THE PROBLEM OF CONSCIOUS OBSERVATION IN QUANTUM MECHANICAL DESCRIPTION[1]

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Epistemological consequences of quantum nonlocality (entanglement) are discussed under the assumption of a universally valid Schrödinger equation and the absence of hidden variables. This leads inevitably to a *many-minds interpretation*. The recent foundation of quasi-classical neuronal states in the brain (based on environmental decoherence) permits in principle a formal description of the whole chain of measurement interactions, including the *behavior* of conscious observers, without introducing any intermediate classical concepts (for macroscopic "pointer states") or "observables" (for microscopic particle positions and the like) — thus consistently formalizing Einstein's *ganzer langer Weg* from the observed to the observer in quantum mechanical terms.

Keywords: entanglement, quantum measurement, Everett interpretation

1 Introduction

John von Neumann seems to have first clearly pointed out the conceptual difficulties that arise when one attempts to formulate the physical process underlying subjective observation within quantum theory [1]. He emphasized the latter's incompatibility with a psycho-physical parallelism, the traditional way of reducing the act of observation to a physical process. Based on the assumption of a physical reality in space and time, one either

[1] The first part of this article is the slightly revised version of a paper with the same title that was informally circulated in 1981 by means of the Epistemological Letters of the Ferdinand-Gonseth Association in Biel (Switzerland) as Letter No 63.0. (Therefore, terms such as "new" or "recent" in this part refer to that year.) In its Conclusion, this paper introduced the term "multi-consciousness interpretation" for a variant of the Everett interpretation that has since been rediscovered several times (more or less independently), and become known as the "many-minds interpretation" of quantum theory.

assumes a “coupling” (causal relationship — one-way or bidirectional) of matter and mind, or disregards the whole problem by retreating to pure behaviorism. However, even this may remain problematic when one attempts to describe classical behavior in quantum mechanical terms. Neither position can be upheld without fundamental modifications in a consistent quantum mechanical description of the physical world.

These problems in formulating a process of observation within quantum theory arise as a consequence of quantum nonlocality (quantum correlations or “entanglement”, characterizing generic physical states), which in turn may be derived from the superposition principle. This fundamental quantum property does not even approximately allow the physical state of a local system (such as the brain or parts thereof) to exist [2]. Hence, no state of the mind can exist “parallel” to it (that is, correspond to it one-to-one or determine it).

The question does not only concern the philosophical issue of matter and mind. It has immediate bearing on quantum physics itself, as the state vector seems to suffer the well known reaction upon observation: its “collapse”. For this reason Schrödinger once argued that the wave function might not represent a physical object (not even in a statistical sense), but should rather have a fundamental psycho-physical meaning.

This sitation appears so embarrassing to most physicists that many tried hard to find a local reality behind the formalism of quantum theory. For some time their effort was borne by the hope that quantum correlations could be understood as statistical correlations arising from an unknown ensemble interpretation of quantum theory. (An ensemble explanation *within* quantum theory can be excluded [2].) However, Bell’s work has demonstrated quite rigorously that any local reality — regardless of whether it can be experimentally confirmed in principle or not — would necessarily be in conflict with certain predictions of quantum theory. Less rigorous though still quite convincing arguments had been known before in the form of the dynamical completeness of the Schrödinger equation for describing isolated microscopic systems, in particular those containing quantum correlations (such as many-electron atoms).

Although the evidence in favor of quantum theory (and against local realism) now appears overwhelming, the continuing search for a traditional solution may be understandable in view of the otherwise arising epistemological problems. On the other hand, in the absence of any empirical hint how to revise quantum theory, it may be wise to accept the description of physical reality in terms of non-local state vectors, and to consider its severe consequences seriously. Such an approach may be useful regardless of whether it will later turn out to be of limited validity.

The conventional ("Copenhagen") pragmatic attitude of switching between classical and quantum concepts by means of *ad hoc* decisions does, of course, not represent a consistent description. It should be distinguished from that wave-particle duality which can be incorporated into the general concept of a state vector (namely, the occupation number representation for wave modes). Unfortunately, personal tendencies for local classical or for non-local quantum concepts to describe "true reality" seem to form the major source of misunderstandings between physicists — cf. the recent discussion between d'Espagnat and Weißkopf [4].

It appears evident that conscious awareness must in some way be coupled to local physical systems: our physical environment has to interact with and thereby influence our brains in order to be perceived. There is even convincing evidence supporting the idea that *all* states of awareness reflect physico-chemical processes in the brain. These neural processes are usually described by means of classical (that is, local) concepts. One may speculate about the details of this coupling on purely theoretical grounds [5], or search for them experimentally by performing neurological and psychological work. In fact, after a few decades of exorcizing consciousness from psychobiology by retreating to pure behaviorism, the demon now seems to have been allowed to return [6]. On closer inspection, however, the concept of consciousness *as used* turns out to be a purely behavioristic one: certain aspects of behavior (such as language) are rather conventionally associated with consciousness. For epistemological reasons it is indeed strictly impossible to derive the concept of *subjective* consiousness (awareness) from a physical world. Nonetheless, subjectivity need not form an "epistemological impasse" (Pribram's term [7]), but to grasp it may require combined efforts from physics, psychology and epistemology.

2 The Epistemology of Consciousness

By inventing his malicious demon, Descartes demonstrated the impossibility of *proving* the reality of the observed (physical) world. This hypothetical demon, assumed to delude our senses, may thereby be thought of as part of (another) reality — similar to an indirect proof.

On the other hand, Descartes' even more famous *cogito ergo sum* is based on our conviction that the existence of subjective sensations cannot be reasonably doubted. Instead of forming an epistemological impasse, subjectivity should thus be regarded as an epistemological gateway to reality.

Descartes' demon does not disprove a real physical world — nor does any other epistemological argument. Rather does it open up the possibility of a *hypothetical* realism, for example in the sense of Vaihinger's *heuristic fictions* [8]. Aside from having to be intrinsically consistent, this hypothetical reality has to agree with observations (perceptions), and describe them in the most economical manner. If, in a quantum world, the relation between (ultimately subjective) observations and postulated reality should turn out to differ from its classical form (as has often been suggested for reasons of consistency), new non-trivial insights may be obtained.

While according to Descartes my own sensations are beyond doubt to me, I cannot *prove* other people's consciousness even from the presumption of their *physical* reality. (This was the reason for eliminating it from behavioristic psychology.) However, I may better (that is, more economically) "understand" or predict others' behavior (which I *seem* to observe in reality) if I *assume* that they experience similar sensations as I do. In this sense, consciousness (beyond solipsism) is a heuristic concept precisely as reality. *There is no better epistemological reason to exorcise from science the concept of consciousness than that of physical reality.*

A consequence of this heuristic epistemological construction of physical *and* psychic reality is, of course, that language gives information about the speaker's consciousness. This argument emphasizes the epistemologically derived (rather than dynamically emerged) nature of this concept. However, only that part of others' consciousness can be investigated, that manifests itself as some form of behavior (such as language). For this reason it may indeed be appropriate to avoid any fundamental concept of consciousness in psychobiology. This requires that conscious behavior (behavior as though being conscious) can be completely explained as emerging — certainly a meaningful conjecture. It would have to include our private (subjectively experienced) consciousness if a psycho-physical parallelism could be established. Only for such a dynamically passive parallelism (or epiphenomenalism) would the physical world form a closed system that in principle allowed complete reductionism.

Before the advent of quantum theory this ivory tower position of physics could be upheld without posing problems. If, on the other hand, the nonlocal quantum concepts describe *real* aspects of the physical world (that is, if they are truly heuristic concepts), the parallelism has to be modified in some way. Such a modification could some day even turn out to be important for experimental psychobiology, but it is irrelevant whenever nonlocality can be neglected, as for present-day computers or most neural processes. However, the quasi-classical activities of neurons may be almost as far from consciousness as an image on the retina. The concept of "wholeness" — often emphasized as being important for complex systems such as the brain — is usually insufficiently understood: in quantum theory it is neither a mere dynamical wholeness (that is, an efficient interaction between all parts) nor is it restricted to the system itself. Dynamical arguments require a *kinematical wholeness of the entire universe* (when regarded as composed of *spatial* parts) [2]. It may be neglected for certain ("classical") aspects only — not for a complete microscopic description that *may* be relevant for subjective perceptions.

3 Observing in a Quantum World

One possible consequence of these problems that inevitably arise in quantum theory would be to abandon the heuristic and generally applicable concept of a physical reality — explicitly [9] or tacitly. This suggestion includes the usual restriction to formal rules when calculating probability distributions of *presumed* classical variables in situations which are intuitively understood as "measurements" (but insufficiently or even inconsistently distinguished from normal "dynamical" interactions). Clearly, no general description of physical processes underlying awareness could be given in the absence of a physical reality, even though macroscopic behavior (including the dynamics of neural systems) can be described by means of the usual pragmatic scheme. This is quite unsatisfactory, since subjective awareness has most elementary meaning without *external* observation (that would be required in the Copenhagen interpretation). Epistemologically, any concept of observation must ultimately be based on an observing subject.

This "non-concept" of abandoning microscopic reality is not at all required, as has been pointed out before [2, 10]. Instead, one may regard the state vector as "actual" and representing reality, since it *acts* dynamically (often as a whole) on what is observed. Moreover, in view of Bell's analysis of the consequences of quantum nonlocality, it appears questionable whether anything, and what, might be gained from inventing novel fundamental concepts (hidden variables) without any empirical support. Two different solutions of the measurement problem then appear conceivable: von Neumann's collapse or Everett's relative state interpretation [11]. In both cases a (suitably modified) psycho-physical parallelism can be re-established.

A dynamical collapse of the wave function would require nonlinear and nonunitary terms in the Schrödinger equation [12]. They may be extremely small, and thus become effective only through practically irreversible amplification processes occurring during measurement-like events. The superposition principle would then be valid only in a linearized version of the theory. While this suggestion may in principle explain quantum measurements, it would not be able to describe definite states of concsiousness unless the parallelism were restricted to quasi-classical variables in the brain. Since nonlinear terms in the Schrödinger equation lead to observable deviations from conventional quantum theory, they should at present be disregarded for similar reasons as hidden variables. Any proposed violation of the superposition principle must be viewed with great suspicion because of the latter's great and general success. For example, even superpositions of different vacua have proven heuristic (that is, to possess predictive power) in quantum field theory.

The problems thus arising when physical states representing consciousness are described within wave mechanics by means of nonlinear dynamical terms could possibly be avoided if these nonlinearities were themselves *caused* by consciousness. This has in fact been suggested as a way to incorporate a genuine concept of free will into the theory [13], but would be in conflict with the hypothesis of a closed physical description of the world.

If the Schrödinger equation is instead assumed to be universal and exact, superpositions of states of the brain representing different contents of consciousness are as unavoidable as Schrödinger's superposition of a dead and alive cat. However, because of unavoidable interaction with the environment, each component must then be quantum correlated with a different (almost orthogonal) state of the rest of the universe. This consequence, together with the way how we perceive the world, leads obviously to a "many-worlds" interpretation of the wave function.[2] Unfortunately this name is misleading. The quantum world (described by a wave function) would correspond to *one* superposition of myriads of components representing *classically* different worlds. They are all dynamically coupled (hence "actual"), and they may in principle (re)combine as well as branch. It is not the real world (described by a wave funtion) that branches in this pic-

[2] Everett [11] suggested "branching" wave functions in order to discuss cosmology in strictly quantum mechanical terms (without an external observer or a collapse). I was later led to similar conclusions as a consequence of unavoidable quantum entanglement [2] — initially knowing neither of Everett's nor of Bell's work.

ture, but consciousness (or rather the state of its physical carrier), and with it the *observed* (apparent) "world" [2]. Once we have accepted the formal part of quantum theory, only our experience teaches us that consciousness is physically determined by (factor) wave functions in certain *components* of the total wave function.[3] The existence of "other" components (with their separate conscious versions of ourselves) is a heuristic fiction, based on the assumption of a general validity of dynamical laws that have always been confirmed when tested. When applied to classical laws and concepts, an analogous assumptions leads to the conventional model of reality in space and time as an extrapolation of what is observed. In the quantum model, *a collapse would represent a new kind of solipsism*, since it denies the existence of these otherwise arising consequences.

Everett related his branching to the practically irreversible dynamical decoupling of components that occurs when microscopic properties become correlated to macroscopic ones. This irreversibility requires specific initial conditions for the global state vector [5]. Such initial conditions will then, for example, also cause a sugar molecule to permanently send *retarded* "information" (by scattering photons and molecules) about its handedness into the universe. In this way, their relative phases become nonlocal, and thus cannot affect the physical states of local conscious observers (or states of their brains) any more. The separation of these components is dynamically "robust". There is no precise localization of the branch cut (while a genuine dynamical collapse would have to be *specified* as a dynamical law).

Nonetheless, Everett's branching in terms of quasi-classical properties does *not* appear sufficient to formulate a psycho-physical parallelism. Neither would this branching produce a definite factor state for some relevant part of the brain, nor does every decoherence process somewhere in the universe describe conscious observation. Even *within* a robust branch, most parts of the brain will remain strongly quantum correlated with one another and with their environment.

Everett's branchings represent objective measurements — not necessarily conscious observations. A parallelism seems to be based on a far more fine-grained branching (from a local point of view) than that describing measurements, since it should correspond one-one to subjective awareness. The

[3] It would always be possible to introduce additional (entirely arbitrary and unobservable) variables as a hypothetical link between the wave function and consciousness. Given their (hypothetical) dynamics, the required quantum probabilities can then be postulated by means of appropriate initial conditions. An example are the classical variables in Bohm's pilot wave theory [14].

conjecture here is: does the (not necessarily robust) branching that is conceptually required for defining the parallelism then readily *justify* Everett's (apparently objective) branching into quasi-classical worlds?

The branching of the global state vector Ψ with respect to *two* different conscious observers (A and B, say) may be written in their Schmidt-canonical forms [5],

$$\Psi = \sum_{n_A} c^A_{n_A} \chi^A_{n_A} \phi^A_{n_A} = \sum_{n_B} c^B_{n_B} \chi^B_{n_B} \phi^B_{n_B} \quad , \tag{1}$$

where $\chi^{A,B}$ are states of the respective physical carriers of consciousness (presumably small but not necessarily local parts of the central nervous system), while $\phi^{A,B}$ are states of the respective "rests of the universe". In order to describe the macroscopic *behavior* of (human) observers, one has to consider the analogous representation with respect to the states $\tilde{\chi}$ of their whole bodies (or relevant parts thereof),

$$\Psi = \sum_{k_A} \tilde{c}^A_{k_A} \tilde{\chi}^A_{k_A} \tilde{\phi}^A_{k_A} = \sum_{k_B} \tilde{c}^B_{k_B} \tilde{\chi}^B_{k_B} \tilde{\phi}^B_{k_B} \quad . \tag{2}$$

In particular, the central nervous system may be assumed to possess (usually unconscious) "memory states" (labelled by m_A and m_B, say) which are similarly robust under decoherence as the handedness of a sugar molecule. Time-directed *quantum causality* (based on the initial condition for the global wave function) will then force the Schmidt states $\tilde{\chi}^A$ and $\tilde{\chi}^B$ to approximately factorize in terms of these memory states [15],

$$\Psi \Rightarrow \sum_{m_A \mu_A} \tilde{c}^A_{m_A \mu_A} \tilde{\chi}^A_{m_A \mu_A} \tilde{\phi}^A_{m_A \mu_A} \approx \sum_{m_B \mu_B} \tilde{c}^B_{m_B \mu_B} \tilde{\chi}^B_{m_B \mu_B} \tilde{\phi}^B_{m_B \mu_B} \quad , \tag{3}$$

where μ_A and μ_B are additional quantum numbers. The "rest of the universe" thus serves as a sink for phase relations.

In general, the robust quantum numbers m_A and m_B will be partly correlated — either because of special interactions between the two oberservers (communication), or since they have arisen from the same cause (that is, from observations of the same event). These correlations define the concept of objectivization in quantum mechanical terms.

The genuine carriers of consciousness (described by the states χ in (1)) must *not* in general be expected to represent memory states, as there do not seem to be permanent contents of consciousness. However, since they may be assumed to interact directly with the rest of the $\tilde{\chi}$-system only, and since phase relations between different quantum numbers m_A or m_B would immediately become nonlocal, memory appears "classical" to the conscious observer. Each robust branch in (2), hence also each m-value, describes essentially an independent partial sum of type (1) when observed [16]. The empririically relevant probability interpretation in terms of quasi-classical branches (including pointer positions) may, therefore, be derived from a similar (but fundamental) one for the *subjective branching* (with respect to each observer) that according to this interpretation defines the novel psychophysical parallelism.

As mentioned before, macroscopic *behavior* (including behavior as though being conscious) could also be described by means of the pragmatic (probalistic) rules of quantum theory. An exact Schrödinger equation does not imply deterministic behavior of conscious beings, since one has to expect that macroscopic stimuli have microscopic effects in the brain before they cause macroscopic behavior. Thereby, interaction with the environment will intervene. Everett's "relative state" decomposition (1) with respect to the subjective observer state χ may then considerably differ from the objectivized branching (3), that would be meaningful with respect to all conceivable "external" observations. This description may even put definite meaning into Bohr's vague concept of *complementarity*.

4 Conclusion

The multi-universe interpretation of quantum theory (which should rather be called a *multi-consciousness interpretation*) seems to be the only interpretation of a universal quantum theory (with an exact Schrödinger equation) that is compatible with the way the world is perceived. However, because of quantum nonlocality it requires an appropriate modification of the traditional epistemological postulate of a psycho-physical parallelism.

In this interpretation, the physical world is completely described by Everett's wave function that evolves deterministically (Laplacean). This global quantum state then defines an indeterministic (hence "branching") succession of states for all observers. Therefore, the world itself *appears* indeterministic — subjective in principle, but largely objectivized through quantum correlations (entanglement).

This quite general scheme to describe the empirical world is conceptually consistent (even though the parallelism remains vaguely defined), while it is based on the presently best founded physical concepts. The latter may some day turn out to be insufficient, but it is hard to see how any future theory that contains quantum theory in some approximation may avoid similar epistemological problems. These problems arise from the contrast between quantum nonlocality (confirmed by Bell's analysis as part of *reality*) and the locality of consciousness "somewhere in the brain". Quantum concepts should be better founded than classical ones for approaching these problems.

5 Addendum

The above-presented paper of 1981 has here been rewritten (with minor changes, mainly regarding formulations), since the solution of the quantum mechanical measurement problem proposed therein has recently gained interest, while the Epistemological Letters (which were used as an informal discussion forum between physicists and philosophers interested in the "new quantum debate") are now hard to access. The dynamical dislocalization of phase relations (based on [2, 15]) referred to in this article in order to justify robust Everett branches has since become better known as *decoherence* (see [17]), while the "multi-consciousness interpretation" mentioned in the Conclusion has been rediscovered on several occasions. It is now usually discussed as a "many-minds interpretation" [18, 19, 20, 21, 22, 23], but has also been called a "many-views" [24] or "many-perceptions" interpretation [25].

The conjectured quasi-classical nature of those dynamical states of neurons in the brain which may carry memory or can be investigated "from outside" has recently been confirmed by quantitative estimates of their decoherence in an important paper by Tegmark [26]. To most of these states, however, the true physical carrier of consciousness somewhere in the brain may still represent an *external* observer system, with whom they have to interact in order to be perceived. Regardless of whether the ultimate observer systems are quasi-classical or possess essential quantum aspects, consciousness can only be related to factor states (of systems assumed to be localized in the brain) that appear in *branches* (robust components) of the global wave function — provided the Schrödinger equation is exact. Environmental decoherence represents *entanglement* (but not any "distortion" — of the brain, in this case), while *ensembles* of wave functions, representing various *potential* (unpredictable) outcomes, would require a dynamical collapse (that has never been observed).[4]

[4] A collapse would be *conceivable* as well in Bohm's theory, where memory and objec-

An essential role of the conscious observer for the occurrence of fundamental (though objective) quantum events was apparently suggested already by Heisenberg in his early "idealistic" interpretation of *a particle trajectory coming into being by our act of observing it*. Bohr, in his later Copenhagen interpretation, insisted instead that classical outcomes arise in the apparatus during irreversible *measurements*, which he assumed not to be dynamically analyzable in terms of a microscopic reality (cf. Beller [27]). This first *classical* link in the chain of interactions that forms the observation of a quantum system can now be identified with the first occurrence of decoherence (globally described as a unitary but practically irreversible *dynamical* process — see [28]).

However, Bohr's restriction of the applicability of quantum concepts as well as Heisenberg's uncertainty relations were meant to establish *bounds to a rational description of Nature*. (The popular simplistic view of quantum theory as merely describing stochastic dynamics for an otherwise classical world leads to the well known wealth of "paradoxes", which rule out any local description but have all been *derived* from the superposition principle, that is, ultimately from an entangled global wave function.) Von Neumann's "orthodox" interpretation, on the other hand, is somewhat obscured by his use of observables, which should have no *fundamental* place in a theory of interacting wave functions. His postulate of a dynamical collapse representing conscious observations was later elaborated upon by London and Bauer [29], while Wigner [13] suggested an active influence of the mind on the physical state (that should better not affect objectively measurable probabilities). Stapp [21] expressed varying views on this problem, while Penrose [30] speculated that human thinking, in contrast to classical computers, requires genuine quantum aspects (including superpositions of neuronal states *and* the collapse of the wave function).[5]

The Everett interpretation leads to its "extravagant" (unfamiliar and unobservable) *consequences*, because it does not invent any new laws, variables or irrational elements for the sole purpose of avoiding them. Lockwood

tive thought seems to be still described by neuronal *quantum* states, rather than by the classical configurations which according to Bell [14] would have to describe physical states corresponding to consciousness.

[5] There seems to be a certain confusion between logical *statements* (that is, tautologies), which have no implicit relation to the concept of time, and algorithmic *procedures*, performed in time in order to *prove* them. (Undecidable *formal* statements are meaningless, and hence not applicable.) A dynamical collapse of the wave function must not be regarded as representing "quantum logic" (or "logic of time"). This misconception appears reminiscent of the popular confusion of *cause* and *reason*.

[19] is quite correct when he points out the essential role of decoherence for the many-minds interpretation (see also [23]). This unavoidable "continuous measurement" of all macroscopic systems by their environments (inducing entanglement) was indeed initially discussed [2] precisely in order to support the concept of a universal wave function, in which "branching components" must be *separately* experienced.

Heisenberg once recalled [31] that Einstein had told him (my translation): "Only the theory may tell us what we can observe. ... On the whole long path (*ganzer langer Weg*) from the event to its registration in our consciousness you have to know how Nature works." Einstein did thus *not* suggest that the theory has to postulate "observables" for this purpose (as the first part of this quotation is often understood). Formal observables are useful only since the subsequent part of this chain of interactions can *for all practical purposes* be described in terms of classical variables, after initial values have been stochastically *created* for them somewhere in the chain. However, most physicists would now agree on what to do (in principle) if quantum effects should be relevant during some or all intermediary steps (cf. [32]): they would have to calculate the evolution of the corresponding series of entangled quantum systems, taking into account decoherence by the environment where required. There is then no need for genuine classical variables anywhere, since Tegmark's decohered neuronal (quantum) states form an appropriate "pointer basis" for the application of quantum probabilities. These probabilities need not characterize a stochastic dynamical process (a collapse of the wave function), but would describe an objectivizable splitting of the (state of the) mind if the Schrödinger equation were exact. In Bohm's quantum theory, on the other hand, states of the mind would be related to "surreal" classical trajectories which are guided by — hence would be *aware* of — a branch wave function only [14].

Therefore, I feel that the Heisenberg-Bohr picture of quantum mechanics can now be claimed dead. Neither classical concepts, nor any uncertainty relations, complementarity, observables, quantum logic, quantum statistics, or quantum jumps have to be introduced on a fundamental level (see also Sect. 4.6 of [28]). In a recent experiment [33], interference experiments were performed with mesoscopic molecules, and proposed for small virus. Time may be ripe to discuss the consequences of similar *Gedanken* experiments with objects carrying some primitive form of "core consciousness" [34] — including an elementary awareness of their path through the slits. How can "many minds" be avoided if their coherence can be restored?

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