functions corresponding to single eigenstates (see the formula in a previous

[14] E. Schrödinger, *op. cit.*

paragraph), it relates the indeterminacy of the observer's knowledge as to the actual state of the system to be resolved through an act of a measurement with a respective probability. It does not aspire to correlate the condition of the system with an objective reality before the measurement is accomplished. Within the Copenhagen paradigm, the representation of the cat as suspended between life and death in a superposition state is intrinsic to the theory for the purpose of computing probabilities and makes no 'reality' claims. It is worthwhile to mention that this 'low–risk' approach to quantum mechanics is often referred to as 'pragmatic'.[15] Following the intuition of Werner Heisenberg, the act of the observation of the cat actualizes its potency to assume a given state from among all that are available, namely, dead or alive. The emphasis, however, is laid on the increase of the observer's knowledge in regards to the cat's destiny rather than on the objective fact of calling the cat to a definite existence out of the limbo of a superposition state.[16] Consequently, to say that it is the intervention of an observer that decides on the fate of the cat within the framework of the Copenhagen interpretation, does not quite square with the predominantly epistemic character of this interpretation.

Another concern in regards to the Schrödinger's Cat paradox as seen by the Copenhagen Interpretation has been raised by Roger Penrose. It challenges the epistemic character of this interpretation by proposing to place two observers of the experiment: one inside of the box and the other one outside of it.[17] There is no doubt that the one inside the box would observe the cat at a much earlier stage of the experiment as compared to the one outside the box. The immediate question that arises at this point is when exactly the reduction **R** of the 'kitty' wave function

[15] Ch. Isham, *op. cit.*, 81.

[16] W. Heisenberg, *Physics and Philosophy*, New York: Harper & Brothers Publishers 1958, 54.

[17] R. Penrose, *The Emperor's New Mind: Concerning Computers, Minds and the Laws of Physics*, Oxford: Oxford University Press 1989.

occurred? Inside the box or outside of it? Since the Copenhagen Interpretation bears primarily epistemic character, the wave function represents the knowledge of the observer and not the actual state of a system investigated. Indeed, this knowledge changed at different times due to their spatial separation within the experimental setup attesting to the minimal applicability of the Copenhagen Interpretation in the description of physical reality. Simply, it does not have much to say what indeed happened to the cat.

The final issue that demonstrates the drawbacks of the Copenhagen Interpretation relates to the restricted range of quantum treatment, namely, only in regards to the system studied. This introduces the observer/observed dichotomy mentioned in the paragraph above where the observer remains external with respect to the object of his investigation and is treated according to the precepts of classical physics. Consequently, quantum mechanics contains no conditions for its experimental verification within the Copenhagen Interpretation. It is precisely on these grounds that the interpretation is presently no longer considered as satisfactory and both its extensions as well as entirely new approaches are discussed. One of the preliminaries and in some ways prophetic intuitions in this area was given by Johann von Neumann (1932) who suggested that both the system measured and the measuring device be treated uniformly according to the same quantum formalism. Although the great complexity of the measuring apparatus due to its multi–atomic composition will introduce obvious formal intricacies, the fact that the atoms and particles it contains are subject to quantum laws justifies this crucial assumption. Moreover, the observer/observed dichotomy is practically eliminated whereby quantum mechanics gains new perspectives for broadened applicability. In such circumstances, the reduction of a wave vector might appear as an objective physical process unrelated to the subjective knowledge of an observer. These developments shift the tone of quantum mechanical interpretations towards physical realism.

In the article mentioned above Schrödinger states that:

> It is typical of these cases that an indeterminacy originally restricted to the atomic domain becomes transformed into macroscopic indeterminacy, which can then be resolved by direct observation. That prevents us from so naively accepting as valid a "blurred model" for representing reality. In itself it would not embody anything unclear or contradictory. There is a difference between a shaky or out–of–focus photograph and a snapshot of clouds and fog banks.
>
> We know that superposition of possible outcomes must exist simultaneously at a microscopic level because we can observe interference effects from these. We know (at least most of us know) that the cat in the box is dead, alive or dying and not in a smeared out state between the alternatives. When and how does the model of many microscopic possibilities resolve itself into a particular macroscopic state? When and how does the fog bank of microscopic possibilities transform itself to the blurred picture we have of a definite macroscopic state. That is the measurement problem and Schrödinger's cat is a simple and elegant explanation of that problem.[18]

The concern indicated here is definitely prior in regards to the measurement problem insofar as it poses the fundamental question whether a single particle quantum superposition state can be transferred on a macroscopic entity such as a cat. It is by no means trivial for, although the EPR experiments indicate the reality of superposition states for microscopic particles such as photons or electrons, a cat containing approximately 10^{26} atoms in its corpus will occasion numerous complex interactions and thus affect cat's total wave function (provided that such can be even thought of). In order to really appear in a superposition state (as described by the wave function above), a quantum cat would need to develop a strong interference between its being dead or alive as it occurs in case of subatomic particles. Mathematically speaking,

[18] E. Schrodinger, *op. cit.*

this necessitates that both a dead and an alive cat would somehow need to be correlated in phase of their motion so as to give rise to the magnitude of the interference term in the wave function expression. The common sense experience, reveals that such state of affairs is simply not observed. And rightly so, because a dead cat just does not move so there is nothing to be correlated with the one that is still alive.

4. DECOHERING THE QUANTUM CAT

Relatively recent advancements in quantum mechanics led to a plausible clarification of the lack of quantum interferences in macroscopic objects. They rely on two cardinal ideas mentioned previously, namely, (1) the entire 'observer/observed' arrangement is subject to a uniform quantum mechanical description, (2) quantum states are not only of epistemic value but they portray real physical properties. In other words, this approach extends the perspective of quantum mechanics insofar as it reaches beyond the boundaries of a system under study and situates quantum evolutions within the context of system's interactions with the environment. This idea underlies the so called *consistent histories interpretation* of quantum mechanics, first proposed by an American theoretical physicist, Robert Griffiths, in 1984 and further developed by Roland Omnes (1988) as well as Murray Gell–Mann and James Hartle in 1990.[19] A *history* is a sequence of quantum mechanical events ordered on a timescale to provide a series of 'snapshot' probes of an evolving quantum process so that a probability can be uniformly assigned to an entire history and not to a single observable. The authors of the interpretation claim that it yields a suitable framework of applying probabilities provided that certain consistency conditions are met. The main advantage of the histories interpretation is that it attempts

[19] Cf. Ref. 7.

to 'absorb' the measurement problem, that is, its broadened perspective permits the treatment of a measurement as intrinsic to any real quantum process and not as an external perturbation by an observer.

One of the major concerns within the histories interpretation is the quenching of the macroscopic quantum interferences as exemplified by the Schrödinger's Cat paradox. This issue has been hinted at in a quite simplified manner in a previous paragraph and in theoretical physics it is referred to as the effect of *decoherence*. Decoherence was first discovered by a German physicist Hans Dieter Zeh in 1970.[20] Detailed studies of this phenomenon conducted in 1970's and 80's revealed that decoherence is one of the most efficient processes in physics responsible for the vanishing of the macroscopic interferences. Following the intuition of Johann von Neumann, its fundamental assumption is that the same set of quantum laws applies both to the measuring device and the measured system such as an atom or a particle. In particular, one can consider a device that measures the z–component of an atomic spin that can assume only two values: $+\frac{1}{2}$ or $-\frac{1}{2}$. According to von Neumann's model of measurement, the measuring device consists of a simple needle with a ruler and its state before the measurement (needle at zero) is characterized by a wave function $\Psi_0(x)$ with a narrow peak at 0.[21] Upon the interaction with an atom with the z–spin component $\frac{1}{2}\left(-\frac{1}{2}\right)$, the measuring device's response is $+1(-1)$, respectively, with an appropriate wave function $\Psi_+(x)(\Psi_-(x))$ peaking narrowly for values of x in the closest vicinity of $+1(-1)$. The problem complicates when an atom with a definite x–spin component enters the measuring device for it leaves the z–component indeterminate. The spin wave

[20] H.D. Zeh, *Found. Phys.* 1 (1970) 69.

[21] The clarification of the phenomenon of decoherence is based on R. Omnes, *Quantum Philosophy: Understanding and Interpreting Contemporary Science*, Princeton and Oxford: Princeton University Press 1999, 199–202.

function in the z–direction assumes the following form:

$$\Psi_z = \frac{1}{\sqrt{2}}(\psi_{+1/2} + \psi_{-1/2}).$$

In such a case, the wave function of the measuring device tuned to the measurement of the z–component is given by:

$$\Psi(x) = \frac{1}{\sqrt{2}}(\psi_+(x) + \psi_-(x)).$$

$\Psi(x)$ expresses directly the magnitude of macroscopic quantum *interferences* or, from the point of view of the Schrödinger's Cat paradox, its square yields the probability of finding the cat in a counterintuitive quantum superposition state as suspended between life and death.

Regardless of whether the macroscopic entity that 'takes over' the quantum state of a microscopic particle is an alive cat or a piece of laboratory equipment, both contain approximately 10^{27} to 10^{28} atoms. Consequently, a correction needs to be made to the expression for $\Psi(x)$ to account for all the single coordinates in the entire ensemble of atoms. This is accomplished by introducing a set of cumulative variables y that account for the microscopic features of the measuring device as well as for surrounding experimental conditions. The amended wave function is now written as $\Psi(x, y)$. Both $\psi_+(x, y)$ and $\psi_-(x, y)$ are very complicated functions of y and they show great sensitivity to the position of a pointer. Since $\Psi(x, y)$ is a linear superposition of $\psi_+(x, y)$ and $\psi_-(x, y)$, its magnitude depends on the value of the sum of these two wave functions. In the case of wave functions in general, this is achieved when the functions are *coherent*, that is, the difference of their phases is not a function of time. For instance, this is one of the prime conditions for obtaining great light intensity amplification in lasers. In contrast to the laser action, significant difference in microatomic and environmental conditions of a needle at both readings of $+1$ and -1 in the measuring device (e.g., friction) combined with significant needle position sensitivity of $\psi_+(x,y)$ and $\psi_-(x,y)$ will result in the phase difference of these functions being random in time (uncorrelated) thereby leading to practical extinction of the value of their summation. In other words, the coherence of $\psi_+(x,y)$ and $\psi_-(x,y)$ is lost. This effect of quenching of the macroscopic quantum interferences is called *decoherence*. From the point of view of mathematical formalism, decoherence effects the diagonalization of the matrix of density so that with all off–diagonal elements equal to zero, no coupling among the quantum eigenstates occurs. Accordingly, the dead Schrödinger's Cat is significantly dephased with respect to the alive one whereby both 'kitty' wave functions no longer remain in the fine phase tuning. In such circumstances, the value of their summation is negligible and the probability of observing Schrödinger's Cat in the superposition state envisioned by the paradox is zero. The solution of the Schrödinger's Cat paradox consists in asserting that following the effect of decoherence, extremely rapid quenching of quantum interferences between its being dead and alive, precludes cat's existence in the quantum superposition state. In short, there is no quantum cat: it is either dead or alive, never both. Or, following Roland Omnes:

> One can therefore assert that a quantum superposition of macroscopic states is never produced in reality. Decoherence is waiting to destroy them before they occur. The same is true for Schrodinger's Cat: the stakes are put down as soon as a decay has been detected by the devilish device, before the poison phial is broken. The cat is only a wretched spectator.[22]

[22] R. Omnes, *Understanding Quantum Mechanics*, Princeton: Princeton University Press 1999, 227.

5. TOWARDS QUANTUM LOGIC

It has been briefly remarked above that the effect of decoherence is related to friction. Friction belongs to a large class of physical phenomena called *dissipation*. Dissipation appears in a marked variety of mechanical, electric, magnetic as well as chemical processes. Interestingly enough, physical system that are not dissipative, do not undergo decoherence. For instance, some macroscopic systems such as superconductors exhibit typical quantum effect such as tunneling.[23] Also, the ordinary light (a beam of photons) reveals an interference pattern demonstrated in the famous Young experiment. Decoherence is then closely correlated with the dissipation (damping) phenomena. Theoretical predictions yield the following simple relation between the decoherence coefficient μ and the damping coefficient γ:

$$\mu = \frac{\gamma M k T}{\hbar^2}$$

where M is the mass of a macroscopic system, k—Boltzmann constant, T—temperature and $\hbar$—Planck constant. The square of the Planck constant in the denominator of the above equation indicates that the process of decoherence in dissipative macroscopic systems is very efficient (rapid). Joos and Zeh established that the interaction with the 3^0K microwave radiation is sufficient to yield decoherence in approximately 10^{-23} seconds. Presently, decoherence is confirmed by a number of sophisticated experiments. For instance, a group of physicists in Austria observed the transition from quantum to classical behavior in carbon–70 molecules passing through a double slit at temperatures higher than 1000K.[24] Decoherence can be then viewed as a real physical process that neutralizes quantum interferences at the macroscopic level.

---

[23] J. Clarke, A.N. Cleland, M.H. Devoret, D. Esteve, J.M. Martinis, *Science* 239 (1988) 992.

[24] L. Hackermüller et. al., *Nature* 427 (2004) 711.

The close relation of decoherence with dissipation suggests that the time arrow for both is established by the rules of thermodynamics, namely, the direction of increasing entropy. In other words, the direction of decoherence is dictated by the specificity of events it correlates. In a hypothetical case, one could visualize the reversed macroscopic process of going from the state of a dead and live cat as it normally occurs at the conclusion of the paradoxical experiment to an alive one at the beginning. What renders such transition impossible is the retrieval of the microscopic complexity of the internal wave functions describing the state of each macroscopic cat of a decent size engaged in such imaginary process. Moreover, such directionality (irreversibility) of the process of decoherence corroborates with the consistency conditions for meaningful quantum histories as proposed by Griffiths. In light of these conditions, to go contrary to the arrow of decoherence would be to proceed against the quantum logic: to act in a manner that is meaningless. As Roland Omnes points out, decoherence is by far the most efficient mechanism that secures the validity of quantum logic, that is, its correspondence with the common sense experience. In another instance, he stresses the profound character of decoherence as a process that enables the emergence of the classical macroscopic world out of the quantum realm:

> The result is much more significant: any property that can be asserted as a consequence of decoherence will afterward remain valid forever; it cannot be invalidated by later events. This means that the concept of fact is perfectly valid in quantum mechanics. If one adopts Bohr's definition of a phenomenon as a conceivable fact, then all phenomena can be considered as classical properties resulting from decoherence.[25]

[25] R. Omnes, *Quantum Philosophy*, 206.

6. CONCLUSIONS

It is commonly accepted that the phenomenon of decoherence clarifies the Schrödinger's Cat Paradox.[26] Inasmuch as in light of the arguments provided this assertion seems to be intuitively fitting, the solution of the paradox alone does not warrant a decisive answer to all conceptual difficulties of quantum mechanics that led to the formulation of the paradox by Edwin Schrödinger. For instance, such fundamental issue as the ontological status of the quantum picture of the micro–world still generates numerous discussions among physicists and philosophers. This obviously correlates with the assumed interpretation of quantum mechanics. At the first glance, the spectrum of positions in this matter splits into two opposing groups: (a) those who treat the wave function only as a formal tool to accumulate the knowledge about a system under study and (b) those who associate the wave function with quantum reality. Interestingly enough, the recognition of the validity of the paradox must at least presuppose some latent acknowledgment of the reality of the quantum world.

Furthermore, the solution of the Schrödinger's Cat paradox does not permit complete elucidation of the measurement problem. In a way, this is the reason why Roger Penrose does not accept decoherence as a full explanation of the paradox. However, his assessment of decoherence as the paradox's explanatory tool in comparison to other interpretations of quantum mechanics such as Copenhagen (Bohr), many worlds (Everett), consistent histories (Griffiths) and pilot waves (otherwise known as hidden variables, de Broglie, Bohm) seems to be more favorable.[27] Penrose's goal is not only to understand why quantum interferences are not seen in the macroscopic realm but to justify the objective character of the procedure of wave vector reduction **R**. In

[26] C.P. Sun, X.F. Liu, D.L. Zhou, S.X. Yu, *Eur. Phys. J. D* 17 (2001) 85–92.

[27] R. Penrose, *The Road to Reality: A Complete Guide to the Laws of the Universe*, New York: Alfred A. Knopf 2005, 782–791, 802–812.

other words, he aims at providing exhaustive explanation of this procedure, that is, to fully expose how one crosses from unitary evolution of wave function **U** to a single outcome of a measurement that is a unique fact. Contrary to that, Roland Omnes sees the objectification process as extrinsic to the theory inasmuch as

> the relation between a theory and physical reality is no part of a theory. The condition of this relation must be added to the theory itself, and this is where the requirement of uniqueness enters. Uniqueness must be prescribed and one cannot expect to find it directly in the theory.[28]

It seems that Omnes' approach leaves more flexibility within the theory itself by leaving the objectification procedure outside. Thus, decoherence does not directly yield the dead or alive cat as a unique experimental outcome of the paradox. Following the diagonalization of the density matrix, it assures that the facts of a cat being killed and remaining alive are separated whereby it guarantees that the objectification procedure will not yield a cat in a superposition state. The resolution of the Schrodinger's Cat paradox does not strictly demand to probe into the nature of the procedure. The fact that both Roger Penrose and Roland Omnes admit the role of gravity in objectification has certainly no meaning for a poor cat ultimately relieved from the clutches of the multistate wave function.

SUMMARY

SCHRÖDINGER'S CAT

The Schrödinger's Cat paradox was proposed in 1935 by Edwin Schrödinger, one of the founders of quantum mechanics, as an attempt

[28] R. Omnes, *Understanding Quantum Mechanics*, Princeton: Princeton University Press 1999, 243.

to visualize the macroscopic realization of a quantum superposition state. A cat is placed in a sealed box together with a vial of poison. A two–state particle (e.g. an electron) is sent into a detector in the box resulting either in a broken or an intact vial and a dead or live cat, respectively. The main problem consists in whether the superposition state of a microscopic particle can be transferred upon the macroscopic cat, that is, whether the cat can exist in a superposition state, being simultaneously dead and alive. Since the standard Copenhagen interpretation is unable to assign any reality to the quantum superposition state, the paradox finds no resolution within the regime of this interpretation. Von Neumann's insistence on the uniform treatment of both microscopic (quantum) and macroscopic (classical) objects according to the laws of quantum mechanics provides a more consistent framework for the resolution of the paradox. In particular, the discovery of the phenomenon of decoherence, whereby the disappearance of the quantum interferences at the macro level is accounted for, suggests the onset of an extremely efficient interference relaxation process (10^{-23}s) upon the interaction of the two state particle with the detector. As a result, Schrödinger's cat can exist macroscopically either as dead or alive and never as a combination of both. Decoherence not only aids the resolution of the Schrödinger's Cat paradox but also sheds light upon the mechanisms by which the macro–world emerges from the microscopic quantum realm.

STRESZCZENIE

KOT SCHRÖDINGERA

Paradoks kota Schrödingera został zaproponowany w 1935 przez jednego z twórców mechaniki kwantowej, Edwina Schrödingera, jako próba zobrazowania makroskopowego odpowiednika superpozycji stanów kwantowych. Eksperyment myślowy polega na umieszczeniu żywego kota w szczelnie zamkniętej komorze, do której wstawiono fiolkę z trucizną. Do detektora cząstek znajdującego się również w komorze wysyła się jedną cząstkę dwustanową, np. elektron, która opisywana jest

funkcją falową będącą złożeniem (superpozycją) dwóch stanów cząstki. Główny problem polega na tym, czy stan cząstki, jako złożenie dwóch stanów czystych, może zostać przeniesiony na makroskopowego kota lub, mówiąc prościej, czy możliwe jest istnienie kota jednocześnie żywego i martwego. Ponieważ standardowa interpretacja kopenhaska mechaniki kwantowej nie przypisuje żadnej realnej rzeczywistości superpozycjom stanów, paradoksu kota Schrödingera nie da się rozwikłać w jej obrębie. Możliwość taka pojawia się jednak na gruncie prac prowadzonych przez Johanna von Neumanna, który postulował przyjęcie zunifikowanego opisu świata mikroskopowego i makroskopowego za pomocą praw mechaniki kwantowej. W szczególności, odkrycie zjawiska dekoherencji, tłumaczącego zanik interferencji kwantowych na poziomie makro, sugeruje występowanie bardzo szybkiego procesu relaksacji interferencji (10^{-23}s) w wyniku oddziaływania dwustanowej cząstki z detektorem. W rezultacie kot Schrödingera może istnieć tylko albo jako żywy, albo martwy a nigdy jako kombinacja obydwu naraz. Dekoherencja nie tylko pomaga wyjaśnić paradoks kota Schrödingera, lecz pozwala również głębiej wniknąć w mechanizmy emergencji świata makro z mikroskopowej rzeczywistości kwantowej.