Article

The Role of the Observer in the Everett Interpretation

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ABSTRACT

The role attributed to the observer in various interpretations of quantum mechanics as well as in classical statistical mechanics is discussed, with particular attention being paid to the Everett interpretation. In this context, the important difference between "quasi-classical" (robust against decoherence) and "macroscopic" or "physically given" (redundantly documented in the environment) is pointed out.

Key Words: quantum measurement, decoherence, information, representative ensembles

NeuroQuantology 2013; 1: 97-105

1. The observer in traditional quantum mechanics

When Werner Heisenberg discovered his matrix mechanics, which denies the existence of definite values for classical physical variables such as position and momentum of an electron before they are measured, he invented a historically unprecedented role for "*human observers*". He assumed that properties of microscopic objects are *created* in an irreversible act of observation – for him confirmation of the superiority of an idealistic world view instead of materialism, realism and reductionism (see Beller, 1999). In particular, the concept of time (including its arrow) would become a fundamental extra-physical prerequisite for the formulation of this process as well as of other physical laws. This point of view was soon supported by his friends Wolfgang Pauli and Carl Friedrich von Weizsäcker. It seemed to become even strengthened when Heisenberg's early attempts to understand his uncertainty principle simply as a consequence of unavoidable perturbations of the electron during measurements (for example by means of his "electron microscope") failed as a consistent explanation.

Niels Bohr later subscribed to a somewhat different position by assuming that the outcome of a measurement is *objectively* created as a classically describable property in the measurement apparatus. However, he rejected all attempts to analyze this measurement as a dynamical physical process, since he also denied any observer-independent microscopic reality in order to avoid otherwise apparently arising consistency problems. Such a creation or coming-into-being of physical properties in measurements "outside the laws of nature" (Pauli) is also assumed to give the trivial statement that "unperformed measurements do not have any results" a non-trivial meaning by denying the existence of properties that *could* be measured (that is, determined by a mere increase of information). However, this *quantum creationism* of classical properties may not only require that "the click in the counter occurs out of the blue … and without being

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Received Feb 16, 2013. Accepted March 10, 2013.
*e*ISSN 1303-5150

causally preceded by a decay event in the atom" (Ulfbeck and Bohr, 2001), but also the phenomenon of quantum teleportation (see below).

Erwin Schrödinger expected initially that the single particle wave function he had postulated describes the real electron, and thus explains the uncertainty between its apparently observed position and momentum by means of the Fourier theorem. However, he could not understand the apparently required quantum jumps between different standing waves that represent the observed energy *eigenstates*. For a long time he also tried to somehow avoid the formally arising consequence of entangled many-particle wave functions – although precisely this entanglement offers an explanation of the apparent jumps (as we know today). When Max Born invented his interpretation of wave functions as probability amplitudes for the occurrence of classical particle properties, entanglement was usually but insufficiently interpreted as representing no more than probability correlations. So Heisenberg later spoke somewhat mystically about the wave function as representing "human knowledge as an intermediary kind of reality" – an idea that seems to have been revived in the recently quite popular (but similarly insufficient) information theoretical approach to quantum theory. This "quantum Bayesianism" is the most recent form of a shut-up-and-calculate mentality.

Meanwhile, John von Neumann (in his book about the Mathematical Foundations of Quantum Mechanics) had studied the possibility of describing the measurement process as a quantum mechanical interaction between the object and the apparatus. In strong contrast to Bohr's view, he represented states of a macroscopic "pointer" by quantum mechanical wave packets rather than in classical terms. The unitary interaction, when applied to an initial microscopic superposition, would then lead to superpositions of macroscopically distinct pointer positions, entangled with different positions of the measured particle, for example. Therefore, von Neumann had to postulate a stochastic collapse (or "reduction") of the wave function as a new kind of dynamics supplementing the Schrödinger equation. He called it a "first intervention" – probably since at that time mainly energy *eigenstates* were studied, while quantum dynamics then appeared to consist solely of quantum jumps between them. The time-dependent Schrödinger equation (his "second intervention") was mostly used to calculate probabilities for such jumps, although it can also describe moving wave packets. The collapse proposal came close to Born's original version of his probability interpretation, which was to postulate transitions between initial and final *wave functions*. It was only later re-interpreted by Pauli as describing probabilities for the creation of certain values of classical (such as particle) properties.

However, von Neumann did not finish his quantum dynamical considerations with the apparatus. He included even the observer as a quantum system. In this way, the collapse became important for him in order to re-establish a "psycho-physical parallelism", which seems to be impossible if the observer remained entangled with the apparatus and thus simultaneously in several different states. In order to achieve this goal, the collapse or any other probability interpretation could be equally applied at each step of the "indivisible chain of interactions between the observer and the observed" (Weizsäcker's words). This freedom was also referred to as the variability of the "Heisenberg cut". For Heisenberg, it was a fundamental element in his interpretation of quantum theory (Bacciagaluppi and Crull, 2009), while Bohr preferred to apply it at some not very precisely specified border line separating the microscopic and the macroscopic worlds within the measurement apparatus.

The conscious observer was further discussed as the key element of the quantum measurement process by London and Bauer (1939). Eugene Wigner even suggested explicitly the possibility of an active influence of consciousness on the physical world (Wigner, 1962), but dropped this proposal when he learned about the concept of what was later called decoherence (Wigner, 1970). Attempts to confirm such effects in the form of deviations from Born's rule, caused by the observer's mind, have indeed failed. Quantum indeterminism thus seems to have nothing to do with an apparent "free will" (as hoped for by Born himself). While I therefore prefer to understand von Neumann's "psycho" part in his parallelism in the sense of a mere epiphenomenon accompanying even a purely passive physical part, Max Jammer compared it with Anaxagoras' dualistic doctrine of Matter and Mind when he quoted (adding his suggested modern interpretation in parentheses – Jammer, 1974): "The things that are in a single world are not parted from one another, not cut away with an axe, neither the warm from the cold nor the cold from the warm" (superpositions!?), but "when Mind began to set things in motion, separation took place from each thing that was being moved, and all that Mind moved was separated" (reduction!?).

Other interpretations of quantum mechanics, such as Bohm's, are often claimed *not* to require an observer as an essential part. Although the observer does indeed not assume a specific role in the dynamics of this theory, John Bell pointed out that it is tacitly based on the assumption of an observer being physically described solely by the "classical" and thus local variables that are here simply *assumed* to exist in addition to the non-local wave function (Bell, 1981). Collapse theories, on the other hand, would not only have to be able to explain the occurrence of quasi-classical narrow wave packets for all macroscopic variables, but also definite states of the conscious observer system if one wants to eliminate (rather than merely decohere, that is dislocalize) superpositions of different states of awareness.

2. The observer in classical statistical physics

The observer has always played an essential role in the empirical sciences, simply because they are based precisely on observations performed by humans by physical means. This remark may appear trivial, but its consequences are non-trivial for all physical concepts that depend on "incomplete information", such as in statistical mechanics (Zeh, 2007). Why do we regard the position and shape of a solid body as "physically given" even when we do not know them, while we describe its molecules objectively by a distribution of possible states characterized by a certain temperature parameter, for example? Since in a Laplacean world all variables are equally real, any such distinction must be based on the vaguely defined difference between what *we* can easily observe and what would require a certain instrumental effort to find out. Such distinctions, often based on arguments of dynamical stability in contrast to rapid and uncontrollable change, are certainly relevant in practice, but the boundary separating their realms may vary – for example when we decide to take into account local fluctuations of certain equilibrium values, or, more drastically, during phase transitions.

This dependence of certain physical concepts on incomplete knowledge is particularly obvious in Willard Gibbs' approach to statistical thermodynamics, which is based on Γ-space distributions and appears related to general concepts introduced by Thomas Bayes. Boltzmann's μ-space distributions, on the other hand, seem to represent real states rather than information. However, they, too, are based on incomplete information in an essential way, for example on some coarse graining or smoothing of the real (discrete) distribution in μ-space and the non-distinction between particles which are in principle distinguishable by their different trajectories. So one may here already raise John Bell's fundamental question "Information by whom ...?", while the other part of this question "... and about what?" would be answered as "about points in Γ-space" – but this answer fails to explain the empirically required absence of the factorials $N!$ that would classically result from counting particle permutations.

The physically important entropy can then be defined by the size of the ensemble of microscopic states representing a macroscopic situation (or, equivalently, by their mean probability in such an ensemble). The precise definition of this ensemble is in general not very relevant, since entropy is defined as a logarithmic measure, such that an uncertainty by a factor of X in the size of the ensemble in Γ-space would merely give rise to a relative correction of the order $\ln X/10^{20}$. Therefore, one may readily interchange slightly different "representative ensembles" without doing much harm. Precision of ensemble measures does become essential, though, for questions of principle, such as in measurements or in considerations regarding Maxwell's demon or Szilard's engine. The difference between a canonical and a micro-canonical ensemble is also physically meaningful, as only the former contains the entropy of lacking information about fluctuations in an open system.

Microscopic determinism would lead to the conservation of the size of an arbitrary ensemble (its formal ensemble entropy). However, if physical entropy is defined as a function of *given* macroscopic properties, it is at most indirectly related to an ensemble that represents information held by an observer. In particular, physical entropy is defined as an extensive (additive) quantity, while ensemble entropy is *not*, since it would strongly depend on dynamically arising probability correlations between subsystems. This is the reason why Boltzmann's μ-space entropy may increase in time even for deterministic collisions between the particles; μ-space information is thereby deterministically transformed into irrelevant information about correlations. More importantly, in irreversible phase transitions new macroscopic variables (such as droplet positions in a condensation process) or new order parameters often evolve out of microscopic variables. In this case, lacking information about thermal degrees of freedom (physical entropy) is transformed into lacking information about macroscopic variables (that is, information entropy in the genuine sense of Claude Shannon). Hence, physical entropy *can* be lowered if we regard macroscopic properties as "given" as soon as they arise. While this is essentially a matter of definition of physical entropy, the true surprise comes when one adds the (human?) observer to the chain of interacting systems in analogy to von Neumann's description of quantum observations. Deterministically, different macroscopic properties are then correlated with the new and different states of an observer. If the latter is assumed to *know* what he has observed, the ensemble describing his lack of knowledge would be reduced without violating microscopic determinism – in this way reducing the initial ensemble entropy from his point of view! Quantum-mechanically, this observation process would require a collapse of the wave function. One may even conceive of a classical version of *Wigner's friend* in this case. (In all these examples, the unavoidable dynamical formation of *uncontrollable* correlations such as by molecular collisions, which is the major source of irreversibility, has been disregarded for simplicity).

The situation described above is related to Maxwell's demon, who was proposed to use his presumed initial knowledge about molecular motions in order to reduce thermal entropy. Leo Szilard demonstrated by means of a thought experiment that the demon's entropy must correspondingly increase if he is regarded as a physical object, too. Therefore, the experimenter, who would have to observe the gas molecules in order to act as a demon, must not be regarded as an extra-physical system (in Rolf Landauer's language: information is physical). Charles Bennett (Bennett, 1987) concluded in accordance with traditional formulations of the second law that Maxwell's demon cannot work in a cyclic process that would be required for a perpetuum mobile of the second kind, because he would then have to get rid of his information in order to close the cycle. However, lowering the ensemble entropy in an *individual* process as indicated above would nonetheless be possible in principle by interaction with the information-defining observer. On the other hand, any observer must have got rid of quite a lot of entropy in order to come into being in a process of self-organization.

The (*neg*)entropy of information about macroscopic properties is usually negligible when compared with thermodynamic entropy. For this reason, observers are in practice often regarded as extra-physical, or as possessing unlimited information capacity and even defining their own arrow of time. This position becomes problematic, in particular, when applied to quantum states and thereby assuming that pure states represent a novel concept of "quantum information" that does not have to be counted in any definition of entropy. For consistency, any incomplete information has to be represented by an ensemble of physical possibilities. In a classical world, all measurement outcomes are in principle determined in advance by the global microscopic state, and may thus be "observed" (with or without perturbation) rather than being created. While microscopic variables can usually be regarded as randomized before being measured, macroscopic ones are redundantly "documented" in their environment (for example by the light they have scattered and that might later be received by observers). For this reason they appear to be "objectively given"; one cannot conceive of *one* individual document only being different in order to define a different past. This retarded documentation of macroscopic "facts" requires a strong time asymmetry of the physical world that establishes its "causal appearance" and lets the macroscopic past appear fixed. The fate of such unavoidable documents is simply neglected in most speculations about "time travel".

3. The observer in the Everett interpretation

Hugh Everett first recognized that we don't have to postulate a dynamical collapse of the wave function (even when we assume the wave function to describe reality) if we accept instead that the subjective observer may simultaneously exist in various "versions" *i* that result from von Neumann's unitary formulation of a quantum observation,

$$\begin{aligned} &\left(\sum_i c_i \psi_i^S\right)\psi_0^A \psi_0^O \\ &\rightarrow \left(\sum_i c_i \psi_i^S \psi_i^A\right)\psi_0^O \\ &\rightarrow \sum_i c_i \psi_i^S \psi_i^A \psi_i^O =: \sum_i c_i \psi_i^{rel} \psi_i^O . \end{aligned} \tag{1}$$

Its first step is sometimes called a "pre-measurement". The suffixes *S, A, O* indicate the system, apparatus and observer, respectively, while for simplicity any information medium, such as light, is here regarded as part of the apparatus. The states ψ_i^{rel} on the right hand side are identical with the potential final states of a stochastic collapse process that would according to the orthodox interpretation have to occur before the outcome can be observed. According to Everett, they define the "relative state" of the outside world with respect to the physical state of the subjective observer ψ_i^O (therefore the title "Relative State Interpretation" of Everett's original publication). The observer, although remaining quite passive in (1), evidently assumes a crucial role in Everett's description as a consequence of the nonlocality of quantum states (Zeh, 2000; Mensky, 2005; Tegmark, 2012). If unitary quantum dynamics applies universally, one obtains a superposition of different versions of all observers described by separate wave packets in configuration space – just as there are different observers (at different locations in space) in one classical world. Emphasis on this aspect has led to the name "many minds" or "multi-consciousness" interpretation, since the relative state with respect to the observer's mind describes the oberserver's "frog perspective" of the quantum world – traditionally regarded as a dynamically resulting collapse component. (See the explicit examples of complete observations later in this section.)

Everett's conclusion was almost unanimously rejected by the physics community at its time for several reasons (if not just emotionally because of its unconventional nature). The major one was that the wave function had traditionally been regarded as meaningful only in the microscopic world, or at most until the Heisenberg cut is applied, whereupon it was assumed to "lose its meaning". Those who did regard the general validity of the wave function as a possibility raised another objection: the expansion

$$\psi^{total} = \sum_i c_i \psi_i^{rel} \psi_i^O$$

is defined with respect to any basis ψ_i^O chosen for the observer system (including states which would represent superpositions of different states of awareness). In von Neumann's first step of Equ. (1), the *i*-basis is usually defined by means of a phenomenological "observable" that is used to characterize a measurement, no matter whether an observer ever enters the scene in order to read off the result. This basis was later called the "pointer basis" (Zurek, 1981). If the observer system *O* itself was precisely defined (as one might hope for a minimum system representing consciousness), one could use the essentially unique Schmidt canonical representation, in which *both* subsystem bases are exactly orthogonal. However, this representation would fluctuate in time and strongly depend on the precise boundary between the observer system *O* that seems to form the physical side of a psycho-physical parallelism and the rest of the quantum world (Kübler and Zeh, 1973). It is thus not appropriate to describe objective measurements by an apparatus.

The problem of how to define an objective pointer basis that is sufficient for all practical purposes was resolved by the theory of environmental decoherence (Zeh, 1970; Joos *et al.,* 2003). Accordingly, the relative states in (1) have to include, in an essential way, an uncontrollable and normally inaccessible environment of the macroscopic apparatus, hence

$$\psi_i^{rel} = \psi_i^S \psi_i^A \psi_i^{env} . \tag{2}$$

Because of the unavoidably arising *i*-dependence of the environmental states ψ_i^{env}, a superposition of macroscopically different states ψ_i^A, formed in a unitary measurement, is immediately and irreversibly dislocalized. In this way, the "normal" and usually unavoidable environment of a macroscopic system induces a preferred basis for the pointer variable or other quasi-classical property that is objectively characterized by its robustness against further decoherence. The experimental confirmation of decoherence was historically the first clear indication that entangled wave functions are valid and meaningful beyond closed microscopic systems, although this entanglement must be far more complex than envisioned by von Neumann and Everett with their simplified model. The *i*-dependent effect in the environment does here *not* have to represent any usable information or documentation, since a thermal environment suffices to achieve decoherence. Therefore, only a minority of quasi-classical variables may be assumed to be "physically given" (macroscopic) – see below. Although it remains conceivable that the unbounded dislocalization of superpositions (decoherence) will at some point lead to an instability caused by some very small, as yet unknown deviation from global unitarity, this would not make any difference in practice as long as it cannot be directly observed. All observed quantum jumps would then nonetheless have to be described by a decoherence process.

Because of the locality of all interactions, the preferred basis is usually the position basis of a pointer or other macroscopic variable. Although a reversal of this dislocalization of superpositions would in principle be compatible with the Schrödinger equation, it is excluded by the arrow of time characterizing our world (regarded as a fact rather than a law – namely the absence of any advanced or "retro-causal" correlations or entanglement that might have local effects in the future). The nonlocal superpositions that are "caused" according to (1) when taking into account the environment can then not be relocalized any more in practice. On the other hand, they cannot disappear from the universe unless the Schrödinger dynamics were violated. Therefore, any description of reality in terms of a unitarily evolving wave function requires an Everett interpretation.

Realistically, the macroscopic "apparatus" that leads to an observation in (1) would not only have to include the thereby required information medium or registration device, but even the human sensory organs and much of his neuronal system. Both are macroscopic in the sense of being decohered by and documented in their environments (Tegmark, 2000), and both are (partly, at least) external to any reasonable subjective observer system (the physical carrier of consciousness). The neuronal apparatus is indeed a particularly fine-grained (complex) system whose variables can be assumed to be always "given". However, this further decoherence does not affect the measurement proper as an objective physical process in the apparatus. The precise localization of consciousness in the physical world remains an open problem - similarly as it did in classical descriptions, although one may expect that it has ultimately to be described in quantum mechanical terms.

After decoherence by the environment, the macroscopic system may for all practical purposes be characterized by its reduced density matrix (no more than a formal tool), such as

$$\rho_{red}^A = \sum_i |c_i|^2 \overset{*}{\psi}{}_i^A \;\; \psi_i^A .$$

Although this density matrix is identical to the one that would represent the ensemble of states postulated by a collapse, it does by its very definition *not* represent an ensemble. However, the global superposition (1) – including the environment – now consists of various dynamically autonomous world components which describe different macroscopic properties. Therefore, the different observer states ψ_i^O, whatever their precise definition, cannot dynamically feel the presence of the "other worlds" that are described by the states $\psi_{i'\neq i}^{rel}$ any more. This consequence is sufficient for the theory to consistently describe all our observations in an apparently classical universe. Note that the molecules forming a gas, for example, are also decohered into narrow wave packets by their mutual collisions, and thus approximately define a quasi-classical μ-space distribution, but this does *not* justify quasi-deterministic trajectories for them. Their collisions would appear stochastic in such a quasi-classical description (thus justifying Boltzmann's *Stosszahlansatz*). For this reason, their positions, although selected by decoherence, cannot be assumed to be "given" in each Everett branch (Zeh, 2007).

After the dynamical autonomy of Everett branches has thus been clearly established by decoherence, the localization of the subjective observer system in states existing within these branches appears indeed so plausible or "normal" that, for example, some Oxford quantum philosophers regard the quantum measurement problem as solved by the combination of decoherence and Everett without explicitly mentioning the observer – again in analogy to the classical concept of an observer-independent reality (Saunders *et al.,* 2010). Nonetheless, this physical specification of the observer is an important element of the theory that can only be empirically justified by the nature of subjective awareness.

As an example, consider two spatially separated microscopic systems entangled with one another as in a Bell state. If one of them is locally measured, *both* get immediately entangled with the apparatus and its local environment – nothing else yet. An observer at the location of the other microscopic system, say, will participate in the entanglement only after having received a signal about the outcome. Only thereafter will he be in different states in the different "worlds" that were dynamically separated from one another by the irreversible decoherence of the pointer position, but which together still form but *one* quantum world. If he decides to measure and observe also the microscopic system at his own location (before or after receiving the first signal – thus including delayed choice experiments), his state splits further in order to separately register and become aware of the quasi-classical outcomes of *both* measurements. When repeating the total measurement many times, he would in "most" of his resulting versions in very good approximation confirm the frequencies predicted by Born's rule (and thus their correlations that violate Bell's inequality) – provided the branches containing his various versions are *assumed* to possess statistical weights according to their squared norms when defining what is meant by "most versions". Any other conceivable statistical weights that would, in contrast, *not* be conserved under the Schrödinger equation (such as the ill-defined *number* of branches itself) would lead to probabilities that might later change under further measurements which are asymmetrically performed in some branches only. Everett considered this consequence as a proof of Born's probability measure (Byrne, 2010) - while it might otherwise represent a circular argument.

All those "weird consequences" of quantum mechanics that have recently been "discovered" and subsequently much discussed in the media can similarly and consistently be described solely in wave mechanical terms, since this is precisely how they all were (or could have been) predicted. Their weirdness is merely a consequence of the traditional attempt to describe the observed world in local classical terms. The reader may himself analyze the so-called quantum teleportation protocol in purely quantum mechanical terms as a second example in order to confirm that everything that appears being teleported (or its local causal predecessor) must be prepared in advance by subluminal means at its target position in one of the components of the required entangled wave function (Zeh, 2010). Teleportation and other "esoteric" phenomena would only be required if local properties were *created* in measurements (as assumed in the Copenhagen interpretation). It becomes evident in this way that entanglement cannot merely represent information, even though one may *pretend* that an initial superposition is transformed into an ensemble representing lacking information as soon as decoherence has become irreversible in a chain of interactions that might lead to an observation. (The cat has to be assumed to have died – if it ever did so in the corresponding "world" – long before the box was opened.) As this *apparent* global collapse is not a *physical* process, it may even be defined to "*occur*" superluminally, although such unphysical dynamics can obviously not be used to send information. This restriction of quantum reality to one (not yet known) effective branch wave function at the time when decoherence has become irreversible is certainly convenient and thus pragmatically justified, but physics students should be expected to understand its meaning in a complete and consistent theory (as just described).

Any proposal for a *genuine* (physical) collapse would have to be precisely specified in order to be meaningful, and it has thereby to avoid inconsistencies with the principles of relativity. On the other hand, any conceivable empirical confirmation of such a violation of the Schrödinger equation might readily falsify Everett's interpretation, while an *unspecified* collapse proposal can hardly ever be falsified. Most specified collapse models contain free parameters that would leave them non-falsifiable as long as these parameters do not have to violate certain bounds in order to fulfill their purpose of predicting definite measurement outcomes. Therefore, the dispute about a collapse of the wave function in contrast to Many Worlds should not be a matter of belief or religion. There simply exist two classes of possibilities whose consequences should be further analyzed and tested, while the original Copenhagen interpretation with its fundamental classical concepts seems to be deprived of all motivation by the success of the decoherence program. The same argument applies to Bohm trajectories. It should also be obvious that the wave function can carry information only if it represents a physical (real) object.

The consistent description of quantum phenomena according to Everett's interpretation means that the observed quantum indeterminism does not represent a stochastic dynamical process in nature, since the global wave function is assumed to evolve deterministically. Rather, it reflects the multiple future history of an observer in this deterministic quantum world – comparable to a process of cell division in a classical world that could thereby also remain deterministic. Without a subjective observer, there would be no justification for any frog's perspective that may select branches. However, this indeterminism of the observer's history is objectivized with respect to those versions of different observers (including "Wigner's friends") that are correlated according to their entanglement. Their versions who "live" in the same world branch always agree about the outcome of measurements, while their other versions do not have to disappear from reality; it is sufficient that they cannot communicate any more with one another. This entanglement between different observers is the same as that between an observer and his apparatus in Eq. (1).

So we may have to conclude that the Everett interpretation, which is a direct consequence of the Schrödinger equation (and thus falsifiable by the conceivable discovery of a fundamental collapse dynamics), is indistinguishable in practice from the pragmatic but never precisely defined Copenhagen interpretation. However, in contrast to the latter it is conceptually consistent. In other words: it is compatible with the concept of a well-defined (though nonlocal) micro-physical reality. In particular, it avoids all irrational concepts such as spooky action, complementarity, or an "uncertainty" of its basic kinematical terms (namely wave functions), and therefore does not offer any justification for speculations about supernatural or extraphysical phenomena. On the other hand, the possibility that the selection of *our* Everett branch required some improbable events in accordance with the weak anthropic principle cannot be excluded.

Acknowledgement
I wish to thank Erich Joos for his critical revision of the manuscript.

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