QUANTUM NO-GO THEOREMS AND CONSCIOUSNESS

Danko Georgiev

Our conscious minds exist in the Universe, therefore they should be identified with physical states that are subject to physical laws. In classical theories of mind, the mental states are identified with brain states that satisfy the deterministic laws of classical mechanics. This approach, however, leads to insurmountable paradoxes such as epiphenomenal minds and illusionary free will. Alternatively, one may identify mental states with quantum states realized within the brain and try to resolve the above paradoxes using the standard Hilbert space formalism of quantum mechanics. In this essay, we first show that identification of mind states with quantum states within the brain is biologically feasible, and then elaborating on the mathematical proofs of two quantum mechanical no-go theorems, we explain why quantum theory might have profound implications for the scientific understanding of one's mental states, self identity, beliefs and free will.

Keywords: brain · classical mechanics · compatibilism · determinism · free will · indeterminism · mind · no-cloning theorem · quantum mechanics

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I. INTRODUCTION

In neuroscience it is assumed that *consciousness* is a product of the brain whose function is governed by Newtonian (classical) physical laws. In this viewpoint, all brain processes that give rise to conscious experience can be reduced to chains of causes and effects, which although immensely complex operate as a clockwork mechanism [36]. In contrast, quantum mechanics tells us that the fundamental constituents of matter obey probabilistic laws, such that there is not a single predetermined future outcome, but a multitude of *potentialities*, only one of which is to be *actualized* [10, 31, 53]. The predictions of quantum theory were experimentally proven to be so accurate that at present there is a little doubt that the nature is governed by quantum laws.

Because consciousness is an ambiguous term that may refer to many different things, we introduce a formal definition, which is more or less identical to the one given by Thomas Nagel [44] and David Chalmers [16].

Definition 1. Consciousness is a collective term that refers to the subjective character of our mental states, our ability to experience or to feel. A conscious state is a state of experience. The terms *consciousness*, *mind* and *experience* will be used interchangeably hereafter.

There are several unresolved problems in the theory of consciousness, which might benefit from quantum mechanical analysis. Here, we will formulate only those problems that are relevant for our discussion and will refer the reader elsewhere for a general introduction to the theory of consciousness [22].

Problem 1. Because the material world in classical deterministic physical theories is causally closed, there is no room for consciousness, or if consciousness is allowed it can only be in the form of a causally ineffective epiphenomenon. If the brain states produce conscious experiences, then these experiences cannot possibly have an effect upon brain dynamics, which is already fully determined by the fundamental physical quantities of the brain such as mass, charge, length and time [35, 52]. For epiphenomenalists our subjective (intuitive) feeling that our consciousness is causally effective is just an illusion produced by the brain [60]. However, according to the evolution theory something that is not causally effective cannot lead to evolutionary advantage and cannot be selected by natural selection [36, 37].

Problem 2. Because the future in classical deterministic physical theories is predetermined, genuine free will and moral responsibility are impossible. If there are no future alternatives allowing for choices to be made, then we cannot be responsible for our actions, no more than a falling stone is morally responsible for breaking someone's leg. Subjectively (intuitively) it feels as if our *consciousness* is able to make choices between alternative future possibilities, but for classical determinists this is just another illusion produced by the brain [9, 55, 56, 60].

Since the counterintuitive results from the classical approach to the theory of consciousness stem from the deterministic laws, any quantum theory of consciousness attempting to resolve Problems (1) and (2) cannot be based on interpretations of quantum mechanics that endorse a form of conspiracy determinism (description of such conspiracy theories of quantum mechanics can be found in [42]). The indeterminism provided by the standard axioms of quantum mechanics (including the Born rule) motivates an increasing number of scientists to search for a reinterpretation of quantum theory in which *consciousness* is fundamentally connected with the process of *choice making* or *actualization* of alternative future possibilities [7, 26, 27, 47, 51, 61]. Noteworthy, the indeterminism is not the only important feature of quantum mechanics, which makes it relevant to the study of biological systems and consciousness (cf. [2–6, 25, 28]). There are several quantum mechanical no-go theorems that may be important for neuroscience and philosophy of mind provided that following weak proposition is true:

Proposition 1. *The brain can sustain quantum coherence for any (possibly short but physically feasible) period* *of time and the mind state produced by the brain depends on or could be identified with the quantum state of the brain for this short period of time.*

In order to justify this proposition, first we will note that quantum physical calculations do not show that quantum coherence cannot occur at all in the hot, noisy and wet brain. Instead, the calculations show that the life-time of quantum coherent states in the brain cannot be on a millisecond timescale [43, 54, 58]. Thus we come to a central question in neuroscience and theory of consciousness, namely, is there any evidence that conscious processes operate on a millisecond timescale? The calculated decoherence time for quantum states within cytoskeletal proteins was estimated to be ≈ 0.1 picosecond [58] and it was argued that *quantum effects* on a picosecond timescale could have impact upon the brain function [24, 27]. Therefore, if conscious processes in the brain were not assumed to be on a millisecond timescale, but on a picosecond timescale or faster, there would be no physical objection to quantum effects being involved in consciousness. In fact, classical neuroscience provides no proof that our minds operate on a millisecond timescale, it only establishes that our minds do not operate on a timescale slower than that.

A major group of experimental tests trying to estimate the duration of each conscious step are based on measuring of *reaction times* [12–15]. While it is true that reaction times are of the order of tens to hundreds of milliseconds, such measurements provide only an upper bound on the duration of each conscious step. If we can perform a cognitive task and react in millisecond timescale, it would be incorrect to construct a theory in which each conscious step lasts seconds or minutes. On the other hand, such experiments cannot show that each conscious step was not in fact much shorter, for example picoseconds [24]. To further clarify why measuring of reaction times provides only an upper bound for the duration of conscious steps, let us consider the operation of a personal computer. The personal computer has a human interface to get the input (keyboard and mouse) and provide the output (monitor), and a processor equipped with working memory, which is used to perform the computational tasks. The devices that provide the human interface operate at a millisecond timescale, for example the image on the monitor usually is refreshed every 10 ms corresponding to a frequency of 100 Hz. However, the processor could operate at a much faster timescale of picoseconds, which for modern processors could correspond to a frequency of 5 GHz. It is clear that measuring the refresh rate of the monitor does not really say how fast the processor of the computer is. Such measurement can establish only an *upper bound* according to which the processor could not operate at a timescale longer than 10 ms (or equivalently, at frequency lower than 100 Hz). Essentially the same argument applies to physiological experiments measuring reaction times of human volunteers. While it is true that the brain cortex communicates at a millisecond timescale with the sensory organs to obtain information and with muscles to output information using electric impulses propagating along the nerve fibers (axons), this does not imply that the conscious processing and the duration of mental states within the brain cortex occur also at a millisecond timescale. On the contrary, any attempt to construct a quantum mechanical theory of brain function leads to the prediction that the relevant dynamical timescale is not slower than picoseconds [24, 26, 27, 58].

Another group of experimental tests trying to estimate the duration of each conscious step are based on subjective reports of perceived temporal order of non-simultaneous sensory inputs. The first such psychophysical "investigation of the simplest mental processes" was performed by Sigmund Exner [19–21], and further corroborated by different research groups [34, 38, 49]. It was found that the minimal time window between two different sensory inputs allowing for subjective assessment of their non-simultaneity and temporal order is ≈ 30 ms [34, 38, 49]. These data, together with clinical reports of patients with time agnosia (who are conscious but do not experience subjective passage or flow of time) confirm the possibility of having consecutive conscious steps, which are nonetheless experienced as "simultaneous" [24]. Therefore, subjective reports on experienced passage of time cannot be used to determine the duration of each conscious step. The psychophysical tests, too, can establish only an upper bound on the duration of each conscious step, which cannot be longer than ≈ 30 ms.

Finally, there is a group of experimental tests such as electroencephalography (EEG) or functional magnetic resonance imaging (fMRI) that can monitor changes in brain activity in real time. Although it is possible to monitor the brain activity with arbitrarily high temporal resolution, there is no whatsoever theoretical way to determine from such data what is the duration of each conscious step. Establishing certain correlations between wakefulness and patterns of brain activity cannot provide even an upper bound for the duration of each conscious step. Functional observations are meaningful only when combined with psychophysical tests, but the latter will just show that each conscious step is no longer than ≈ 30 ms as discussed above. What is remarkable is that those who believe that the mind is a product of classical millisecond brain processes calculate quantum mechanically brain decoherence timescale of the order of picoseconds and from that conclude that quantum mechanics is irrelevant for mental processes and theory of consciousness [40, 58]. But we have just shown that such argument is fallacious. The reaction times, psychophysical tests or functional studies could provide at best only an upper bound for the duration of each conscious step. If one constructs a theory in which the conscious processes are much faster than the reaction times measured by physiological experiments, then the calculated brain decoherence timescale of the order of picoseconds would just confirm or corroborate the quantum mechanical theory of mental states instead of disproving it [24].

Having shown that the current status of the classical theory of mind operating at millisecond timescale is nothing but a pure belief, we proceed with analysis of two quantum mechanical no-go theorems that are little known to neuroscientists and classical philosophers of mind, and discuss the scope of their implications. The subsequent exposition is organized as follows: in Section II we explain why the wide-spread philosopher practice to take as granted that one can read, copy, clone, multiply and/or erase safely *information* is fundamentally flawed; then in Sections III and IV we provide the proofs of two quantum mechanical no-go theorems and discuss how they are interconnected; finally in Section V we apply those theorems to the mind-brain problem and obtain novel insights into one's self identity, beliefs and free will.

II. CLASSICAL INFORMATION VERSUS QUANTUM INFORMATION

Current neuroscience is exclusively built upon the concept of *classical information*, which can be *read, copied, multiplied, stored, processed* with the use of irreversible Boolean gates and/or *erased*. An example of *classical information* is the string of bits, 0's and 1's, that encode a digital movie recorded onto DVD. One can watch the DVD, copy the information from the DVD any number of times, and even erase the DVD in order to re-write it with new information. The classical bits of information or *c-bits*, possess all of the above properties and intuitively these properties seem to be essential for our understanding of what information is.

Nevertheless, in quantum mechanics the individual carriers of information do not share most of the properties possessed by c-bits. We will refer to the carriers of quantum information as quantum bits, or simply *q-bits*. One of the peculiar properties of the quantum information contained in the quantum state (wavefunction) of a q-bit is that in general it *cannot be observed or read (i.e. cannot be deduced from experimental data)* as in the case of the c-bits stored on DVD [1, 11]. If we have a quantum version of DVD storing a string of q-bits, in general *we cannot copy* the string of q-bits [17, 62], we cannot process the stored quantum information using irreversible Boolean gates [59], and *we cannot erase* the quantum information (at best we can achieve *swapping* that is moving the information around without deleting it) [46]. Furthermore, the Bell and Kochen-Specker no-go theorems [8, 41] do not allow for quantum mechanics to be completed and/or explained with the use of classical hidden variables that are local or non-contextual [32]. At a first glance all this could be perplexing, however these results are provable as mathematical theorems using the standard Hilbert space formalism of quantum mechanics. Here we will provide mathematical proofs only of the first two no-go theorems.

III. QUANTUM STATES ARE NOT OBSERVABLE

Theorem 1. *Unambiguous determination of an unknown individual quantum state (wavefunction) $|\Psi_A\rangle$ of a q-bit A is impossible [11].*

Proof. In order to determine the state of a quantum system we could perform a measurement. Every measurement can be represented by some observable (that is a Hermitian operator) $\hat{P} = \hat{P}^\dagger$ whose eigenvalues are exhibited as the measurement outcomes. In order to be able to decide from the outcomes whether or not the system was in a given state $|\Psi_A\rangle$, there needs to be at least one outcome which occurs with certainty if the state was $|\Psi_A\rangle$, and which will certainly not occur if the state was some state $|\Phi_A\rangle$ different from $|\Psi_A\rangle$. Since the quantum mechanical probabilities are expectations of some positive semidefinite operators $\hat{P}$ representing the event in question, it follows that $\langle\Psi_A|\hat{P}|\Psi_A\rangle = 1$ and $\langle\Phi_A|\hat{P}|\Phi_A\rangle = 0$. These equations are equivalent to $\hat{P}|\Psi_A\rangle = |\Psi_A\rangle$ and $\hat{P}|\Phi_A\rangle = 0$. Therefore, $\langle\Phi_A|\Psi_A\rangle = \langle\Phi_A|\hat{P}|\Psi_A\rangle = \langle\Psi_A|\hat{P}|\Phi_A\rangle^* = 0$ which is to say that $|\Psi_A\rangle$ and $|\Phi_A\rangle$ are mutually orthogonal. *Because there is no measurement of q-bit A that would allow one to distinguish unequivocally between any pair of non-orthogonal states, it follows that unambiguous determination of an individual quantum state $|\Psi_A\rangle$ of a q-bit A is impossible by only measuring the q-bit A.* This weaker result is sufficient for proving the subsequent Theorem 2. We note that if there were a way to copy the original q-bit A multiple times before we measure the q-bit A, then we would have been able to measure these copies as well and use the results to reconstruct the quantum state of the original q-bit A. However, the impossibility to clone unknown quantum states is established by Theorem 2 and this concludes the proof of Theorem 1. □

Here, we would like to remark that Theorem 1 follows from the standard Hilbert space formalism of quantum mechanics in which the space of states of a quantum mechanical system forms a *vector space* instead of a *set* [57]. In the early days of quantum mechanics many of the important quantum mechanical results were considered to be a consequence of the Heisenberg uncertainty principle, which was understood as an empirical regularity (employing no or only a bare minimum of theoretical terms) whose purpose was to build up a fully fleshed physical theory explaining the empirical data [33]. At present we already have constructed a powerful axiomatization of quantum theory (see [48]), so we derive Heisenberg uncertainty relations as theorems and no longer use them as a starting point for derivation of other quantum mechanical results. Indeed, manipulation of vectors in a Hilbert space is much more easier compared to detailed analysis of thought experiments in the fashion Heisenberg did (cf. [33]).

IV. QUANTUM NO-CLONING THEOREM

Theorem 2. *An unknown quantum state $|\Psi_A\rangle$ of a q-bit A cannot be cloned to another q-bit B* [17, 62].

Proof. Suppose that we have a two-level q-bit A, whose *unknown* quantum state $|\Psi_A\rangle$ we wish to copy. The state can be generally written as

$$|\Psi_A\rangle = \alpha|0_A\rangle + \beta|1_A\rangle \tag{IV.1}$$

where $|0_A\rangle$ and $|1_A\rangle$ are two orthogonal basis states in two-dimensional Hilbert space $\mathcal{H}$, and the complex coefficients α and β are unknown. In order to make a copy, we take a q-bit B with an identical Hilbert space and initial state $|e_B\rangle$, which must be independent of $|\Psi_A\rangle$ (of which we have no prior knowledge). The composite system is then described by the tensor product

$$|\Psi_A\rangle \otimes |e_B\rangle \tag{IV.2}$$

There are only two ways to manipulate the composite system. One possibility is to perform an observation (measurement of q-bit A), which forces the system into some eigenstate of the observable and corrupts the information contained in the q-bit A. This precludes achieving a copy of q-bit A. A second alternative is to control the Hamiltonian of the composite system, and thus the time evolution operator $\hat{U}$, which is *linear*. For any fixed time interval, $\hat{U}$ would act as a copier provided that

$$\hat{U}|\Psi_A\rangle \otimes |e_B\rangle = |\Psi_A\rangle \otimes |\Psi_B\rangle \tag{IV.3}$$

for all Ψ. This must be true for the basis states as well, so

$$\hat{U}|0_A\rangle \otimes |e_B\rangle = |0_A\rangle \otimes |0_B\rangle \tag{IV.4}$$
$$\hat{U}|1_A\rangle \otimes |e_B\rangle = |1_A\rangle \otimes |1_B\rangle \tag{IV.5}$$

Then eq.IV.1 and the linearity of $\hat{U}$ imply

$$\begin{aligned}\hat{U}|\Psi_A\rangle \otimes |e_B\rangle &= \hat{U}(\alpha|0_A\rangle + \beta|1_A\rangle) \otimes |e_B\rangle \\ &= \alpha\hat{U}|0_A\rangle \otimes |e_B\rangle + \beta\hat{U}|1_A\rangle \otimes |e_B\rangle \\ &= \alpha|0_A\rangle \otimes |0_B\rangle + \beta|1_A\rangle \otimes |1_B\rangle \end{aligned}\tag{IV.6}$$

This is generally not equal to $|\Psi_A\rangle \otimes |\Psi_B\rangle$, as may be verified by plugging in $\alpha = \beta = \frac{1}{\sqrt{2}}$. Indeed if one starts with $|\Psi_A\rangle$ being a superposition of the basis states $|0_A\rangle$ and $|1_A\rangle$, the time evolution operator $\hat{U}$ will create an *entangled state*, so $\hat{U}$ cannot act as a general copier. The latter result is known as the *no-cloning theorem.* □

The above argument illustrates something very interesting, namely that if $|\Psi_A\rangle$ is not in one of the two basis states for which our copying machine is originally designed, the putative copy will be *entangled* with the original q-bit. If we measure the original q-bit, we will corrupt the *entangled copy* as well. In general, the copy that we can achieve is a pseudo-copy, because it is entangled with the original q-bit and will be corrupted when the original q-bit is measured. For completeness we could add that if $|\Psi_A\rangle$ were in one of the two basis states, the copy will be a true copy, yet we will not know this. Since there is an infinite number of possible basis states, the chance for production a true copy is equal to the chance of guessing correctly the unknown quantum state, which is one out of infinite number of possible states. Or in other words, there is an infinite number of copying machines that can copy only a pair of basis states, and since originally the quantum state is unknown to us, the chance to choose at random the correct copying machine is *zero*.

V. IMPLICATIONS FOR THE MIND-BODY PROBLEM

Physics is a scientific discipline supposed to study all things that exist within the Universe. Because our minds do exist in the Universe, they are physical by definition and should be subject to physical laws. The important question, however, is what kind of physical laws: classical or quantum? Every scientific theory addressing the mind-body problem should have an entity referred to as *mind* even though in mind-brain identity theories the term *brain* is usually preferred for reasons that have to do with conventions and/or personal taste, not logic (logically if two terms are identical you can use them interchangeably). Furthermore, the mind in every scientific theory should be subject to certain (classical or quantum) physical laws. The third option, according to which the mind is not subject to any physical laws, should be considered experimentally rejected since we cannot perform miracles at will.

In a classical theory of mind (in which the mind is governed by classical physical laws), one could in principle conceive thought experiments in which one is able to observe and/or create perfect copies of one's mind (and brain). As a consequence one is able to prove various paradoxical results such as (i) the observability of mental states from third person perspective, (ii) the existence of self-locating beliefs, (iii) the non-existence of self identity, and (iv) Frankfurt's thesis that free will could exist in cases where the subject could have not done otherwise.

Interestingly, the two quantum mechanical no-go theorems proved in Sections III and IV show that most of the intuitive properties of classical information (the ability to be observed, copied or multiplied) do not hold for quantum systems. For example, if we have a quantum version of DVD with unknown file on it, in general we will be able neither to copy the DVD, nor to read it (even though imperfect copying or partial reading is possible). Thus in quantum theories of mind (in which the mind is governed by quantum physical laws), the quantum mechanical no-go theorems forbid mind observations or copies to be made and invalidate the proofs of the above-mentioned paradoxical results. The latter conclusion is our novel contribution to the main-body problem.

A. Privacy of mental states

A physical state is *observable*, if it can be deduced from performed experimental measurements upon the state. In classical physics all physical states are observable in principle. In quantum physics, however, unknown quantum states are *unobservable* and cannot be deduced from experimental measurements as shown by Theorem 1. Most people intuitively feel that our *mental states* are *private* and cannot be observed from third person perspective. Nevertheless, the successful application of functional brain imaging techniques, such as positron emission tomography (PET) or functional magnetic resonance imaging (fMRI), for studying cognitive processes in humans, provided certain researchers with optimism that mental states *could be observed* from third person perspective [29, 30, 39]. Such optimism might be pseudojustified with the use of Karl Popper's demarcation criterion according to which scientific theories should be experimentally testable [50]. If unobservable entities cannot be directly deduced from experimental tests, then any theory proposing entities unobservable from third person perspective must be pseudoscience. However, such conclusion might be premature because one can similarly apply the demarcation criterion to quantum mechanics and argue that it is pseudoscience due to the fact that it contains unobservable quantum wavefunctions. Since quantum mechanics is the most successful physical theory we currently have, it is more reasonable to conclude that Karl Popper's demarcation criterion has its limits of application. In particular, neither quantum mechanics nor the theories of mind appear to be within the domain where the demarcation criterion should be applied. Furthermore, there are good (intuitive) reasons to think that a successful theory of mind will come out with essentially unobservable mental states. If the proposal for mental states being quantum coherent states in the brain turns out to be true, then Theorems 1 and 2 automatically ensure the privacy of mental states making them unobservable for external measuring devices (with the caveat that what can be observed should be an eigenvalue of some observable $\hat{P}$, hence providing only incomplete information about the quantum state).

B. Self-locating beliefs

In an interesting paper Elga proposed the existence of *self-locating beliefs*, which might be used to create a serious doubt in one's mind whether he himself is the *original* or he is just a *duplicate* of the original [18]. Let us imagine the fictitious situation in which a malicious creature called Dr. Evil is in orbit around Earth in its spaceship, which is indestructible. After 24 hours Dr. Evil will be able to destroy the Earth by bomb. Unfortunately for him, just before doing so, he receives a letter from Earth's Philosophy Defense Force, which never lies. In the letter is said that they have created 99 duplicates of Dr. Evil, which have exactly the same experiences as Dr. Evil himself and that for example at the very same moment each duplicate is also reading the letter. Moreover, if the duplicates do not surrender at once, the Earth's Philosophy Defense Force will torture the duplicates. The question is: "how seriously should Dr. Evil consider that he is a duplicate?". Elga (2004) argues that the answer is: "very seriously" and that Dr. Evil should surrender. In this case the belief that there is a 99% chance that he is a duplicate should be *self-locating* in the real Dr. Evil too. If however the Dr. Evil's mind is a product of quantum coherent process in his brain, the no-cloning theorem implies that the Earth's Philosophy Defense Force cannot create even a single duplicate of Dr. Evil. Therefore the concept of *self-locating belief* is bogus and Dr. Evil cannot be defeated.

C. Self identity

In classical neuroscience the idea that the *personal identity* including one's own *mind*, *self*, and *free will* is entirely contained in the molecular and biological structure of the brain (c-bits) implies that a duplicate identity could be created that is identical in every way except physical *location*. Thus the neural net organization, neurons, synapses, molecules would be identical and in identical physical relationship to the others in the duplicate, and every neuron and synapse would be in an identical state of depolarization at the instant of duplication. This creates well known problem with the notion of one's *self identity* as it leads to paradoxical existence of one mind in two different places. Moreover the whole construction of the duplicate is conceived by some philosophers as an argument against the existence of the *self* or at least that preservation of one's important psychological features does not suffice for *self identity* [45]. Though none of the proposed classical solutions to the outlined paradox is satisfying, if mind states are quantum states of the brain, then one can use Theorem 2 to argue against the possibility for duplication of the self. In contrast with classical theories where one can in principle duplicate complex systems such as the brain, in quantum theory such duplication is impossible and the *duplication* elsewhere in space would be as likely as the miracle of *spontaneous creation* of one's brain. Thus, quantum theory provides a better physical formalism for the existence of the *self* compared to the classical Newtonian theory.

D. Compatibilism and free will

Compatibilism is a philosophical position according to which *free will* is possible even if the physical world is governed by deterministic laws and one does not have the option to choose among multiple future possibilities. Although it looks impossible to explain how one can have free will without given the option to choose among at least two future possibilities, an argument proposed by Frankfurt [23] was widely celebrated as providing such explanation. Frankfurt's argument attempts to establish that one might act on one's own will despite of the fact that one could have not done otherwise [23]. For the construction of the argument Frankfurt supposes that (1) an external agent could observe (deduce from experimental measurements performed with an advanced device) your mental states and monitor your future decisions and (2) could use an advanced device in order to rearrange the firing of your neurons in such a way that you will do a certain action A only in case you have not chosen to do A. From the given premises it is easy to see that if you have chosen to do A you have done it on your own will, despite of the fact you could not have done otherwise. Although Frankfurt's argument seems to establish the credibility of compatibilism in the framework of classical theory of mind, it is completely demolished if the mind states happen to be quantum states of the brain. As a consequence of Theorem 1, it follows that if one's mental states are quantum states then no external agent would be capable to observe or monitor the mental (quantum) state of a quantum coherent system, because any measurement itself will alter the state of the observed quantum system. Indeed, it is impossible for a classical philosopher to defend any form of compatibilism without utilizing some of the main operations that could be performed upon classical information such as observing or copying of c-bits. Furthermore, within the light of the discussed quantum mechanical no-go theorems, it becomes transparent that Frankfurt's argument is a logical fallacy based on the assumption that "mental states are c-bits with free will" with subsequent derivation of the intended conclusions about one's mental states and free will from the postulated c-bit properties. Without the implicit c-bit assumption it becomes impossible to construct a thought experiment in which a subject has no choice to do otherwise, yet exerts his free will. It seems that Frankfurt makes the error because it is inconceivable for him that there could be any form of information that is different from a c-bit. Thus, quantum mechanics not only provides alternative future possibilities that could be actualized, but also guarantees the existence of free choices by forbidding external monitoring of one's mental states.

VI. CONCLUDING REMARKS

It has been argued that quantum coherence in the brain might be too short and therefore irrelevant for the mind-brain problem [58] or that quantum mechanics has nothing to contribute to the mind-brain problem [63]. The authors of the latter work [63] have expressed the "hope that the rejection of the role of consciousness in quantum mechanics will also lead us to re-evaluate the proposals that quantum mechanics is vital for explaining the consciousness. Having these two deep mysteries disentangled one from the other might be an important step forward towards understanding each of them." In this work we have shown that such skepticism is premature because if mental states are even short-lived quantum brain states then quantum mechanical no-go theorems apply and provide novel insights for the understanding of one's mental states, self identity, beliefs and free will. In particular, if the mental states are quantum states of the brain they cannot be observed (deduced from experimental measurements) by an external observer and the privacy of our mental life is guaranteed by quantum mechanical laws. Furthermore, the concept of self-identity is not subject to classical paradoxes resulting from putative duplications of the self. In addition, the quantum no-go theorems invalidate Frankfurt's celebrated argument for compatibilism and restore the credibility of our intuition that we could not have exerted our free will if there were no alternative options to choose from.

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