PHYSICS VS. SEMANTICS: A PUZZLING CASE OF THE MISSING QUANTUM THEORY

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A case for the project of excising of confusion and obfuscation in the contemporary quantum theory initiated and promoted by David Deutsch has been made. It has been argued that at least some theoretical entities which are convenionally labelled as "interpretations" of quantum mechanics are in fact full-blooded physical theories in their own right, and as such are falsifiable, at least in principle. The most pertinent case is the one of the so-called "Many-Worlds Interpretation" of Everett and others. This set of idea differs from other "interpretations" in that it does not accept reality of the collapse of Schrödinger's wavefunction. A survey of several important proposals for discrimination between quantum theories with and without wavefunction collapse appearing from time to time in the literature has been made, and the possibilities discussed in the framework of a wide taxonomy.

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I myself feel impelled to the fancy—without daring to call it more—that there does exist a limitless succession of Universes, more or less similar to that of which we have cognizance.

Edgar Allan Poe, *Eureka: A Prose Poem* (1848)

1. Introduction: background of the crime

At the beginning of XXI century, we may conclude that in the course of the last several decades quantum mechanics has enjoyed-in quality, if not in quantity-an empirical success equal to or greater than the classical Newtonian physics enjoyed over several centuries. Apart from countless technically impressive experiments unanimously confirming its predictions, like the establishing of EPR-type correlations over kilometer-based distances,[1,2] quantum coherence of large molecules like C_{60},[3] or sustaining quantum coherence in macroscopic phenomena,[4] its numerous technological applications are rapidly becoming part of the everyday life of billions of people. Even more speculative and fantastic possibilities are on the horizon, like quantum computing and nanotechnology (e.g. Ref. 5).

However, this brilliant experimental success story has been marred by theoretical problems, often justifiably raised to the level of "intellectual scandal".[6] This pertains, of course, to the classical "problem of quantum measurement". Practical successes have been, with a surprisingly wide publicity, used to defuse what might be called "Schrödinger's time bomb", i.e.

gravity of the problem of measurement, or "quantum jumps", or "reduction of the wavefunction", etc. Our attitude in this paper is that such defusing is just a rhetorical trick. In order to debunk this trick, it is necessary to reconsider the meaning of some of the most widely used concepts in the entire story.

We shall therefore reformulate this issue in the form of "missing quantum theories case": why do we fail to recognize several distinct quantum theories in their own right? Why should we be content in this case (contrary to the entire history of science) not to inquire which-of the existing alternatives-does adequately or even best of its rivals describes the physical processes and events involved? We would be entitled to ask for such a description *even if there were none offered in the literature so far*; so it is incomprehensible why should we show restraint when we have several well-established views on the matter. In the dichotomy of the title of this article, it seems that, unfortunately enough, semantics has gotten an upper hand in most of the literature so far. This situation certainly calls for a rectification.

Specifically, we would like to inquire into status of Everett's quantum theory. As Tegmark[7] emphasizes, it "has survived 25 years of fierce criticism and occasional ridicule to become the number one challenger to the leading orthodoxy". However, as we shall see, Tegmark himself is somewhat ambiguous in regard to its epistemological status. Thus, after being for a long time "guarded secret" of quantum theory (Bryce DeWitt), Everett's theory has entered a new phase of denial: it is denied that it is a quantum theory in its own right, and it is relegated into a status of "interpretation" or a "picture". A great contribution to this mystification comes from the deeply rooted English acronym MWI (Many-Worlds Interpretation), containing the confusing misnomer (or so we shall argue) "interpretation". But, the same demystification project is perfectly applicable to most of other contenders for the correct solution of the puzzle of quantum measurement; in particular the theories with dynamical reduction[(8−10)] are positively affected. Their explanatory project can only benefit from the resolution of semantic confusion reigning in the field. The desire for "advancing the level of discussion" is a commonplace, be it in scientific meetings, editorial policies, or just bread-and-butter research work. However, some prejudices comprising the reigning confusion in quantum theory make the true advancement in discussion rather unfeasible.

An important motivation for clearing of this confusion is the (in)famous criticism of Everett's theory (and many-worlds/histories theories in general) as violating Occam's razor. This intuitively understandable, but *wrong* notion stems directly from the semantic confusion. If Everett's scenario is truly an interpretation, and thus is not refutable, as many maintain (e.g. Ref. 11), than it is really questionable whether the ontological enlargement it posits is really appropriate. After all, who would bother with the ontological baggage if it has no physical impact *per definitionem*?[1] However, if we accept (for reasons elaborated below, or for some others) that Everett's

[1]This is still not the standard application of Occam's razor, but is a valid criticism nonetheless!

is a full-fledged quantum *theory*, we should apply Occam's razor in its true form, that is, ask how many *epistemological* entities it postulates (that is, whether it has more or less assumptions than its rivals); we argue below that the ontological side of the story is purely a practical matter.

One cautionary note: since terminology plays such a big role in the discussions of quantum foundations, it should be good to define something of it from the start. We shall use the term "version" of the quantum theory as *neutral* in the sense that it does not presuppose the methodological verdict, in contradistinction to such terms as "view" and "interpretation". Versions A and B may turn out to be two different theories (that is what we investigate), or they may be just interpretations or views of the same underlying theory.

2. Investigation: is there really a problem of interpretation?

It is rather well-known fact in epistemology that interpretive programs (in science generally) still do not possess a satisfactory, clear-cut definition. One of the leading experts in the field of interpretations of physical theories thus recently writes:[12]

> Examining this spectrum of possible moves made in interpreting fundamental theories shows us that there they fall into a crude sort of order. Begin with interpretive programs that 'leave the theory alone' altogether restricting the interpretive work to philosophical commentary on the existing scientific body of

> work. Then move on to those interpretive programs that invoke 'reconstructions' of the theory of varying degrees of strength. Minimally one may simply look to alternative axiomatizations of the theory. More radically, one may look to seriously new formalizations of the theory that barely resemble the theory in its orthodox garb. Then consider those interpretive programs that invoke serious eliminative programs, keeping only a subset of the original theory's consequences of the original theory. Finally think of those most radical of all interpretations, those that invoke new levels of ontology and structure altogether, declaring the original theory perhaps incomplete, or, in some cases perhaps, even incorrect in some of its conclusions.

Here we have reached the borderline which is significant in our actual case. Sklar concludes this account with important moral:

> This last kind of 'interpretation' amounts, of course, to doing 'new science' altogether. Here there is plainly going to be a continuous transition between what we might think of as interpretation that invokes novel scientific elements of this last sort, and programs, rather, of replacing the theory in question by some brand-new scientific alternative. Just how far does one have to go in adding to a theory or in rejecting portions of it and replacing them with genuinely new scientific surrogates before one ought to stop talking of 'interpreting' the original theory

> and speak instead of replacing it with some allegedly superior alternative theory? I doubt that one can draw any principled line between replacing a theory and 'merely interpreting' it, but the absence of such a hard and fast distinction does not in itself force us to repudiate the claim that overall replacing theories and interpreting them are two distinct scientific programs with separate motivations and distinct procedures.

We have quoted this *in extenso*, since there are several important morals to be taken here, before venturing to the specific realm of quantum mechanics interpretations and "interpretations". First, we notice obvious difference between collapse (like the Copenhagen) and no-collapse (like Everett's) theories in this respect: we have von Neumann's postulate on collapse (projection, reduction, etc.) in the former, but not in the latter. Thus, their formalizations are certainly different. This even more forcefully applies to the dynamical reduction theories like GRW, who need to supply not only an analogue to the collapse postulate, but also values of new constants of nature involved in the collapse dynamics. Note that distinction here is much more significant than in the case of comparison of Newtonian with Cartan's differential-geometrical classical mechanics; the latter case is part of the interpretive endeavor at its best.

One point is chronological. The radical move of Everett which gave us a truly universal quantum theory came only in the aftermath of the foundational discussions of 1930s. Thus, our perspective is somewhat inverted in comparison with what could be understood as a "regular" chronological relationship between theory and interpretive projects centered on it. This inversion has undoubtedly caused deformation of our views about the aims and goals of the interpretive projects in this particular case. In particular, "replacing" paradigm is inapplicable here; rather, we again have a sort of branching (of theories, not worlds!).

In recent extremely interesting comments on Michael Lockwood's work, one of the most prominent quantum physicist of today, David Deutsch, expresses somewhat different sentiments toward the interpretive issue in physics, and notably quantum mechanics:[6]

> But in fact, there is only one known interpretation of quantum theory. Nor should we find this surprising. It is quite exceptional in science for there to be a dispute about the interpretation of a theory. The only example I can think of in modern physics concerns the 'spin-two-field' re-interpretation of the General Theory of Relativity (which involves replacing the curvature of Einstein's spacetime by a force field that produces gravity in a flat spacetime). The creationist re-interpretation of the fossil record as having been fabricated by God in 4004 BC also comes to mind. In addition to these disputes over rival conceptions of reality, there have sometimes been disputes between a realistic theory and an instrumentalist doctrine that denies that the theory describes reality. For example the Inquisition

> in Galileo's time permitted advocacy of the heliocentric theory if it was regarded purely as a means of predicting astronomical observations, but not if it was interpreted as a factual theory of where and what the planets and the Earth are. Similar instrumentalist doctrines have been applied to quantum theory. What these miscellaneous revisionist views of scientific theories have in common is a loss of philosophical nerve in situations where, as Lockwood puts it, "there are no conservative options". That is, they are not so much bona fide rival ontologies struggling to be heard, as psychological manoeuvres whose purpose is to blind their defenders to evidence of something unwelcome: the motion of the Earth, the curvature of spacetime, dinosaurs, or other universes.

Deutsch, of course, is probably the foremost proponent of what we call here MWT, and he labels *the* quantum mechanics. The same analogy of quantum theory/interpretation issue with the situation in astronomy around AD 1600 has been invoked by Barrow and Tipler in their well-known monograph on the anthropic principles.[13]

Now, let us consider the situation in general terms. Theory A is different from theory B if either

(1) propositions of A predict new phenomena, non-existent in B, subject (*even if only in principle*) to an empirical verification;

or

(2) the formal parts (”mathematics”) of A and B are different.

For our purposes in this essay, we put the requirements (1) and (2) on equal footing, while being fully aware that this is not warranted in the general case. Confusion on application of these criteria to the solutions of the quantum measurement puzzle reigns not only among physicists, but among philosophers of science, who should know better. Thus, Price[(13)] repeatedly refers to GRW theory as ”interpretation” though it does satisfy both (1) and (2). That GRW does satisfy (2) is fairly obvious, since that theory proposes addition of nonlinear terms to the Schrödinger equation. It seems also clear that with a higher degree of technological sophistication, we could discern effects of those nonlinearity,[(15,16,53,55)] thus justifying invoking of (1). Such examples abound in the literature. Sometimes consolation is taken in modifying the criterion (1) such that it applies to the present human level of capacities for empirical verification. However, such attitude is hypocritical and violates those ”Copernican” principles underlying modern science. Why should we believe that our present level of technological development and sophistication reflects anything else than a passing and ephemeral stage of our interaction with natural environment?

Let us try to investigate this contrary point of view in some detail, in order to demonstrate its incoherencies. By which criteria could conceivably one claim that Copenhagen, Everett, GRW and the rest are just interpretations of the same underlying theory? Only conceivable thing is something along the line of:

(3) A and B are different if they account for different sets of *observed* phenomena.

On this criterion, obviously, Newtonian mechanics is different when compared to *any* version of quantum theory, but Copenhagen, GRW and the rest are still the same theory in (presumably) different interpretations.

However, it is almost self-evident that (3) is epistemologically senseless. Understanding why we should decidedly reject (3) is the crucial piece of work to be done in clearing ourselves of the "intellectual scandal" of QM foundations. First of all, (3) is an essentially anthropocentric assumption, linking the structure of the world with a set of *human* observations in a notable instrumentalist or anti-realist manner. In principle, we have no doubt that the *Newtonian world* is a well-defined and coherent theoretical concept, with clear boundaries. Its limitations have been demonstrated, for instance, by Michaelson-Morley experiments. Wouldn't it be absurd to state that prior to these experiments the Newtonian world has been undistinguishable from any alternative theoretical construct, say the world of relativity? And that it suddenly sprang into being as a distinct theory as a result of these experiments? However, this situation is commonly accepted without questioning in the domain of quantum measurement theories.

Further, the instrumentalist criterion (3) actually questions the role of mathematical description of the physical world. If we believe, with Einstein, Wigner, and many others in "unreasonable effectiveness" of mathematics in describing physical phenomena, and if we wish to avoid the conclusion that it is just an accident, then we are led to believe that at least some of the mathematical structures exist in reality.[17] But if there is some structure $\Im$, it is obvious that we cannot accept any description of the same phenomenon based on a different structure, say $\Re$, which is not isomorphic to $\Im$. In other words, if we prefer an "external" description (cf. Ref. 7), we are necessarily invoking the criterion (2) as the true judge in discriminating between theoretical constructs of physics.[2]

Parenthetically, Everett himself seemed to have no such methodological doubts as to the status of ideas he proposed in his famous 1957. paper: "The new *theory* is not based... The altered *theory* thereby acquires a new character" (Ref. 18, p. 454, emphasis by the present author).

3. The trial: experimental discrimination

There are several experiments or thought experiments proposed in order to discriminate between the collapse and no-collapse in the existing literature. Since these proposals are widely and unfortunately ignored, we shall briefly consider each of them in turn. We consider only the possibility of discriminating between the simplest versions of collapse and no-collapse theories, disregarding "higher-order" possibilities, like the one of non-linear no-collapse theory.[15,16]

[2]Compare Omnès (1994): "It will be said that *a property or a proposition has a physical meaning* when one can give it a truth value, at least in principle. This means that one can conceive, at least in principle, of an experimental device to check whether the property mentioned is true or false." (p. 365, emphasis in the original)

3.1. Quantum suicide and quantum genocide

Probably the most shocking and surprising thought (?) experiment suggested for discrimination between collapse and no-collapse quantum theories is the quantum suicide (or quantum Russian roulette) *Gedankenexperiment.* It has been formulated first by the late quantum physicist Euan Squires[19] in 1986, although a SF story of John Gribbin preceeded it for about a year (more of the background of this curious thought experiment will be available in Ćirković, manuscript in preparation), and has been elaborated upon by Tegmark.[7] Briefly, it consists of the following.

Let Hugh, an experimental physicist, prepare a simple coherent state of, say, spin z-projection of a fermion:

$$\psi = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle) \tag{1}$$

(any other quantum superposition will do equally well). The spin measuring device is coupled to a gun in such way that, after Hugh or anybody else pulls the trigger, spin measurement will take place. The measured eigenstate $|\downarrow\rangle$ will result with firing the gun, and the measured $|\uparrow\rangle$ will result in a harmless "click". One important proviso is that the duration of measurement (including the reaction time of the gun) should be short in comparison to any timescale characterizing human perception. If the gun is aimed at any target other than Hugh himself, he expects to see a seemingly random outcome of each individual measurement: either "bang" or "click" with the probability of a coin toss. If measurements are taken in series of n consecutive measurements (pullings of the trigger), probability of achieving any individual combination of "bangs" and "clicks" is given by the simplest binomial distribution; in particular, the probability n consecutive "clicks" is $p_{n\uparrow} = 0.5^n$. There is no observed-or observable-difference between collapse and "no-collapse" quantum theories at this point. (Metaphysically, Hugh is aware that the complete description is certainly different in these two cases; notably, on the "no-collapse" quantum mechanics he believes in, both a "click" and a "bang" will be realized in each measurement, being the two components of the unbreakable superposition, but he will perceive only one of them due to the rapid environmental decoherence. The decoherence timescale is, even for quite isolated fermion spins, still much shorter than the human perception timescale.)

But now Hugh decides-perhaps upon advice of some respectable quantum theorists-to point the gun to his own head.[3] The state of the entire system, after the first measurement, now evolved from (1) to (symbolically)

$$\begin{aligned} \hat{U}\psi \otimes |\text{experimenter}\rangle &= \hat{U}\frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle) \otimes |\text{experimenter}\rangle = \qquad (2) \\ &= \frac{1}{\sqrt{2}}(|\uparrow\rangle \otimes |\text{"click"}\rangle + |\downarrow\rangle \otimes |\text{"dead"}\rangle). \qquad (3) \end{aligned}$$

It is self-evident that no probability (objective or otherwise) makes sense for Hugh in his $|$"dead"$\rangle$ state. Since we have exactly one observer before and after the measurement, and since the decoherence of branches—the two terms in parenthesis in Eq. (2)—occurred much faster than our experimenter could notice, we may be certain that he will observe spin "up", and *therefore* hear a harmless "click". And the same could be repeated

[3]Hence the name of "quantum Russian roulette" or "quantum suicide".

arbitrarily often! Notice that only physical collapse—as in the "orthodox" Copenhagen interpretation or the dynamical reduction theories—is actually harmful from Hugh's point of view. Since in the "no-collapse" view there is no actual collapse, just fast decoherence between the branches, Hugh will find himself in the strange situation of impossibility of committing suicide, although the gun is loaded and fully functional! This is different from the "outsider" view of, say, assistant in the experiment, who will perceive the bloody deed after at most several repetitions of the experiment (being in one of the decohered branches of the universal wavefunction and being able to perceive the measured spin "down").[4]

This is, of course, the "quantum suicide" experiment of Squires,[(19)] Moravec,[(21)] Zeh,[(22)] Price,[(23)] and Tegmark.[(7)] It seem that the honor to first publish such an idea goes to the late Prof. Euan Squires who in his book *The Mystery of the Quantum World* wrote the following passage:

> It is probably fair to say that much of the 'unease' that most of us feel with the Everett interpretation comes from our belief, which we hold without any evidence, that our future will be unique. What I will be like at a later time may not be predetermined or calculable (even if the initial information were

[4] Compare this elegant expression of a similar doubt on a completely different motivation by Douglas Hofstadter: "Perhaps the greatest contradiction in our lives, the hardest to handle, is the knowledge 'There was a time when I was not alive, and there will come a time when I am not alive.' On one level, when you 'step out of yourself' and see yourself as 'just another human being', it makes complete sense. But on another level, perhaps a deeper level, personal nonexistence makes no sense at all. All that we know is embedded inside our minds, and for all that to be absent from the universe is not comprehensible. This is the basic undeniable problem of life; perhaps it is the best metaphorical analogue of Gödel's Theorem..." (Ref. 20, p. 698).

> available), but at least I will still be one 'I'. The many-worlds interpretation denies this. For an example to illustrate this lack of uniqueness (some would say rather to show how silly it is) we might return to the [double slit] experiment and suppose that the right-hand detector is attached to a gun which shoots, and kills, me if it records a particle. Then after one particle had passed through the experiment, the wavefunction would contain a piece with me alive and a piece with me dead. One 'I' would certainly be alive, so we appear to have a sort of Russian roulette, in which we cannot really lose! Indeed, since all 'aging' or 'decaying' processes are presumably quantum mechanical in nature, there is always a small part of the wavefunction in which they will not have occurred. Thus, to be completely fanciful, immortality is guaranteed - *I* will always be alive in the only part of the wavefunction of which *I* am aware!

It seems that people have been aware of this option during the last decade, since it appears in passing in such influential monographs as Zeh(22) and Price(23). However, the first detailed exposition came only with the paper of Max Tegmark, (7) who called the entire setup "Byzantine". Of course, different variations of the experimental setup are possible. A particularly appalling version is Moravec's(21) form of the "collective" quantum suicide, which can be aptly called *quantum genocide*. Suppose that instead of "only" a life of individual (i.e. our experimenter Hugh), life of the entire humanity depends on the outcome of a single quantum measurement. Can we follow the same line of reasoning in this case? This need not sound so far fetched as it looks on a first glance, since today already there is some concern and "risk assessments" of the outcome of high-energy experiments in accelerators.[24–27] Most prominent of these supposed dangers is the possibility of our present-day vacuum is not the vacuum ground state of the universe, but a metastable local minimum instead. Then, the apocalyptic reasoning suggests, we might unwittingly "help" the vacuum phase transition by conducting an experiment of particularly high energies, during which a small "bubble" of new (i.e. lower energy density) vacuum state forms, which will then tend to expand at near-light speed, consuming all existing forms of matter and effectively replaying phase transitions in the early universe. It is reasonable to suppose that formation of such a bubble is a quantum event, and that the state of matter inside the accelerator is at the appropriate moment given by something like

$$c_1|\text{bubble formed}\rangle + c_2|\text{no bubble}\rangle, \tag{4}$$

c_1 and c_2 being complex amplitudes ($\|c_1\| \neq 0$), essentially the same as the state in (1). Since the state $|\text{bubble formed}\rangle$ will unavoidably lead to the extinction of humanity through its (no matter how complicated) unitary evolution, we may reason the same as in Hugh's setup above, and conclude that it will not, from the point of view of "humanity" (and *eo ipso* any human individual), be ever realized! That is, the experimenters will always perceive the (no bubble) state, and the experiment will be *always* safe, if only c_2 is different from zero. No wonder that Moravec's book contains an explicit reference to the 1964 Stanley Kubric's classic *Dr. Strangelove*, in which a similar "Doomsday Device" is deployed in the black-humoresque Cold War context!

As Squires immediately noticed, all this entails rather bizarre consequences, like alleged "quantum immortality". Do they represent a *reductio* of the coherence of the quantum suicide setup, and thus, since no other fundamental problem is visible, a reductio of the many-world theories? In our opinion it is not so, although this topic is beyond the scope of the present manuscript. Quantum suicide, as it is formulated above, and exposed in Ref. 7, depends on our understanding of the mind-body problem, the central issue in the philosophy of mind and cognitive sciences. This issue is far from being solved; on the contrary, the situation seems to be more hopeless than even the pessimists believed.(28)

In addition, it remains an open and difficult epistemological issue whether this "I-know-but-cannot-tell" type of experiment may discriminate between various theories. A contrary opinion may be heard, based on the statement that the question "what will you perceive" is not a well-defined question in a quantum mechanical context (Prof. Ken Olum, private communication). We cannot enter into discussion of this issue here.

3.2. Plaga's gateway state

If the legitimacy of quantum suicide were universally accepted *even only* *as a thought experiment*, our case would have been solved: Everett's would be proven as the independent quantum theory (or *the* quantum theory, if we follow Deutsch). Further discussion of the issue would have been unnecessary. However, this is not the actual case, in light of the epistemological doubts mentioned. Thus, further possible discriminators are searched for. We shall consider several other thought experiments which could offer the solution, notably ones of Plaga[29,30] and Deutsch.[31,32] In the former case, Plaga introduces a "gateway state" between the two hypothetical worlds created as the outcome of a conventional photon polarization measurement. The gateway is a microscopic part of the apparatus which is isolated sufficiently, so that its decoherence timescale is long, and thus it "sees" the global superposition long enough to be influenced by it. In a detailed technical account, Plaga suggests that sufficiently isolated ions in electromagnetic traps can be used as indicators of such influences, if the experimental setup is ingenious enough, and the instruction given to experimenters can be carried out with sufficient precision. The point of isolation is crucial here: the orthogonality of two wavefunction branches holds only if the measuring device stays always entangled with the environment. This is tantamount to saying that a sufficiently rapid measurement on the system with comparably long decoherence time could detect their interference.

3.3. Popper-Plaga experiment

In a recent paper, Plaga[30] has returned to the topic of discriminating between various quantum theories, motivated by an old suggestion of Sir Karl Popper for an experiment to test the Copenhagen quantum mechanics. The notion—at the bottom of the orthodox theory—which is been tested is the famous assertion that the wavefunction corresponds to nothing in reality, but only to the maximal amount of knowledge an observer can gather about the system. Briefly stated, the idea is to use a weird form of the classical two-photon interference experiment (with a "virtual slit") to show that change in our knowledge of one particle, according to the standard theory, may measurably influence the unitary evolution of another particle, entangled with the first. Such deeply counterintuitive result would confirm the Copenhagen predictions, and if absent, would testify on the independence of the wavefunction of observer's knowledge (in the original form, Popper formulated it as a violation of the uncertainty principle). However, as several earlier authors which Plaga reviews have shown, Popper's experiment is deficient in several ways. But—and here the thrust of the Plaga's discussion lies—it may be amended in a conceptually simple (though unfortunately technically rather difficult) manner to perform different task: to discriminate between the Copenhagen orthodoxy and a realist theory like Everett's.

Plaga explains this in two steps, upgrading the experiment of Kim and Shih,[33] which he calls "extension 1" and "extension 2". While the "extension 1" is equivocal from the point of view of the present discussion since in it the predictions of Copenhagen and many-worlds theories are the same, the "extension 2" proposes an actual discrimination between the two. Notably, Plaga points out that the equivalence of predictions holds only in the approximation that the measuring apparatus is *always* entangled with its environment. Now, if we use a single ion (in a trap similar to the one used for experiment proposed in §3.2) as a detector and it is sufficiently isolated, we may use the same reasoning as for the gateway state to prolong the decoherence timescale; in other words, we can control the entanglement of such a "measurement device". In this—again very challenging from the technical point of view—setup the predictions clearly differ: a particle either shows an increased momentum spread or is localized in the momentum space. Again, issues such as exceedingly low efficiency of "single-ion-detectors" make this experiment unfeasible (or very hardly feasible) at present, but, in principle, we could, at least statistically, with very large number of repetitions, obtain the desired discrimination between quantum theories.

3.4. Deutsch's re-cohering observer

Probably the most sophisticated and potentially decisive experiment aimed at testing whether wavefunction collapse truly occurs has been proposed in an influential paper by David Deutsch[31] (see also Refs. 32, 34). In Deutsch's *Gedankenexperiment*, after two histories decohere in a conventional manner, they are *re-cohered* by a convenient and ingenious manipulation of the relevant Hamiltonians in post-measurement time. In Deutsch's own words, the net result of the experiment is an anomalous lack of correlation (if Everett is right and there is no wavefunction collapse): "The interference phenomenon seen by our observer at the end of the experiment requires the presence of the both spin values, though he accurately remembers having known at a previous time that only one of them was present. He must infer that there was more than one copy of himself (and the atom) in existence at that time, and that these copies merged to form his present self." (Ref. 31, p. 37) The difference between these two examples is that, while Plaga's experiment considers immediate post-measurement interaction of the two wavefunction branches through a gateway state (in fact, it is crucial for the claimed feasibility of this experiment to have an extremely fast measurement procedure), the one of Deutsch deals with post-measurement interaction after an arbitrarily long time. The price paid for this advantage is "only" the necessity of having an operational quantum computer capable of simulating human-level intelligence.[5] This is necessary since we have to be sure that an *observer* has performed an observation and left adequate records of it, and still be able to manipulate the Hamiltonian of the measurement interaction. Thus, Deutsch's experiment belongs to not-so-near

[5]As far as the no-collapse view is concerned, the nature of the computer is in fact irrelevant, since it presupposes quantum mechanics as "the universal theory" (the very title of Deutsch's article), and therefore *any* working computer is already part of the quantum world. If we stick to somewhat more cautious epistemological stance, we should emphasize that the observer in this thought experiment must be quantum in nature, *and* it is crucial that the Hamiltonian expressing his/her internal "self-interaction(s)" is known. In principle, the advances in biophysics might bring about the complete knowledge of microscopic processes within a biological observer (like human brain), as well as the relevant technology to modify such processes in order to intentionally induce necessary changes in the internal Hamiltonian. (Among various other features, this thought experiment thus clearly demonstrates ontological realism inherent in Everett's theory.) However, it seems more realistic that this degree of knowledge and manipulative powers will be reached by a human-made quantum computer.

future as far as technology is concerned, but it is conceptually important, since it shows *demonstrable* difference between "collapse" and "no-collapse" versions of quantum mechanics.

Beside having a large temporal margin, Deutsch's experiment has some other conceptual advantages. It is not "subjective" in the sense of quantum suicide, nor does it invoke controversial probabilistic assumptions, as we shall see is the case with the quantum-cosmological discrimination tests. Unfortunately, it remains very remote from us in the technical sense. But this is of lesser importance for the present discussion, as follows from the fallacy of the criterion (3) above. The important thing is that there is no *counterargument* to Deutsch's experiment potential discriminatory power.[6]

3.5. Quantum gravity and MWT

Page and Geilker[(35)] have suggested that future correct theory of quantum gravity will depend on the correct description of quantum measurement, and that this might lead to observable macroscopic (e.g. gravitational) consequences. They proceeded further to actually test this in a simple experiment involving various spatial configurations of gravitating objects (lead balls), the decision about which has been reached through a quantum-mechanical process (radioactive decay). The interference of "other worlds", i.e. different configurations of masses, has been searched for, and with negative results. Historically, this was the first instance of proposed

[6] Fuchs[(54)] calls Deutsch's experiment "misguided", but does not provide reasons for such an assessment.

observable discrepancy between no-collapse and the standard collapse quantum theories. It has provoked some attention when it appeared, if judged by rather heated comments of Bruce Hawkins and Leslie Ballentine published in *Physical Review Letters*, accompanied by replies of Page, as well as the paper of Whitaker surveying the controversy several years later.[36–39]

Let us for the moment consider the methodological structure inherent in the Page-Geilker proposal. Even if we knew nothing about the details of the future quantum theory of gravity, the principle of correspondence would have told us that in the low-energy limit the classical equations of general relativity, according to which the stress-energy tensor is the source of gravitational field, will hold. Thus, in the semiclassical limit, we expect something like

$$G_{\mu\nu} = 8\pi \langle T_{\mu\nu} \rangle \tag{5}$$

to hold (e.g. Ref. 40). Now, the crucial problem here is the *interpretation of the averaging procedure* in (5). Page and Geilker interpret this as *averaging over the universal wavefunction branches* (or at least those close world-histories corresponding to interactions occurring within the decoherence time of the apparatus), and therein lies their fundamental mistake. As shown by Whitaker,[39] in all different readings one may ascribe to Everett's position this experiment is bound to give a negative result. This is epistemologically as important as the definitely discriminating tests mentioned above: the very controversy followed by resolution testifies that it is a problem in physics, and not metaphysics or semantics.[7]

[7] Situation probably could be different if the timescale of the measurement of Page and

3.6. Quantum cosmology of Page and Bostrom

We may wish to consider an entirely different sort of discrimination between the competing views which is not based on any experiment *in stricto sensu*. Instead, it uses some of the possible applications of each view in quantum cosmology, to estimate its posterior probability, having particular empirical information about the universe. This approach has been initiated by Don Page[41] and recently discussed by Nick Bostrom[42,43]. Interestingly enough, Page briefly mentions Deutsch's argument for the discrimination between collapse and no-collapse theories as the only alternative to the quantum cosmological considerations. While cogently noticing that the claim of impossibility of making an observational distinction between the two is unfounded, Page still maintains that

> [i]n processes with fixed observers that remember their observations, it does seem to be true that there is generally no distinction that a single observer can make between single-history and many-worlds quantum theories that are otherwise identical. This is because then the measure for each observation in a many-world theory is proportional to the probability of that observation in the corresponding single-history theory. This result depends upon the lack of interference between "worlds" in which different observations are made, which is assured if the memory records of the different observations are orthogonal.

Geilker would have been shorter than the decoherence timescale of their apparatus (see §3.2, 3.3 above).

This paragraph contains deep and important—even if not entirely, as we shall try to show here correct—ideas about the possible solutions of the empirical status of no-collapse theories. In essence, Page here argues against "suicidal" and Plaga-type experiments discussed above. Instead, he proposes a Bayesian form of testing of no-collapse ("many-history") vs. collapse ("single history") theories based on the assumed properties of the universal wavefunction.

Suppose that a diligent quantum cosmologist discovers that at some particular epoch in the early history of the universe the universal wavefunction has only two components in the superposition:

$$|\psi_{\text{universe}}\rangle = c_1|\psi_A\rangle + c_2|\psi_B\rangle, \tag{6}$$

where $|\psi_A\rangle$ represents progenitor of the "world A" with amplitude such that $\|c_1\|^2 = 10^{-9}$, and $|\psi_B\rangle$ evolves into the "world B" with probability $\|c_2\|^2 = 1 - 10^{-9}$. Suppose, further, that elucidation of properties of state vectors in these two cases gives that these worlds are characterized in respect to the conditions for existence of (intelligent) observers in the following way

World A: no observers;

World B: some observers.

Common sense indicates that in this toy model we would have obvious reasons to reject the collapse quantum theories, since we observe the existence of observers, namely us, in the universe. This reasoning can be generalized to the case of an arbitrary number of non-empty (from the point of view of observers) worlds. More realistically, the distribution of observers per world may vary; for instance, we may have the situation with the same superposition of the universal wavefunction (6), but now

World A: 10^{10} observers;

World B: 10^{30} observers.

Now we need to apply Bayes' formula to determine the posterior probability of no-collapse theories be true. The probability we are living in the World B is then given as

$$p = \frac{10^{30} \cdot 10^{-9}}{10^{30} \cdot 10^{-9} + 10^{10} \cdot (1 - 10^{-9})} \approx 1. \tag{7}$$

Let us assume that beforehand we believed that there is a 50% probability that no-collapse theories are the true description of reality. Now, this is not entirely obvious, since we need an additional ingredient, namely a probabilistic assumption similar to the following one used by Bostrom:

Self-Sampling Assumption (henceforth SSA): Every observer should reason as if they were a random sample drawn from the set of all observers.

Then, taking into account all the above, we may conclude that we have superbly reasons to reject the collapse theories, assigning probability of only 10^{-9} to what we perceive as overwhelmingly realistic description (that is, our finding in the World B). It might be very difficult to ascertain the "temporally integrated" number of observers. For instance, even the classically uninhabitable universes, say those containing only a black hole mass spectrum, may actually contain an infinite number of observers. Namely, open universes containing only black holes will contain infinitely many black holes, and if Hawking's ideas on the random nature of the black hole evaporation spectrum are correct, than it is to be expected that some intelligent observers will be formed from Hawking's radiation. These would be formed without any previous habitability requirements being satisfied, and thus would be independent of the statistical considerations of inhabitability of various universal wavefunction branches ("worlds"). However, as Bostrom[(42)] proceeds to show, these (in his terminology) "freak observers" cannot meaningfully influence the application of Bayesian reasoning on a large scale. In addition, we need not integrate the number of observers in the entire wavefunction branch ("entire universe"), but only in the same meaningful part of the world, say within the cosmological horizon.

As concluded by Bostrom:

> ...as far as our project is concerned, the important point is that our methodology ought to be able to make this kind of consideration intelligible and meaningful, whether of not at the present time we have enough data to put it into practice.

That is exactly what the present "missing case" is all about: after all, if one wishes to be narrow-empirically minded, than *any* talk going beyond the roughest Copenhagen picture is a waste of time. This applies with equal force to Bohm, GRW or Penrose as to Everett: the measurement problem is a puzzle *exactly* because it lacks a purely empirical solution.[8] Hence its attraction and its beauty.

[8]But we still can make it "intelligible and meaningful".

3.7. Time travel?

The interest for the possibility of the travel through time has been resurgent in recent years, in both research and popular-science domains (e.g. Refs. 44-46). Surprisingly enough, the issue has some consequence for our present topic, as noticed by Deutsch,[47] and recently elaborated in a well-written paper by Grove.[48] A criticism from a philosophical point of view (more in Tegmark's "many words" category) is given in Ref. 52.

Deutsch argues that many-worlds theories allow for backward causation and changing the past, while avoiding classical paradoxes of time travel, like the "Grandfather paradox". Grove considers the possibility of changing the past in both Everett's and the Copenhagen theory and confirms the original Deutsch's conclusion, before continuing to argue that the same possibility of changing the past applies to the Copenhagen theory. However, his arguments are here largely inconclusive, especially when arguing that the Copenhagen orthodoxy can also overcome the "Grandfather paradox". The appeal to acausality of the Copenhagen physics is somewhat rhetorical, since the same type of acausality is absent in the other, purportedly uncontroversial, quantum situations. It is difficult to avoid the conclusion that the time travel in Everett's universe is qualitatively different from analogies in the orthodox version.

4. Conclusions: theories lost and found

We conclude that a revision of the conventional terminology is necessary if we wish to avoid the trap of "intellectual scandal" of Deutsch. Acronym MWI should certainly be changed into MWT ("Many-Worlds Theory")—of course, after we agree on the physical content of this theory, i.e. is it Everett-Deutsch or some other version—if nothing else than to clear the confusion and obfuscation of the real issues involved. The entire corpus of possible empirical discrimination between this (and related "no-collapse") theory and the standard quantum mechanics (as *non*-universal physical theory) and other collapse theories has grown sufficiently large to be ignored. We have seen that some of the discriminatory tests proposed (e.g. Page's and Geilker's) have been shown to be, in fact, not discriminatory; but the very act of showing this testifies that we are dealing with hard science, not metaphysics.

None of the discriminative tests described here are clearly feasible with the current technology and insight, although some of them come close. History of science indicates that it is likely that great improvements in these, and invention of others, experimental tests is likely if they become more widely known and discussed, instead of the current atmosphere of prejudice and endless repetition of old, conservative views. It is worth remembering the famous words of the great late Carl Sagan: "Extraordinary claims require extraordinary evidence." Many-worlds quantum theories would have been indeed accepted long ago as ordinary truth if the evidence for them—as theories describing physical reality—were readily available; indeed, it is a hallmark of simplistic anthropocentrism to assume that the deepest levels of reality are easily/comfortably accessible to our relatively simple epistemic and experimental capacities. An issue deserving further investigation is, of course, the finer discrimination between the Everett-Deutsch MWT and the related theories—like the "Many Minds" of Albert and Loewer, as well as Lockwood—which also postulate universal validity of the Schrödinger unitary evolution. While acknowledge its importance, we cannot enter into the discussion of this issue at present.

Finally, some speculations may be presented as to the sources of semantical confusion on this issue.[9] A part of the background comes in form of ubiquitous inertia of established thought; only a couple of years ago it has still been possible for a distinguished theoretician to write that[(49)] "those who remain adherents [to the "no-collapse" theories] tend to have non-standard views on the nature of scientific theories." Apart from the colorful parallel invoked by Tegmark[(7)] about Galileo who certainly "tended to have a non-standard view" on the then prevailing theories of planetary motions (and one may think of a number of similar parallels, particularly apt in our view being the one on Einstein certainly holding extremely non-standard views on the nature of space and time and theories on them), a more profound issue is awareness of the true *nature of scientific theories.* As we have seen above, something which was difficult enough for the clas-

[9]Thus Deutsch:[(34)] "I must confess that I am at a loss to understand this sociological phenomenon, the phenomenon of the slowness with which the many universes interpretation has been accepted over the years... But why it has taken so long, why is there such resistance, and why people feel so strongly about this issue, I do not fully understand."

sical Newtonian physics (witness all debates and controversies surrounding concepts of "absolute space", for instance), became too muddied when it came to quantum mechanics. It has probably something to do with wider cultural background and human common sense; it is not accidental that quantum mechanics became sort of an outlet for various manifestations of antirealism already present in the contemporary culture (e.g. Refs. 50, 51). If we wish to successfully combat this antirealistic and antirationalist—and in the view of this author deeply decadent and useless—streak, we should stick to the completely rational approach, emancipated from prejudices of authorities of the past, and open-minded about technological capacities of explosively developing experimental techniques. We may lie on the verge of a new generation of spectacular quantum experiments, a generation which will not just confirm or disconfirm our old views, or obtain better numerical precision in agreement of theory and experiment, but will tell us something very deep and profound about the nature of the physical universe. Studies such as Deutsch's, Plaga's, and others reviewed here are the true antidote to all "quantum healing" and all similar new-age gibberish.

Further, it seems that spectacular experimental and technological success of quantum mechanical formalism has blinded at least some theoreticians as to the nature of the explanatory tasks remaining in their domain. This is not at all a novel feature in history of mankind. After all, although Newtonian mechanics has been developed in Europe in XVII century by Galileo and Newton, its practical and technological consequences have been known for centuries, if not millennia, earlier and in various parts of the world; somewhere, like in ancient and medieval China or Hellenistic Greece, its technological applications reached levels of sophistication unrivalled for some time even *after* the Newtonian revolution! In the same manner, accuracy of astronomical predictions (the "empirical" aspect of astronomy) has been very high before Copernicus and Kepler offered a theoretical background for these phenomena. Thus, the unsatisfactory state of affairs in fundamental quantum *theory* is not an isolated or exceptional instance in the history of science. It is to be expected, however, that these fundamental issues are here to stay, no matter how much "practically minded" people closed their eyes at them.

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