Quantum modalities, interpretation of Quantum Mechanics and Special Relativity, and an experimental test for multiple worlds

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Abstract.- This paper investigates the physical, experimentable, reality of multiple worlds of Quantum Mechanics. On the basis of a reflection on the *fundamental principles* of physics (sec. I.A), firmly rejecting the *incomprehension imperative* often associated with Quantum Mechanics (sec. I.B), and strongly relying on an experimental methodology (sec. I.C) and on the superposition principle, we propose a unified interpretation of quantum physics (sec. II), the *potential world modal interpretation*. This framework makes multiple-world and pilot-wave interpretations converge. It also clarifies the concepts of *potential world* and *sub-quantical potential particle*. Then, we turn to Relativity and sketch out an emergence of Special Relativity without "rods and clocks" (sec. III.A) providing a *cinematic and phenomenal interpretation* of SR. We suggest to distinguish between *given* and *received gravitation* and reason on it at a sub-quantical level (sec. III.B) and formulate the *hypothesis that weight is active between potential worlds* (sec. III.C). If this effect follows the von Neumann chain, it should be observable with available techniques (sec. III.D). If correct, this hypothesis could contribute explanations for cosmic inflation, dark matter and the cosmological constant problem (sec. IV). Moreover, our cinematic interpretation of relativity in an expanding universe might lead to a justification of the MOND theory (sec. IV.B.3).

Résumé.- Cet article explore la question de la réalité physique, expérimentable, des mondes multiples de la Mécanique Quantique. En nous appuyant, d'une part, sur une réflexion sur les *principes fondamentaux* de la physique (sec. I.A), rejetant résolument l'*impératif d'incompréhension* qui affuble souvent la Mécanique Quantique (sec. I.B) et s'appuyant sur des principes méthodologiques fondés sur l'expérimentation (sec. I.C), et, d'autre part, sur le principe de superposition, nous proposons une interprétation unifiée de la physique quantique (sec. II), l'*interprétation modale des mondes potentiels*. Celle-ci fait converger les interprétations de type mondes multiples et les interprétations de type onde-pilote et donne une définition précise des concepts de *monde potentiel* et de *particule potentielle* ou *subquantique*. Nous esquissons ensuite un mécanisme d'émergence de la Relativité Restreinte à partir de présupposés subquantiques simples (sec. III.A), sans "règle" ni "horloge". Ceci fonde une *interprétation cinématique et phénoménale* de la Relativité Restreinte. En distinguant entre *gravitation reçue* et *donnée* et en raisonnant à un niveau subquantique (sec. III.B) nous formulons l'*hypothèse que le poids agit entre monde potentiels* (sec. III.C). Si cet effet remonte bien la chaîne de von Neumann, nous proposons de l'observer à l'aide de technologies d'ores et déjà disponibles (sec. III.D). Si notre hypothèse s'avère correcte, elle pourrait contribuer à expliquer plusieurs phénomènes jusqu'alors isolés : l'inflation cosmique, la matière sombre et le problème de la constante cosmologique (sec. IV). Enfin, notre interprétation cinématique de la relativité dans un univers en expansion pourrait conduire à une justification de la théorie MOND (sec. IV.B.3).

Keywords: interpretation of Quantum Mechanics; multiple worlds; modal logic; Quantum Logic; Special Relativity; gravitation; quantum gravity; dark matter; cosmic inflation; cosmological constant problem; MOND

I. INTRODUCTION

A. Raising a question

For nearly 2 500 years, Plato's Cave allegory[1] has inspired many reflections about reality. Drawing a line between phenomena and theories, it emphasizes the difficulty to tell the illusion of habit from the essence of things. In some way, phenomena are the only tangible reality; we can reach for the latter, we can bump on it. But phenomena are in the Cave, their expression is complex, sometimes hard to understand, and does not convey any deep representation. Phenomena are, fundamentally, a scattered reality: the Moon's orbit and the fall of apples fuel no common experience. To gather a solid representation, we need to explore the Cave for an exit, and search for another form of reality: scientific theories. It is indeed some form of reality, a least a methodological one, since we can experience it. But that reality fundamentally lacks objectivity. In Plato's nar-

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[1] *Republic*, §§ 514a–520a. Greek word for "cave" is "σπήλαιον" (*speelaion*): a natural cavity.

rative, Cave people do not want to believe the explorer and they end up killing him. To cope with subjectivity, science has built up, over the centuries, a methodology; yet, as epistemology and the history of science have shown, experiment under-determines theories: the same experimental corpus can lead to numerous different theories. Isaac NEWTON changed our theoretical vision of gravitation and gathered in a single model the Moon's orbit and the fall of apples, showing to mankind an underlying reality. This vision is more sound, more real in a way, but can pass with time: going further out of the Cave, new experience can lead to other seminal theories. Some theories may also be concurrent for centuries, like wave and corpuscular theories for light. Some theories may supersede others, like the Einsteinian v. Newtonian gravitation theories.

PLATO's Cave was somewhat small: as soon as he withdrew his shackles, PLATO's explorer managed to get out of it. Science requires more work; science explorers progress slowly, to add, step by step, some light to ancient puzzles. For us, scientists, theoretical exploration does not only consist of abstract reflections, it is also a means to extend the phenomenal register: it does say where to look, and what to look for — as shown by Urbain LE VERRIER and Johann GALLE for Neptune, or Albert EINSTEIN and Arthur EDDINGTON for General relativity. For that reason, OCKHAM's razor should not be too quick to "shave away" interpretations, as long as they aim at some experimental validation. Thus, our first guiding principle should not be too strict[2].

Principle 1 (*parsimony*). *"We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances." Therefore, to as many as possible natural effects (phenomena), one must assign the same causes (explanations).*

The first modern relativity was the relativity of velocity, formalized and argued by GALILEO. This model does not rule out absolute speed, but does involve that an absolute speed is not phenomenal. On this basis, Albert EINSTEIN did theorize a relativity of space/time, and, later on, a relativity of inertia/gravitation. From such a point of view, inertia, gravitation, space, time, velocity and displacement are effects of perspective. One can read similarly Hugh EVERETT's interpretation (1957) as a relativity of quantum state[3]. Our first main question, in this paper, is *whether* EVERETT*'s interpretation is purely theoretical, i.e. a matter of metaphysics or pedagogy (as it is commonly understood without any significant discussion), or whether the relative state theory could contain experimental reality*. PLATO's Cave explorer discovers new landscapes and, thanks to them, explains shadows on the wall; Hugh EVERETT's work has not reached that point yet. It offers a coherent vision for quantum phenomena, it does enforce principle 1 of parsimony, it is compatible with all we know experimentally, but, still, it is lacking experimental support for at least part of it: multiple worlds. We introduce in this paper a new way of considering this question, to formalize it as a relativity, and to confront it to previous relativity theories. Pushing further the interpretation, we put forward a hypothesis on how gravitation could behave with respect to quantum state relativity. We show that this hypothesis can have an experimental test with existing technologies. In a more speculative part of the paper, we argue that our hypothesis could lead to a common explanation for dark matter, for cosmological inflation, and for gravitation's extreme weakness, compared to other "forces". If our hypothesis happens to be true, gravitation shall no longer be seen, fundamentally, as an interaction in the same sense as electroweak or strong forces. Incidentally, we sketch out some possible reconciliation between Relativity and Quantum Mechanics.

B. Relying of an principle

Richard FEYNMAN[4] once said: "I think I can safely say that nobody understands quantum mechanics." This affirmation circulates mostly in two popular versions: "If people say they understand quantum mechanics, they're lying," or "If someone thinks he understands quantum mechanics, it's because he doesn't." These formulations follow suit with an old catchword: "Those who are not shocked when they first come across quantum mechanics cannot possibly have understood it" (Niels BOHR

[2] The first sentence quotes Isaac NEWTON. The second is inspired by his formulation. In many places he comes back to the idea of a "Nature [...] most simple and consonant to herself".

[3] On a first level of analysis, GALILEO and EINSTEIN share a common relativist approach. However, the parsimony principle leads to different interpretative conclusions for these authors. GALILEO, in his *Dialogue Concerning the Two Chief World Systems* (Galilei, 1992) traces some sort of relativity principle back to archaic physics. Nicolaus COPERNICUS (1998, chap. I.8, p. 63), for example, cite AENEAS: "We set out from harbor, and lands and cities recede." [VIRGIL, *Aeneid*, III 72]. GALILEO resorts to the example of the ship from Venice to Alep and her speed "like nothing" for passengers (Balibar, 2002, pp. 12 sqq.). Galilean relativity is mostly a use of perspective rationale, it does not imply the nonexistence of an absolute celerity. On the other hand, EINSTEIN's Special Relativity follows Ernst MACH very strict interpretation of the parsimony principle and rules out absolute velocities: only relative velocities do really exist. In the present paper we shall not restrict "relativity" to the MACH-EINSTEIN meaning — EVERETT's relativity seems, indeed, closer to GALILEO's "perspective" relativity.

[4] "Probability and Uncertainty—the Quantum Mechanical View of Nature", 6th Messenger lecture (1964). Collected in *The Character of Physical Law* (1967), p. 129.

(Heisenberg, 1958, cit.)). Many other thinkers of Quantum Mechanics propagate a similar conception, which we could call the *incomprehension imperative*. In a way, our current scientific culture forbids, in a very strong manner, the understanding of Quantum Mechanics, leading to some form of resignation: "All of modern physics is governed by that magnificent and thoroughly confusing discipline called quantum mechanics... It has survived all tests and there is no reason to believe that there is any flaw in it... We all know how to use it and how to apply it to problems; and so we have learned to live with the fact that nobody can understand it" (Murray GELL-MANN[5]).

The incomprehension imperative may also be satisfaction with abstruse, absurd or nonsensical "explanations". For example, many courses or popular science, present particles in a double-slit YOUNG-type experiment as passing through "both" slits, or "neither". Some authors, more cautious, present it as a "question that cannot be answered". Is it a failure of pedagogy? Not only! It is a failure of language and reasoning: Garrett BIRKHOFF and John VON NEUMANN (1936) showed, a long time ago, that nature *cannot* be described by Classical Logic alone. To be general and sincere with quantical[6] experiments, one must reason with Quantum Logic (QL) instead of Classical Logic (CL). The sentence that "the electron passes through the left slit and the right slit" is false (zero measure). The statement that "the electron passes through the left slit or_{CL} the right slit" is also false (zero measure). What is true is that it passes through the left or_{QL} the right slit — with a quantum logical "or", i.e. a superposition of states. To reason according to what we experimentally know of our world, we need to adapt our language, and our way of thinking. Fortunately, we have shown that Quantum Logic is equivalent to Classical Logic when propositions commute[7] (Delmas-Rigoutsos, 1997).

Principle 2 (*logic*). *Expression should seek for clarity, comprehension and logical soundness (coherence). Therefore, we must reason about natural phenomena according to Quantum Logic.*

Paul DIRAC[8] contended that "The only object of theoretical physics is to calculate results that can be compared with experiment [...] it is quite unnecessary that any satisfactory description of the whole course of the phenomena should be given". This statement has had a great influence: physicists put a great lot of creative energy on building phenomenological models and theories, but largely neglected their interpretation. Surely, this is a respectable metaphysical creed, but, as surely, it is a sterilizing physical methodology. Representations are psychologically inevitable, so we consider a better option to discuss them, and to push them further to their extreme consequences. To deal with interpretations is a support for heuristics, a support for creativity and for innovative options. We will, here, make a sound hypothesis, unifying various phenomena, but perhaps strange in its consequences. Would experimental tests be negative, it would nevertheless provide valuable information on how to interpret Quantum Mechanics.

C. Suggesting a way out

In astronomy before Johannes KEPLER, one conceived only celestial movements with circles. For that reason, theoretical astronomers designed the epicycles to understand as circular movement combinations what were actually ellipses. Today, the "natural" movement is conceived as being the inertial Galilean movement, so one tends to understand any movement in these terms — or contemporary equivalents: Newtonian gravitation is a fall; Einsteinian gravitation is a pathway of a geodesic. Quintessence, dark matter, dark energy, etc. many of these notions are, quite certainly, contemporary epicycles. Indeed, these notions have a great phenomenal validity, but they do put a heavy shroud of complexity over the picture. Can we not just put together some puzzle pieces we know for sure?

For us, the fundamental opposition between the quantical and the relativist representations of phenomena is that in Quantum Mechanics (QM) a coordinate is a measure, and therefore it results from interactions, whereas in the three Relativities (Galilean, Special, General) a coordinate comes under what epistemology calls "God's eye"[9]: the possibility of an absolute objectivity. But EINSTEIN-PODOLSKY-ROSEN (1935) (EPR) paradox situations showed that such a concept as "God's eye" cannot exist, at least for particles. Any common vision — not to mention theory — pretending to encompass these two representations of the phenomena must solve this omnipresent contradiction. One must make a choice between these two conceptions. In this paper, we will stick to experimental evidence[10]:

[5] 1977, quoted by Ierome Bernard COHEN, *The Newtonian Revolution*, Cambridge University Press, 1983.

[6] To ease the formulation, in this paper, we prefer the adjective "quantical" to mean "quantum mechanical", instead of the noun "quantum". Our intention is also vocabulary accuracy, since reference to quanta are, in some cases, merely historical.

[7] We recall this definition hereunder, see n. 29 and 25.

[8] Cf. *The Principles of Quantum Mechanics*, 1930, p. 7.

[9] Following Hilary PUTNAM.

[10] The following principle is not neutral: since observations are interactions, experimental evidence shows that one cannot reduce indefinitely their effects. The reality can be independent "from the observer", in a sense, but cannot be independent from the observation. In other terms, the methodological realism cannot deny the act of observation.

Principle 3 (*measure*). *All that we know about nature (the phenomena) is known through our senses. Coordinates, momentum and the other physical quantities result from measure operations, and therefore from interactions.*

We will suggest, in this paper, an interpretation of the energy-momentum as a "displacement of effervescence" of a sub-quantical "scrum" from which the particles emerge — similar, in a way, to the virtual particles of Quantum field theories (QFTs). From this "effervescence", there emerges what could be interpreted, in relativity, as a coordinate density, that is a local increase of the remoteness[11] measures — any distance measure being interactions, and, as such, compatible in principle with a quantum interpretation. If we admit this vision, and the observation that gravitation is proportional to the energy-momentum norm, inertia-gravitation should operate at the level of the "scrum", and not only at the level of the emerging particles. To separate clearly these two levels of reality, we will rely on an interpretation of QM we formulate in section II. Then, in section III, we formalize an interpretation of inertia-gravitation in this framework and suggest an experimental test for our hypothesis. In section IV, we explore some consequences of this hypothesis, suggesting a new interpretation for dark matter, cosmological inflation and gravitation weakness.

II. A UNIFIED INTERPRETATION OF QUANTUM PHYSICS

A. The measurement problem and the interpretations

Several formalisms are available to cope with quantum physics (Styer et al., 2002). Since these are generally considered equivalent, we will mostly use wave function formalism, but our considerations are meant for all of these formalisms.

Historically, there is a fundamental methodological distinction between an *observed system*, quantical, an *observer*, considered classical, and a *measuring* process, that may be iterated, based on *observables*, which are mainly classical quantities. For that reason, epistemologically, there are two clearly distinct processes[12]: "quantical" or "unitary" periods, during which evolution is described by a Schroedinger equation, and "wave function collapses" or "reductions" or "projections", that serve as initial conditions for the future and are linked to the past by BORN's rule, similar to an absolute form of probabilities.

[11] See hereunder for the difference between two types of distance: the "remoteness" and the "interval".

[12] VON NEUMANN's processes "2" and "1" (von Neumann, 1955).

This divide is a major epistemological difficulty and has raised a great deal of debate on the "measurement problem". In general, a science is the instrumented construction of an abstraction, called theory, of the reality it observes, called its object; this abstraction[13] tends to encompass, eventually, the totality of the object. In the case of physics, an object could be a physical system considered to be isolated (sufficiently, or ideally), and potentially the whole universe, everything that surrounds us, and, in any case, experimenters. Experimental models have to be surpassed, thanks to theoretical thinking, in order to encompass them. Scientific disciplines, to set up this approach, usually adopt a point of view called "methodological realism", consisting essentially in assuming that there does exist an objective reality accessible by experimentation. In a way, we have systematically presupposed methodological realism in section 1, especially when we expressed our first three principles.

Some authors have objected that in the case of quantum physics, objectivity does not exist, in the sense that any experiment, which is "subjective", disturbs the reality to be observed[14]. Indeed, this makes it more complex to integrate subjectivities into an objective whole, but there is no fundamental obstacle against it: this is very common in the humanities and social sciences, for example. However, one should be cautious. It is not, in general, possible to bestow a truth value to any vulgar proposition, like "the electron passed by the left slit"; and, more generally, there is nothing like a propositional "God's eye". But every *experimental* proposition does have a truth value (for example, the proposition L "an electron was measured to pass through the left slit" has a meaning and a truth value (if no experimental test has taken place, then L is just false). Our principle 3 is a tool to anchor firmly any discussion in methodological realism.

But there is another, deeper, difficulty with realism, i.e. superposition. In Erwin SCHROEDINGER's approach, a fundamental fact, consistent with principle 2, is that when $|\chi\rangle$ and $|\psi\rangle$ are solutions of the Schroedinger equation of a system, then any normalized linear combination of them is also a solution. Three main classes of interpretations for the formalism aim at overcoming this difficulty: the Copenhagen school interpretations (Niels BOHR, Werner HEISENBERG), the pilot-wave theories (Louis DE BROGLIE, David BOHM, John BELL) and the many-world interpretations (Hugh EVERETT, Bryce S. DEWITT).

- According to the Copenhagen school interpreta-

[13] To outline, to abstract is to retain some qualities, some features, of the object, and discard others.

[14] This is especially the case if, instead of an epistemological definition of objectivity, we consider a physical one: being invariant by change of observation conditions.

tions (CSI), following BOHR's ideas, any measurement operation determines a state of the system, prepares it for future measurements, and defines its wave function for later evolution. Each measurement *actualizes* the *possibilities* of the system-observer (inseparable) couple.

- In the pilot-wave interpretations (PWI), the system is described by a wave function (the pilot-wave) and by particles (BOHM), or singular waves (DE BROGLIE). Pilot-wave and its evolution describe all the *possibilities* for the system, and an objective probability for each outcome of a measurement. In each measurement, particles *reveal* which possible outcome happens to be real, which possibility comes true. Any of these particles may have some sort of a history, not necessarily classical since there may be some non-local phenomena; but this history is only knowable at the time of the measurement.

- Third category interpretations, usually called many-world interpretations, following EVERETT's ideas, refrain from giving greater importance to one state over another. The first approach is EVERETT's relative state interpretation (RSI) (Everett, 1955, 1957). Another is what Yoav BEN-DOV (1990) calls "popular many-world interpretation" (PMI) — extremely popular indeed, and generally mistaken for it[15]. In these interpretations, the different solution states, i.e. the different *possibilities*, the different possible evolutions of the system, *are* as *real* as one another. The measurement experiment only provides the observer with partial information relative to his point of view. All versions of the observer, who may be thought of as living in parallel universes, have their own reading of the relative states of the observed system. Theses interpretations have an advantage and are a challenge: the observer as well as the observed system must be taken together in the same possible world models.

In these three interpretation classes there is some notion of possibility and some notion of reality. Clearly, the latter is very different between the classes; moreover, there is a debate about what reality is among pilot-wave interpretations and among many-world interpretations. Such a discussion is not the purpose of this paper — much has already been written on that matter. We shall only focus on common aspects to suggest a common model, especially the notion of possibilities, which seems more unequivocal. All visions of Quantum Mechanics share a common principle about these possibilities[16]:

Principle 4 (*superposition*). *Possible outcomes of an interaction, possible solutions of a system's equation, and supposedly possible worlds are vector spaces. In other words, linear combinations of possible states are possible states.*

We will now come closer to this notion of possibility and define carefully the concept of a possible world. On this basis, we shall build a common interpretation to be used later on as a framework to deal with inertia-gravitation.

Beforehand, we need to consider a usual difficulty opposing principles 4 (superposition) and 1 (parsimony): the objectivity challenge.

B. The objectivity challenge

With principle 3 (measure), we have acknowledged the fact that observation processes are interactions and, thus, cannot be absolutely neutral. This raises up a difficulty on how to apply quantical models to the whole universe. The first historical mainstream interpretations of QM, the Copenhagen school interpretations, focused on observed systems, **S**, and many of these, in one way or another, denied the relevance of the application of QM to observers. Werner HEISENBERG (1958), for example, makes the case that quantum systems integrate both the observer and the observed: they cannot be separated[17]. For these interpretations, quantum theory is only phenomenal and cannot be generalized. Retrospectively, this situation can be seen as a lack of a measure theory. From an epistemological point of view, we then have two theoretical frameworks: one for (quantical) observed systems, one for (classical) observers. As a first step, this was convenient, but it is now insufficient to encompass phenomena like decoherence, which systematically involves the environment, **E**. There is also a need to get rid of the epistemological dependence of QM on classical physics.

Physical works on this matter go back at least to John VON NEUMANN's *Grundlagen* (1932) showing that quantical probabilities reduce to classical ones in a measurement experiment, along what is now called the *von Neumann chain*. Nowadays, works on decoherence and classical appearance of nature, follow this research path

[15] See Ben-Dov (1988) for an historical presentation. PMI emerged with Bryce S. DEWITT reformulation, in the 1970's, putting RSI in the background. At the quantical level, DEWITT reformulation is not coherent with QM results, cf. Ben-Dov (1988) esp. p. 106. Nevertheless, due to decoherence, DEWITT reformulation is, in practice, convenient at the macroscopic level.

[16] We neglect here normalization considerations in formulation.

[17] So, to be exact, CSI denied application of QM to observer *per se*. Since the system and the observation apparatus were conceived inseparable, QM precluded application to the macroscopic reality.

(Zurek, 1991, 2003). We will suppose here that the decoherence phenomena are well known, but let us emphasize that it does not solve *per se* the objectivity challenge, nor does it constitute an interpretation of QM. It seems correct to speak of decoherence as making wave-function evolve rapidly, resulting in its diagonalization on "*a* pointer basis" for an experimental system (at least for pedagogy or heuristics) (Zurek, 1991). But it is nonsense to speak of "*the* pointer basis", not to mention the "pointer basis of the universe". Indeed, in some situations superposition continues on a macroscopic time scale: if we take microscopic aspects into account, pointer bases do not commute[18]. Indeed, one cannot consider the universe as being classical except for some periods/places.

In many sciences, objectivity arises from crossing subjectivities. Hugh Everett have been the first to address this problem physically, and not only philosophically. He notes (Everett, 1955) that interactions $\mathbf{S} \bullet \mathbf{O}_1$, *i.e.* a first observer ($\mathbf{O}_1$) apparatus, are phenomena for a second observer $\mathbf{O}_2$ ([19]). According to Everett, one must be able to analyze experimental observations as interactions between a system, $\mathbf{S}$, an observer, $\mathbf{O}_1$, and, possibly, an environment, $\mathbf{E}$. Moreover, a coherent measure theory must account for intersubjectivity: if there is a second observer, $\mathbf{O}_2$, reciprocal observations must be reconcilable ($\mathbf{O}_2$ from $\mathbf{O}_1$ and $\mathbf{O}_1$ from $\mathbf{O}_2$). He discusses $(\mathbf{E}\bullet)\mathbf{S} \bullet \mathbf{O}_1 \bullet \mathbf{O}_2$ as a fundamental problem and answers it with a relativist rationale, *i.e.* the relativity of states. It is important to emphasize that Everett resorts to the usual wave function formalism of QM[20], from the viewpoint of a second observer. On this basis, he defines the quantical relative information and the relative state functions, and proves evolution rules from which he can derive usual measure observations in a coherent way.

Technically, Everett relies only on QM to deduce his relative states theorems, but this is not sufficient to found an interpretation (RSI) and to assert that all relative states are equally real. For this, we need methodological principles. For some, principle 1 (parsimony) would be enough: a physical theory should describe not only the observed system $\mathbf{S}$, but also the environment $\mathbf{E}$, and the observers, *i.e.* the experimental apparatus $\mathbf{O}$. But for others, specially the Copenhagen interpretation followers, there is a conceptual impossibility here. So we will set up an additional principle[21].

Principle 5 (*objectivity*). *Observers are observable systems and "observers who have separately observed the same quantity will always agree with each other".*

This epistemological principle, that allows a general application of quantum theory, is also fundamental to fully endorse the hypothetico-deductive method[22]. It is also a means to conform to the psycho-physical parallelism advocated by John von Neumann: "it is a fundamental requirement of the scientific viewpoint [...] that it must be possible so to describe the extra-physical process of the subjective perception as if it were in reality in the physical world" (1955, p. 418)(Everett, 1955, p. 7, cit.).

To be more specific, Everett's fundamental point is that in an interaction a system-observer pair, $\mathbf{S} \bullet \mathbf{O}_1$, will eventually evolve (Everett, 1955, p. 54) up to a point where "the relative system states become approximate eigenstates of the measurement" (Everett, 1955, p. 59). If $|L\rangle$ and $|R\rangle$ are observer (i.e. apparatus) states, if $|l\rangle$ and $|r\rangle$ are the corresponding system eigenstates for the measure, and if $\mathbf{S}$ is before the interaction in the superposition state $a\,|l\rangle + b\,|r\rangle$, with $|a|^2 + |b|^2 = 1$, then $\mathbf{S} \bullet \mathbf{O}_1$ evolves eventually to the correlated state $a\,|l\rangle \otimes |L\rangle + b\,|r\rangle \otimes |R\rangle$ ([23]). From $|L\rangle$ version of $\mathbf{O}_1$, (relative) state of $\mathbf{S}$ is $|l\rangle$, whereas it is $|r\rangle$ in the $|R\rangle$ version of $\mathbf{O}_1$. Probabilities are $|a|^2$ and $|b|^2$, respectively, in agreement with Born's rule. For an external observer $\mathbf{O}_2$, there is neither something like a "separation" or "split" of $\mathbf{S} \bullet \mathbf{O}_1$ in two universes, nor a "wave function collapse": $\mathbf{S} \bullet \mathbf{O}_1$ merely evolves unitarily, according to its (extraordinarily complex) Schroedinger equation. Moreover, this evolution will generally become classical very quickly, due to decoherence by the environment $\mathbf{E}$.

C. Potential world modal interpretation

If we follow this example, we can view $|\text{left}\rangle_{\mathbf{S}\bullet\mathbf{O}_1} = |l\rangle_{\mathbf{S}} \otimes |L\rangle_{\mathbf{O}_1}$ and $|\text{right}\rangle_{\mathbf{S}\bullet\mathbf{O}_1} = |r\rangle_{\mathbf{S}} \otimes |R\rangle_{\mathbf{O}_1}$ as some sort

[18] We discuss an example at end of section II.C.

[19] "The question of the consistency of the scheme arises if one contemplates regarding the observer and his object-system as a single (composite) physical system. Indeed, the situation becomes quite paradoxical if we allow for the existence of more than one observer." (Everett, 1955, p. 4)

[20] He himself insists that he uses only "pure wave mechanics" (Everett, 1955, p. 97 e.g.).

[21] We quote Everett (1955, p. 80).

[22] Roughly speaking, in traditional inductive methods, science produces ("induces") theories to sum up all observed experimental facts (and potentially observable ones, by an hypothesis of regularity), whereas the hypothetico-deductive method starts with hypothetical theories, deduces experienceable facts and confronts them with experiments.

[23] Some authors argued that not every situation will evolve this way. This is true; it is not necessary to suppose that such a $\mathbf{S} \bullet \mathbf{O}$ system *will always* evolve that way — that is that $\mathbf{S} \bullet \mathbf{O}$ eigenstates are tensor products of $\mathbf{S}$ and $\mathbf{O}$ states. Everett, indeed, only considers that it does when the interaction is a measurement. For our purpose here, it is sufficient to consider cases *where* $\mathbf{S}$ evolves with $\mathbf{O}$, according to $\mathbf{O}$'s eigenstates, and accept the experimental fact that *when* it does so, it does so according to Born's rule. Why universe evolves that way and why "classical" eigenstates are selected is another question we shall not discuss here, see Zurek (2003).

of "possible worlds". The observer, in a way, exists in two "versions" that cannot exchange information, in EVERETT's framework. But what does the word "possible" mean precisely? There is a lot of confusion about this in the literature. In many readings of RSI, especially in PMI, "possible" means "imaginable": there would exist a "possible world" for any and every imaginable situation, for example a possible world in which this paper would begin with the word "the". This is undue extrapolation: physics knows nothing about it. No experimental evidence suggests such a possibility. To discuss this more consistenly, we will need an unambiguous vocabulary for "possible worlds"[24].

In logic, a formalism exists to deal with possibility (and necessity): modal logic. Nevertheless, classical modal logics will be of no use: we need here a quantical logic, according to principle 2 (logic). In (classical) modal logics, one defines possibilities with (i) a set, the *model*, elements of which are "possible worlds" — we will say *potential worlds*, (ii) a relation of *satisfaction* between worlds and propositions (or statements), and (iii) a relation of *accessibility* between worlds which describes what worlds are possible from the point of view of another world. We shall similarly define Quantum Modal Logic.

One can define a Quantum Logic system with algebra as an orthomodular lattice[25] (Birkhoff and von Neumann, 1936). One can also follow a syntactic approach using deduction (Delmas-Rigoutsos, 1997; Gibbins, 1985, e.g.). In any case, one can conceive Quantum Logic as being the structure of sub-Hilbert spaces of a Hilbert space in the same way as Boolean logic is the structure of subsets of a set[26]. If we want to stick to physics, a simple proposition is a statement that after a specific experiment a specific observable lies within a specific range of values; for example "detector 1 has measured an electron with a speed less than $10\,\mathrm{m.s}^{-1}$" or "photon spin in the direction $\vec{n}$ was measured as positive". Ultimately, simple propositions are always yes-no statements and always about an observation at a specific moment. Technically, one can model a proposition L ="particle goes through the left slit" either by a sub-Hilbert space, $\mathcal{L}$, or by its corresponding projection operator, $\hat{L}$. With the one-dimensional simplification frequently used in pedagogic writing, $\hat{L} = |\text{left}\rangle\langle\text{left}|$ and $\mathcal{L} = \mathbb{C}\,|\text{left}\rangle$. Complex propositions combine simple propositions by conjunction ("and"), disjunction ("or$_{\mathrm{QL}}$") and negation. Conjunction is the intersection of spaces: $\mathcal{A} \wedge \mathcal{B} = \mathcal{A} \cap \mathcal{B}$. Quantical disjunction is the sum of spaces: $\mathcal{A} \vee \mathcal{B} = \mathcal{A} + \mathcal{B}$, *i.e.* all linear combinations of elements in $\mathcal{A} \cup \mathcal{B}$. Quantical negation, contrary to the classical one, is not only a false conjunction, but corresponds to an orthogonal sub-space, $\mathcal{L}^{\perp}$; so there are many ways for a state to satisfy neither a proposition nor its negation. For example, in a double-slit experiment, the "left" and "right" propositions are exclusive, meaning $\mathcal{L} \perp \mathcal{R}$, so the L and R propositions are negation of each other. In English, one can say that "the particle goes either through the left slit, or through the right slit" — with an exclusive "or", but a quantical "or"!

If we consider a whole timeline of the universe, $\psi : t \mapsto |\psi(t)\rangle$, the observed system may satisfy a lot of propositions that can be contradictory; consider, for example, the following history: "the photon has spin up in the direction $\vec{n_1}$", then "it has spin up in the direction $\vec{n_2}$", then "it has spin down in the direction $\vec{n_1}$". So it is important to index propositions according to time, whenever formulations can be ambiguous: "the photon has spin up in the direction $\vec{n_1}$ at time t_1", then "the photon has spin up in the direction $\vec{n_2}$ at time t_2", then "the photon has spin down in the direction $\vec{n_1}$ at time t_3" [27].

By definition, a wave function ψ satisfies a proposition P concerning a time t, if $\hat{P}\,|\psi(t)\rangle = |\psi(t)\rangle$ or, equivalently, if $|\psi(t)\rangle \in \mathcal{P}$; one writes $\psi \vDash P$. Can one consider all states in $\mathcal{H}$, the total reference Hilbert space, as being potential worlds? Probably yes, in very simple pedagogic examples where we use only few dimensions and very short histories; probably not, in the general case: each observation at least doubles the necessary dimensions of $\mathcal{H}$, so any whole timeline may lead to dimensional complexities. Restrictions may need to be applied in the future, but, for a start, we define a potential world $\mathcal{A}$ to be a non-zero sub-Hilbert space of $\mathcal{H}$. Starting from there, *we will restrict the use of the term "potential" to this precise modal meaning*, and leave "possible" to general or informal use. We say that "$\mathcal{A}$ satisfies proposition P" or that "P is true inside $\mathcal{A}$", and we write $\mathcal{A} \vDash P$, if any $|\alpha\rangle \in \mathcal{A}$ satisfies P, except perhaps for some zero-measure subspace. As for EVERETT (1955), a potential world $\mathcal{W}$ will generally be expressed as a recorded history: "observation 1 measured value a for A", "observation 2 measured value b for B", etc.[28]. Let us imagine we add a new ob-

[24] EVERETT is very cautious about that and in (Everett, 1955), he never uses the phrase "possible world", but only "branch".

[25] A lattice is a partially ordered ($\leqslant$) set in which every two elements have a supremum ($\vee$) and an infimum ($\wedge$). It is orthocomplemented if there is a least element (0), a greatest element (1) and an involution reversing order, the orthocomplement $(\cdot^{\perp})$. It is orthomodular if $a \leqslant b$ implies $a \vee (a^{\perp} \wedge b) = b$ (Birkhoff and von Neumann, 1936). One can also define orthomodularity saying $a \leqslant b$ implies that a and b commute or are compatible ($a \smile b$) (Delmas-Rigoutsos, 1997). In this formalism, 0 is false, 1 is truth, order ($\leqslant$) is consequence, supremum ($\vee$) is disjunction ("or"), infimum ($\wedge$) is conjunction ("and") and orthocomplement $(\cdot^{\perp})$ is negation.

[26] A theorem by Constantin PIRON (1964) shows that any finite or denumerable Quantum Logic system can be represented in a projective geometry, and thus as sub-spaces of a Hilbert space.

[27] It is to be noted that in these propositions time is merely a relative index, not a parameter.

[28] We use histories to express potential worlds, not more. This ap-

servation to $\mathcal{W}$, for example X with two values $+$ and $-$; this observation determines two sub-spaces: $\mathcal{X}^+ \perp \mathcal{X}^-$, with $\mathcal{W} = \mathcal{X}^+ \oplus \mathcal{X}^-$. In such a case, we say that $\mathcal{X}^+$ and $\mathcal{X}^-$, and more generally any other sub-Hilbert space of non-zero measure and non-zero orthocomplement $\mathcal{Y}$ is accessible from $\mathcal{W}$; we write $\mathcal{W} \rhd \mathcal{Y}$. The accessibility relation can be thought of as the logical identity of past observable interactions; in (Everett, 1955) it corresponds to shared automatic apparatus memories. In PMI, it corresponds to a world "split" (but this is not a technically precise expression).

As usually in modal logic, we say that P is necessary in $\mathcal{W}$, $\mathcal{W} \models \Box P$, if any world accessible from $\mathcal{W}$ satisfies P: $\forall \mathcal{X} \lhd \mathcal{W}, \mathcal{X} \models P$. By construction, if $\mathcal{W} \models P$, then $\mathcal{W} \models \Box P$, and reciprocally. We can, similarly, define that P is possible in $\mathcal{W}$, $\mathcal{W} \models \Diamond P$, if at least one world accessible from $\mathcal{W}$ satisfies P: $\exists \mathcal{X} \lhd \mathcal{W}, \mathcal{X} \models P$. In our example, $\mathcal{W} \models \Diamond$"$X = +$", $\mathcal{W} \not\models \Box$"$X = +$", and $\mathcal{W} \models \Box$"$A = a$".

One always has $\mathcal{A} \models P \vee P^{\perp}$, but, in general, a potential world may satisfy neither P nor $P^{\perp}$: corresponding observations may not be possible for experimentation. So $\mathcal{A} \not\models P$ does not imply, in general, that $\mathcal{A} \models P^{\perp}$, even when $\mathcal{A}$ is one-dimensional. In classical modal logics, necessity and possibility are dual: $\Diamond P$ is equivalent to $(\Box P^{\perp})^{\perp}$; this is not true, in general, in Quantum Modal Logic. Nevertheless, in a case where $\mathcal{A}$ and P are compatible ($\mathcal{A} \smile \mathcal{P}$)[29], $\mathcal{A} \not\models \Box P$ is equivalent to $\mathcal{A} \models \Diamond P^{\perp}$ ([30]).

Note that Quantum Modal Logic is only a formalism; it does not rule, in general, what is and what is not a possibility. Neither does the Hilbertian wave function formalism. Only the experimental register can give us a clue about what possibly happens and what cannot happen when there is no observation. Nevertheless, one can use these models to make a concept (not only a notion) of observer explicit. Following Everett (1955), one can define an observer as a record of observation memories. An observer **O** resides in a potential world, but not only one: when **O** resides in $\mathcal{P}$, meaning $\mathcal{P}$ satisfies all his memories-propositions, then **O** resides *identically* in any potential world $\mathcal{B}$ from which $\mathcal{P}$ is accessible ($\mathcal{B} \rhd \mathcal{P}$). There are also different versions of **O** in each potential world $\mathcal{A}$ accessible from $\mathcal{P}$ ($\mathcal{P} \rhd \mathcal{A}$). These $\mathcal{B}$-worlds are the only logical past of **O** ("before") and the $\mathcal{A}$-worlds are the various potential futures of **O** ("after"). In each $\mathcal{A}$, **O** sees himself as the only existing version of **O**, even if he can conceive other imaginable versions of himself — note that an *imaginable* version is not necessarily a *potential* version, in the strict sense of our formalism. Note also that, for **O**, $\mathcal{P}$ and all its $\mathcal{B}$-worlds are mutually indistinguishable: no physical means can differentiate them.

In our Quantum Modal Logic formulation, potential worlds correspond to Everett's branches (Everett, 1955), *i.e.* correspond to *sets* of parallel universes, and not to individual universes of PMI[31]. Note that, in any case, this "parallel universes" (PMI) formulation can be useful at a macroscopic level, but it is incorrect at a quantical level, as noted by Yoav Ben Dov (1988) and Bernard d'Espagnat (1994). For example, consider an experiment measuring an electron spin in the direction $\overrightarrow{n_1}$: this leads to worlds $\mathcal{S}_1^+$ and $\mathcal{S}_1^-$. Neither of these worlds can be conceived without superposition: in each one, one can add a measure of spin in a new direction, $\overrightarrow{n_2}$, not parallel to $\overrightarrow{n_1}$; $\mathcal{S}_1^+$ is a superposition of the two accessible worlds $\mathcal{S}_1^+{}_2^+$ and $\mathcal{S}_1^+{}_2^-$. So RSI and Quantum Modal Logic are coherent with a "parallel worlds" popular formulation, but only if one is cautious enough not to figure these worlds as being in Boolean disjunction. In particular, one cannot enumerate the accessible potential worlds in general. As stated by Jean-Marc Lévy-Leblond: from the point of view of the universe, there is only one world[32]. One cannot count potential worlds, but, still, if we reason relatively to some global wave-function, we benefit from conditional probabilities for relative states (Everett, 1955); this provides us with quantical probabilities, similar to classical (Kolmogorov) ones — but not to be confused with them[33]. These probabilities provide a measure, *i.e.* Born's coefficients, which we will use later in this paper.

With our now formal vocabulary, let us come back to our initial question: from inside a potential world, can we get to know something about alternative worlds?

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proach, despite similarities, is fundamentally different from the "consistent histories" of Robert Griffiths and Roland Omnes or the "decoherent histories" of Murray Gell-Mann and James B. Hartle: both are essentially attached to Classical Logic. We will not go further on this matter here; it would need more development.

[29] With (Delmas-Rigoutsos, 1997), let us define $\mathcal{E} \circ \mathcal{F} = \mathcal{E} \cap (\mathcal{E}^{\perp} + \mathcal{F})$, the projection of $\mathcal{F}$ on $\mathcal{E}$, and define $\mathcal{E}$ and $\mathcal{F}$ to be compatible, $\mathcal{E} \smile \mathcal{F}$, by:

$$\mathcal{E} \circ \mathcal{F} = \mathcal{F} \circ \mathcal{E} \iff \mathcal{E} \circ \mathcal{F} = \mathcal{E} \cap \mathcal{F} \iff \mathcal{E} \circ \mathcal{F} \subseteq \mathcal{F} \overset{\text{def}}{\iff} \mathcal{E} \smile \mathcal{F}.$$

[30] Proof.- If $\mathcal{A}$ is a potential world, if P is a proposition and $\mathcal{P}$ the corresponding subspace, and if $\mathcal{A} \smile \mathcal{P}$, then $\mathcal{A} = \mathcal{A} \circ \mathcal{P} + \mathcal{A} \circ \mathcal{P}^{\perp} = \mathcal{A} \wedge \mathcal{P} + \mathcal{A} \wedge \mathcal{P}^{\perp}$. If we suppose that $\mathcal{A} \not\models \Box P$, then $\mathcal{A} \not\models P$, so $\mathcal{A} \wedge \mathcal{P}^{\perp}$ is a non-zero subspace. Since this is a world accessible from $\mathcal{A}$, we infer $\mathcal{A} \models \Diamond P^{\perp}$.

[31] Closer to David Deutch approach, see (Ben-Dov, 1988), p. 113.

[32] "The "many worlds" idea [PMI] again is a left-over of classical conceptions. The coexisting branches here [...] can only be related to "worlds" described by classical physics [...] To me, the deep meaning of Everett's idea is not the coexistence of many worlds, but, on the contrary, the existence of a single quantum one." (Ben-Dov, 1988, cit. p. 79)

[33] Karl Popper (1959) also noted this similarity and founded on it his propensional interpretation of quantical probabilities. He also argued that satistical interpretation is not suitable for it. Contemporary reader would probably be more confortable, on this matter, with Bell's inequalities violation arguments.

D. Qubals and sub-quantical framework

Let us be more precise. Imagine we are in a world $\mathcal{W}$ and we set up an experiment leading to two potential values, for example "yes" and "no". Note that we say here *potential* values and not *imaginable* values: there are two potential worlds $\mathcal{A}^+$ and $\mathcal{A}^-$, both accessible from $\mathcal{W}$. We aim here some SCHROEDINGER's cat-like experiment, but without its complexity: in Erwin SCHROEDINGER's traditional mind experiment (Schrödinger, 1935; Wheeler and Zurek, 1983, cit.), the observer may contemplate the effect of a disintegrating substance, after a certain period of time, so this mind experiment integrates the effect of many different independent atoms — we are here in a situation of mixture rather than superposition. Even if we are content with a unique atom, there may be complex interactions and if the observation is a yes-no experiment at the macroscopic level, we are not always sure it is also the case at the quantical level. The physical description is complex, and the discussions, physical or philosophical, are often very confused, sometimes even nonsensical[34]. We need more unequivocal situations. To be reasonably sure the *imaginable* alternatives correspond effectively to *potential* outcomes, we will focus here on very simple experimental protocols, similar to the ones used to experiment upon the EPR paradox, for example the spin of correlated photon pairs. We can also imagine, for example, a measure of spin of a photon in a direction, following a measure in an orthogonal direction. Let us call such a situation a *quantical binary simple alternative* — a *QuBAl*. It is important here that uncertainty should be of quantical origin and not of statistical origin (there should be no "mixture"), also that it should not be disturbed by an environmental decoherence — in a sense, qubals are anomalies since in most experimental situations the decoherence makes such alternatives disappear very quickly along the von Neumann chain.

Typical qubits, quantical binary digits, seem to be good candidates to provide qubals, quantical binary simple alternatives. The difference between the two is that we will have here no use of the qubit phase, nor, as a matter of fact, of its value. There is also a practical difference: the qubal is a situation, an experimental framework, whereas one now uses the word qubit mainly for technical devices.

In a situation where we really have a quantical binary alternative (a qubal), we have two accessible worlds, $\mathcal{X}^+$ and $\mathcal{X}^-$, each one having a non-zero probability, according to BORN's rule. In that experimental context, our question is now: if we are in $\mathcal{X}^+$, can we know anything of $\mathcal{X}^-$ (if we follow RSI) or, simply, does $\mathcal{X}^-$ exist or not (in PWI, it does not)? If we strictly follow EVERETT's framework, the answer is straightforward: we cannot. No information can go from one world to an inaccessible one. Would this be final, we could not settle between RSI and PWI, and the choice would be essentially a matter of personal convenience — one's metaphysical preference[35]. But EVERETT relied only on "pure Quantum Mechanics", and QM is not final as a description of nature; notably, we still seek for a framework integrating what we know of the quantical phenomena and what we know of inertia-gravitation.

What could be a finer description of reality than QM — a sub-quantical theory? Many options already exist, in many variations, of a different status and of a different extension, especially quantum field theories (QFTs), but, at the time writing, none is universally adopted, nor completely satisfying. A convenient future theory will probably have to alter some aspects of QM or perhaps add some others.

Let us be conjectural now, and combine principle 4 with many physicists' insight of quantical particles as the superposition of "virtual particles". Quite generally, these "virtual particles" follow FEYNMAN's paths conceptions (1948; 1949), as a means of computation or as a heuristic representation for quantum fields theories[36]: these virtual particles are meant to encompass all possibilities within a mathematical model. In our attempt at a theory, let us consider only *potential particles*: particles existing in potential worlds accessible from quantical particle worlds. These potential particles, again, are neither imaginable particles nor virtual particles of a model or another; these are conceived as physical, and hopefully experimentable. Note, however, that their potential worlds may not be quantical potential worlds, but only sub-quantical potential worlds, that might not be accessible to direct experimentation (we will come back to that matter hereunder). Potential particles, surely, do have properties very different from those of quantical particles — in the same way as complex ions in solution may have very different properties from bare ions. For example, if mass is an emerging property, one can imagine that, having no mass, all potential particles propagate at a "displacement pace" c, whereas quantical particles can be measured at various velocity magnitudes. Physics for sub-quantical level has to be theorized; it may be extremely different from quantical and macroscopic ones. At the sub-quantical level of description, there

[34] True or false, a legend reports that Stephen HAWKING said: "When I hear of SCHROEDINGER's cat, I reach for my gun." This is a disconcerting vision, but, a sure way to end the argument.

[35] Many authors discuss this preference based on a version or another of the parsimony principle, but their conclusions are very formulation dependent and did not achieve to convince a large audience. For this reason, we chose a methodological formulation of our principle 1, and aim for no metaphysical use of it.

[36] Virtual particles can also be seen as mathematical artifice to represent fields, similarly to HUYGENS-FRESNEL principle, see e.g. (Feynman, 1948, esp. sec. 7).

may be nothing like a space-time we are used to, but, perhaps, only contiguity and consecution relations. The SCHROEDINGER's equation at the quantical level might just be the result, by symmetry, of the superposition of numerous (perhaps infinite) potential interactions of potential particles. ([37])

For more than a century and a half, fields have been a very fruitful concept of physics. General Relativity (GR) and quantum field theories (QFTs) made it a prime concept of today's physics, pivotal to make wave and corpuscular behaviors converge — fields overtaking classical waves, and corpuscles being quanta of these fields. This approach has led to new understandings and new ways to consider particles, especially with quasi-particles (Cooper pairs, phonons, holes, etc.). But, what are these fields actually? Are they physical objects or merely theoretical reifications of physical relations[38]? Fields represent infinite numbers of degrees of freedom — even a *continuous* infinite number ($\beth_1 = 2^{\aleph_0}$), for example in the form of a Fock space. What could this mean *physically*? We will suppose here that all fields emerge from potential particles[39]. The reader can consider this as real (as a hypothesis), or act "as if" and consider this as mere heuristics.

Since pure Quantum Mechanics phenomena cannot distinguish between PWI and RSI and does not allow information to go from one potential world to another inaccessible world, we will now consider another option, within our conjectural sub-quantical framework, relying on gravitation.

III. INTERPRETATION ELEMENTS FOR GRAVITATION

We will not unify General Relativity (GR) and Quantum Mechanics (QM) here, but our framework can help sketch out some aspects of a merged theory. It could certainly not be something like "$\mathbf{GR} \oplus \mathbf{QM}$" (metaphorically speaking), since many phenomena are on the fringe of both application domains, even in our near phenomenal environment. So, many authors are rather searching for something like "$\mathbf{GR} \otimes \mathbf{QM}$": this line of research is appealing and somehow general, but it does assume that fundamental phenomena of one theory are not already consequences of the other. We shall discuss this point, relying firmly on SCHROEDINGER's linearity (principle 4) and some experimental facts.

In the search for such an integration, we immediately encounter a conceptual difficulty, well summed up by David BOHM: "In relativity, movement is continuous, causally determinate and well defined; while in quantum mechanics it is discontinuous, not causally determinate and not well defined"[40]. One could add that QM deals with particles of no dimension, while GR diverges on punctual bodies, dealing rather with densities. Clearly, a mere rapprochement would lead nowhere. We need to have a look at core concepts.

A. Emergence of Special Relativity

1. Relativity without "rods and clocks"

Howard ROBERTSON (1949) showed that Special Relativity (SR), and thus grounds for GR, can be deduced from some general postulates and three experimental facts. We will follow his reasoning but reduce its hypotheses, to enforce our previous principles.

His first postulate is that "there exists a reference frame — EINSTEIN's 'rest-system' — in which light is propagated rectilinearly and isotropically in free space with constant speed c". The notion of reference frame, with abstract "rods" and "clocks" is, in general, incompatible with our principle 3: no measure exists *in abstracto*, but one can adapt ROBERTSON's postulate without impairing his reasoning[41]:

Principle 6 (*reference observer*)**.** *An observer* **O** *exists, for which, in free space, light propagates rectilinearly and isotropically at a constant velocity c.*

ROBERTSON (1949), then, postulates "the existence of a reference frame [...] — EINSTEIN's 'moving system' — which is moving with any given constant velocity [...] with respect to [first reference frame]", also supplied with abstract "rods and clocks". We will disregard this postulate and only suppose that we can observe, in moving systems **S**, relative remoteness and relative duration, as an application of our principle 3. Both are evaluated from interactions internal to **S**, but outcomes of these measures can be traced from the outside, **O**. Here, note that the *remoteness* and *duration* are space and time distances

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[37] Other authors proposed similar hypothesis, following hydrodynamical interpretation of QM (MADELUNG fluid), notably BOHM (1957, p. 33), presenting quantum particle as a condensation of a sub-quantical fluid, see (Ben-Dov, 1988, p. 190).

[38] By reification of a relation we mean constituting as an object what is really relation between objects: for example the Newtonian gravitational potential of a body **M** is a reification of the gravitational force between **M** and test masses (real or virtual).

[39] NEWTON, relied on forces for its mechanics, but prevented reflexion about their nature: "hypotheses non fingo". In 1936 EINSTEIN (Cohen-Tanoudji and Spiro, 2013, cit., p. 471) argued we should found physics theory on fields. Here we are, now, with a very efficient tools, but again not forging hypotheses about it. Perhaps are we in a time to build other tools.

[40] David BOHM, *Wholeness and the Implicate Order*, 1980, xv.

[41] Isotropy and constancy of light speed is one of the best verified facts, up to 17 orders of magnitude (Eisele et al., 2009), still, we state it as a principle, not merely as a fact, since we need to postulate, at least methodologically, a reference observer (not necessarily unique).

at the macroscopic and quantical levels for **S**; one can speak also of *coordinates*. Their measure emerges from sub-quantical mechanisms, and therefore can have structures very different from those of sub-quantical contiguity and consecution *intervals*. For speed, we will use the terms *velocity* and *rapidity*, as usual, for the macroscopic and quantical phenomena; at the sub-quantical level, we will speak of *displacement pace* (table I). Epistemologically, in strict application of principle 3, this means that we do not necessarily view matter as *being in* space-time, but merely as *having* coordinates, as *descriptive* qualities (emerging qualities, as we shall see).

macroscopic / quantical	sub-quantical
position in space-time	placement in sub-space and time
remoteness, duration, coordinates	interval (of contiguity and consection)
velocity, rapidity	displacement pace

Table I vocabulary for usual quantities

We know nothing, yet, about sub-quantical intervals and displacement paces. As far as we know, the sub-quantical space (the *sub-space*) may be continuous, even Euclidean, or may be a grid, a network, or merely a relation, with the interval relation having emerged by some sort of geometrization mechanism *à la* PERELMAN[42]. We will not suppose much more on that matter now; but, with the two previous postulates, we shall suppose the phenomena regular enough so that coordinates are near Euclidian and local transformation can be linearly approximated.

So, with ROBERTSON (1949), let us suppose **S** is moving at velocity $c\vec{\beta}$ and use clever axis representation (movement along x axis, especially); the transformation has (locally) the following form:

$$\Lambda_\beta = \begin{pmatrix} a_0 & \beta a_1/c & 0 & 0 \\ \beta a_0 c & a_1 & 0 & 0 \\ 0 & 0 & a_2 & 0 \\ 0 & 0 & 0 & a_2 \end{pmatrix}. \qquad (1)$$

The first fact to determine Λ_β is the MICHELSON-MORLEY type experiments, in **S**:

Fact 1 (MICHELSON-MORLEY). *"The total time required for light to traverse, in free space, a distance l and to return is independent of its direction."*

[42] Grigori PERELMAN uses Ricci-Hamilton flow to homogenize the metric on manifolds, and proves that any 3-dimensionnal manifold can be geometrized. One can imagine a similar mechanism to make the local sub-space interval relation build up from an initial simple unstructured contiguity relation.

If we suppose this fact to be general, one can consider a light beam making any angle from the x axis, and then one finds the Lorentz-Fitzgerald contraction as a consequence: $a_2 = a_1/\gamma$ — with Lorentz factor $\gamma = {}^1/\sqrt{1-\beta^2}$. Then, ROBERTSON (1949) adds KENNEDY and THORNDIKE experimental result as: "The total time required for light to traverse a closed path in [a reference frame] is independent of the velocity [of this frame] relative to [first reference frame]". The important thing is that we do not need to suppose c constant in **S**, but simply deduce it from being constant in **O**. We will state this experimental result as:

Fact 2 (KENNEDY-THORNDIKE). *"The total time required for light to traverse a closed path", as experienced from a system* **S**, *"is independent of the velocity of"* **S** *"relative to"* **O**.

Following ROBERTSON, again, one finds that $a_0 = a_1 = \gamma g_\beta$ and $a_2 = g_\beta$. Eventually, one may conclude that Λ_β is a Lorentz transformation ($g_\beta = 1$), if we add a third fact — *i.e.* the IVES and STILWELL experiments:

Fact 3 (time dilation). *"The frequency of a moving atomic source is altered by the factor" $1/\gamma$ relative to the "velocity of the source with respect to the observer."*

This fact makes use of two relatively moving observers, but this can be interpreted coherently with our principle 3.

ROBERTSON wanted to show that one can "replace the greater part of Einstein's postulates with findings drawn inductively from the observations", but our small reformulation, here, shows a more general fact. In any theory obeying our postulates and coherent with these three experimental facts, local coordinates, measured from systems moving at constant velocity for a reference observer, should be transformed according to a Lorentz transformation, at least for linear approximation.

As a consequence, any sub-quantical theory from which one could derive these facts would be coherent with SR and would have locally a Minkowskian metrics (with linear approximation). Let us now specify our attempt at a theory. Next section will be essentially speculative.

2. Special relativity emerging from potential particles

Some clues, mainly from contemporary theories, especially due to renormalisability questions, suggest that sub-quantical potential particles should be thought of without inertial mass. The latter would be acquired through a coupling mechanism. Present research favors the BROUT-ENGLERT-HIGGS-HAGEN-GURALNIK-KIBBLE (BEH) mechanism, *i.e.* interaction with BEH bosons, with some recent experimental support (ATLAS collaboration, 2012). We will not rely on the BEH theory but, in coherence with it, let us only suppose all sub-quantical potential particles are massless. Accordingly, all of them have a displacement pace of the same magnitude (in some sort of sub-space-time). Between two interactions, the displacement pace of a potential particle is uniform and has a specific direction[43]. Potential particles move like ideal non-interacting photons, whereas quantical particles do engage in interactions in different potential worlds, and so correspond to superpositions of potential particles. The less a photon interacts, the closer the "mean" displacement pace of its superposition will be, in magnitude, to the common pace. So, if we suppose that velocity accounts for some sort of "mean" displacement pace, light with minimum interaction will always have the same velocity magnitude, c, which we can identify with the only displacement pace magnitude of potential particles (to a factor[44]). If the sub-space-time is supposed isotropic, this would also account for principle 6 and fact 1. Note that we presuppose no sub-quantical notion of inertia or relative motion: on the contrary, all displacements occur at same pace, and all interactions emerge from combination and emission of sub-quantical potential particles in diverse directions[45]. This accounts for fact 2.

For fact 3, we need to be more precise in our hypotheses. Let us imagine that the velocity of a quantical particle is some sort of mean displacement pace of potential particles. For a (set of) potential particle(s) p, let us note ν_p its quantity and $\overrightarrow{n_p}$ its displacement pace direction[46], both operators on quantum states. For potential particles participating in a quantical system S, let us define a mean pace:

$$\overrightarrow{\beta_S} = \frac{\sum\limits_{p\in S} \nu_p \overrightarrow{n_p}}{\sum\limits_{p\in S} \nu_p}. \tag{2}$$

In this formula, one can recognize velocity: $c\overrightarrow{\beta_S}$, energy: $E_S = h\sum\limits_{p\in S}\nu_p$, and momentum: $\frac{E_S}{c}\overrightarrow{\beta_S} = \frac{h}{c}\sum\limits_{p\in S}\nu_p\overrightarrow{n_p}$ (47).

If these potential particles have a balance between the potential directions (isotropy in pace), emerging velocity is zero. The velocity magnitude would rise with a common orientation in some direction of displacement pace. In the limit, if a vast proportion of displacement paces of potential particles heads in one direction, the emerging velocity magnitude will be close to c. Now, let us imagine two mono-directional streams of potential particles; if they have the same direction, they have no potential for interaction, since they are displaced at the same pace — the greyhound cannot catch the rabbit. At angle π, on the opposite, the probability of interaction by unit of time is at a maximum. At angle θ, we can imagine a relative interaction progressing with $1-\cos\theta$. In this theory, accelerating a quantical particle in a direction is just adding potential particles in the same direction: each interaction then tends to replace more frequently a potential particle in the opposite direction by a potential particle with another direction, and so raises the level of directionality.

Let us suppose that for two quantical particles potentially interacting, there is a factor $(1-\cos\theta)$ on their wave function describing their propension to interact; this factor reduces the potential presence of particles and thus increases the time before interaction occurs. At the sub-quantical level, this $(1-\cos\theta)$ factor corresponds to $(1-\overrightarrow{n_{p_1}}\cdot\overrightarrow{n_{p_2}})$. It is linear, and so the factor for two potential particle sets, for example two quantical particles, becomes $(1-\overrightarrow{\beta_{S_1}}\cdot\overrightarrow{\beta_{S_2}})$. If these two sets participate in an object — *i.e.* a greater set — with velocity $c\overrightarrow{\beta}$, then let us decompose $\overrightarrow{\beta_{S_a}} = \overrightarrow{\beta}+\overrightarrow{b_a}$. If we suppose this bigger set to be homogeneous enough, then $b_a \ll \beta$ (48). Therefore, the dynamics factor becomes

$$\begin{aligned} 1-\overrightarrow{\beta_{S_1}}\cdot\overrightarrow{\beta_{S_2}} &= 1-\beta^2-\overrightarrow{\beta}\cdot(\overrightarrow{b_1}+\overrightarrow{b_2})-\overrightarrow{b_1}\cdot\overrightarrow{b_2} \\ &\approx 1-\beta^2. \end{aligned} \tag{3}$$

If we share this factor equally between the two sets, by symmetry, we get the following factor: $\sqrt{1-\beta^2} = 1/\gamma$. With these hypotheses, γ appears as a directionality factor, and $1/\gamma$ as a time dilation factor for moving objects. This accounts for fact 3: proper time emerges as a collective property (without need to consider mass).

The theory we have sketched out could make SR emerge in a QM context, without any need to naturalize a Minkowskian space-time. Contrary to EINSTEIN's SR, in our theory, length contraction and time dilation

[43] We suppose it to be rectilinear, for now, but geometry of sub-space-time may appear to be more complex.

[44] This is only for supporting understanding, since we have no access to contiguity intervals independently of consecution intervals. We could as well consider displacement pace magnitude to be 1 and state the contiguity interval to be exactly the consecution interval between two events directly connected by a potential particle. For that reason, we use the same term "interval", for both space and time.

[45] For potential particles, there can probably be no notion of a trajectory: since quantical particles of the same type are indistinguishable, i.e. logically identical, so should be underlying potential particles. A potential particle, in a potential world, only exists between two interactions.

[46] Quantity and direction are time dependent. The quantity term should be specified in a more formal theory. For now we can think of it either as homologous to frequency for photon or as a number of inseparable potential particles or as some sort of intrinsic BORN's rule coefficient (since we do not take into account potential worlds in following formula). It is also a convenient means to keep non existing particles (not yet existing or no more existing) in same formula; in that case $\nu_p = 0$ and direction is undefined.

[47] If $\beta_S < 1$, we can set $\gamma_S = 1/\sqrt{1-\beta_S^2}$ and define usual relativist homologous of these quantities.

[48] The closer β will be to 1, the more homogeneous the object will be, relative to the displacement pace.

would appear as phenomena, not perspective effects[49]. Note also that it makes relative four-velocities emerge from displacement paces, which may thus be absolute.

Scholium 1. Our theory, which technically provides an alternative to EINSTEIN's SR, supports an interpretation of SR which we will name *cinematic interpretation*, as opposed to the usual Einsteinian ontic interpretation. These two interpretations differ metaphysically, since the cinematic interpretation allows an absolute space and has got absolute displacement paces, whereas the ontic interpretation acknowledges only relative space-time and velocities. But, at a physical — experimental — level, both interpretations expose only relative velocities, and both acknowledge only Galilean frames as privileged frames.

Scholium 2. With our attempt at a theory, the phenomena (*i.e.* causality) propagate at a maximum velocity c, but, still, some correlations, as in EPR-like experiments — in qubals, are instantaneous, since they depend on potential worlds.

B. Inertia and energy induction of weight

The usual General Relativity interpretation views gravitation as a reciprocal effect between particles and a special object called space-time. This does not completely rule out mechanisms where gravitation would emerge from effects of the curvature of coordinates on quantum phenomena. For example, Andrei SAKHAROV (1967) suggests that gravitation could emerge from "quantum fluctuations of the vacuum if space is curved". So, should gravitation be quantified, or should it be differently dealt with? Let us start with an analysis of some elements of knowledge about motion and gravity.

JOHN Philoponus first introduced a notion of impulse (*impetus*) or of a "power to move" to account for the continuation of movement[50], a notion later expanded by IBN SĪNĀ, Jean BURIDAN and GALILEO, leading to the laws of conservation of momentum and (what we now call) kinetic energy by Christiaan HUYGENS (Locqueneux, 2009). Isaac NEWTON's *Principia* (1687) define inertia as a "*vis insita* or innate force of matter", as a "*vis inertiae* or force of inactivity", or as a "power of resisting by which every body as much as in it lies endeavors to persevere in its present state whether it be of rest or of moving uniformly forward in a right line"; NEWTON adds it is essentially mass. A few lines above, NEWTON opens the *Principia* with a paragraph stating that weight is proportional to mass as an experimental fact. Inertia, mass and weight are here proportional or equivalent.

EINSTEIN's equivalence, NEWTON's equivalence and also GALILEO stating that all weighting objects fall at the same velocity, are nowadays considered to be variations of an *equivalence principle*. This "principle" is often ill-defined as a physical concept since it is generally deeply interwoven with mechanics. For example, in Newtonian mechanics, NEWTON's and GALILEO's equivalences are logically equivalent. We will not completely specify this notion, and we will consider the *weak equivalence principle* (WEP) to be the equivalence of inertia and gravitation: inertial mass and weighting mass for Newtonian mechanics, inertial energy and ponderous energy nowadays. The experimental register for this equivalence is considerable; it goes back, at least, to Simon STEVIN's *Principles of statics* (1586) and have nowadays a precision of 10^{-14} with the MICROSCOPE satellite experimentation (Touboul et al., 2017); so no theory can dispense with it. Some form of equivalence is also deeply rooted in SR. As early as 1905, EINSTEIN notes, in the "$E = M.c^2$" paper (1905), that, in SR, energy content (whatever this means) decomposes into kinetic energy (K) plus a constant, the energy content at rest. On that basis, if a body symmetrically emits light for energy L, EINSTEIN notes that $K_{\text{before}} - K_{\text{after}} = (\gamma - 1)L$. Since $K = \frac{1}{2}M.v^2$, at first approximation, he concludes: "If a body gives off the energy L in the form of radiation, its mass diminishes by L/c^2 [...] If the theory corresponds to the facts, radiation conveys inertia between the emitting and absorbing bodies." Here, EINSTEIN assimilates inertia (*Trägheit*), moving mass, and energy content (*Energieinhalt*) — later on, this will be a cornerstone of GR. This reasoning is very general in its form, and thus valid also in our sketch framework with emerging kinetic energy: emitting light diminishes the rest energy content.

So, let us acknowledge this equivalence and consider inertia and (ponderous) energy as equivalent. What link can we make between this energy and quantical or subquantical energy, especially in our sketch framework?

Let us turn to gravitation. NEWTON's gravitation law (1687) shows a reciprocal force between two bodies C (context) and T (test) being $G.M_C.M_T/d^2$. NEWTON's work also expresses acceleration for a test body, based on WEP: $G.M_C/d^2$. This expression is independent from the test mass, which helps virtualize it and reify potential gravitation as a field — for a test mass small enough not to disturb the context body. Experiments (now numerous) show that gravitation concerns every object, with or without mass. EINSTEIN generalizes this consideration and postulates we can decompose the gravitation phenomenon into two parts which we call here received and given gravitation. *Received gravitation* is theorized by the fact that inertial movement, that is movement receiving no other influence than gravitation, follows a

[49] Bernard D'ESPAGNAT (1994) relates that John BELL emphatically advocated an interpretation of relativity as phenomenal.

[50] Before him, movement was not something to model mathematically; for example, for ARISTOTLE, weight was a *clinamen*, a final tendency to be in a low place, and motion needed an effective motor to continue its course.

geodesic of a special object, the space-time. Received gravitation concerns inertia, and experimental evidence suggests that it is compatible with equivalence: it is the same for all forms of energy content. *Given gravitation* is theorized by the fact that bodies with a energy density field $\hat{T} = (T_{\mu\nu})$ create a curvature of the space-time object such that

$$\left(\frac{1}{2}R - \Lambda\right).g_{\mu\nu} - R_{\mu\nu} = -\frac{8\pi G}{c^4}T_{\mu\nu} \ , \qquad (4)$$

where $(g_{\mu\nu})$ is the metric of space-time, $(R_{\mu\nu})$ is this metric's Ricci curvature tensor, modeling its propagation, G is NEWTON's constant, and Λ is a "cosmological" constant which we will come back to below[51]. We only know direct experimentation of given gravitation for mass energy, but on the one hand cosmological evidence suggests that it can account only for a small part of the observed gravitation phenomenon, and, on the other hand symmetry with received gravitation suggests that tensor $\hat{T}$ should enroll any form of energy content. So, in GR, inertia (inertial energy) is now better described by tensor $\hat{T}$, a generalization of energy-momentum in the form of energy content density and flux[52]. Nonetheless, the question remains partially open for QFT vacua: since they allow no energy transfer, and since they are omnipresent and isotropic, whether they should be counted in this energy content. This question also makes sense for CMB and CνB[53], that may have no cinematic reality with respect to GR.

More generally, according to Emmy NOETHER's theorem, in QM, energy-momentum is conceived as a symmetry of the model (*i.e.* of the Lagrangian). So it does correspond to the physical phenomena, but only to a constant. It may also incorporate model artifacts, *i.e.* some symmetries of the model with no phenomenal (experienceable) counterpart. Certainly, these artifacts can be compensated for by a categorial quotient or gauge theories, but at the cost of ease and heuristics. So the quantical energy-momentum may not correspond exactly to the GR energy content.

In our sketch framework, any potential particle, massless, is supposedly associated with a quantity ν corresponding to an energy in $h.\mathrm{s}^{-1}$ or a momentum in $\frac{h}{c}.\mathrm{m}^{-1}$. As a heuristic, one may thus view energy-momentum as some sort of effervescence of potential particles (each one counted with its quantity ν), or some sort of sub-quantical scrum. Emerging as a superposition of sub-quantical potential particles, energy is this scrum's time frequency, and momentum its space frequency. More potential particles make more inertia emerge. We insist that this is a heuristic view: since potential particles are continuously being absorbed and emitted, from the quantical or above level viewpoint, we essentially count the superposition; much in the same way as the HUYGENS-FRESNEL principle represents wave propagation as a continuous re-emission of punctual sources on wave surfaces, one can think of a trajectory as a superposition of numerous Feynman diagrams of potential particles, corresponding to minimum dimensional sub-spaces of potential worlds[54]. In this picture, from a sub-quantical level viewpoint, quantical particles merely exist as correlated propagations of interaction. If our view is correct, the traditional view of gravitation as an interaction between two inertias, or two energy contents, holds no more. Two collectives cannot indeed interact *per se*: interaction should also mean something at the sub-quantical level. We will now formulate an experimentable proposal on that matter.

C. An hypothesis about weight

Clifford WILL, in his review of experimental tests of GR (2014), considers that "it is possible to argue convincingly that if EEP [Einstein's equivalence principle][55] is valid, then gravitation must be a 'curved space-time' phenomenon, in other words, the effects of gravity must be equivalent to the effects of living in a curved space-time. As a consequence of this argument, the only theories of gravity that can fully embody EEP are those that satisfy the postulates of 'metric theories of gravity' [. . .]". Note that "living in a curved space-time", in our framework, following principle 3, is a matter of measured coordinates and may be an emerging property of space-time, or even of sub-space.

So, pushing our investigations further, the question is now: on which level of physical modeling does gravitation play? We can see three main possibilities.

1) We can imagine gravitation as being essentially a quantical level phenomenon.

In that case, GR curved metrics may emerge from sub-quantical phenomena in some way similar to what we

[51] There is experimental support for G being constant, under a 10^{-12} per year (Will, 2014, p. 50). According to usual conventions, Greek letters indices range for space-time coordinates.

[52] So, it is still a model of matter presence in space-time, but not only massive matter. Matter is to be thought of as anything with energy content.

[53] Cosmic microwave / neutrino background radiations. See sec. IV.C.1.

[54] It may be infinite, but we only consider infinite here as a limit case, according to principles 1 and 3. In finite case, 1-D sub-spaces are potential worlds, because of non-zero measure.

[55] Following Robert DICKE, *Einstein's equivalence principle* is WEP plus *local Lorentz invariance*: "the outcome of any local non-gravitational experiment is independent of the velocity of the freely-falling reference frame in which it is performed", plus *local position invariance*: "the outcome of any local non-gravitational experiment is independent of where and when in the universe it is performed" (Will, 2014, p. 9).

suggested for SR. Or, one can also imagine that gravitation plays essentially at the sub-quantical level, with two options:

2) Sub-space, *i.e.* intervals, is "curved" by energy content, not unlike the case of QFTs in curved space (B. Unruh, S. Hawking, R. Penrose, R. Wald).

3) Some sort of "force" is exerted between potential particles.

There has been a lot of research on quantical gravitation, leading, for the time being, to no generally accepted theory. We will therefore leave the first hypothesis aside. The second hypothesis is at the very least untimely: it would be too speculative for our roughly sketched theory, since we have no idea, yet, of the mathematical structure of intervals. We will explore here the third hypothesis.

Is gravitation exerted at the quantical particle level? Does it use some sort of vector potential particles, *i.e.* gravitons, the favored path for present research? Or does gravitation differ from the "other interactions"? There is another way of addressing these questions: is weight an in-world phenomenon, *i.e.* a phenomenon limited to each potential world, like "other interactions", or is it exerted across worlds, that is also between worlds otherwise inaccessible?

In our hypothetical theory, inertia and gravitation appear to be proportional to the energy of all potential particles in a given location. More precisely, it corresponds to linearity with respect to mass for given and received Newtonian gravitation, to linearity of given Einsteinian gravitation of the stress-momentum-energy tensor, and to linearity of the geodesic movement of received Einsteinian gravitation. If this theory is correct, this suggests that gravitation given by a body, resulting from its energy content would apply to all potential particles indifferently, and thus its given gravitation would apply to *all* potential worlds. Considering this phenomenon the other way round, test bodies would receive a gravitation that would be the superposition of gravitation from *all* possible worlds. Pushing the hypothesis further, if $|\psi\rangle = a\,|\psi_1\rangle \overset{\perp}{+} b\,|\psi_2\rangle$, with $|a|^2 + |b|^2 = 1$, we could imagine that received gravitation should be something like $g = |a|^2\, g_1 + |b|^2\, g_2$. Let this be our hypothesis, and let us look at possible experimentable consequences.

Hypothesis (*trans-world gravitation*)**.** *Gravitation acts at the sub-quantical level, and produces its effects between worlds in coherence with the coefficients of* Born*'s rule.*

A lot of *conjectures* and *suggestions* have been made to explain some experimental difficulties with gravitation. Our assumption, on the contrary, is an experimental *hypothesis*, as we shall see in the following section. Would it be in accordance with the experiment, it would also institute Born's coefficients, or propensity probability, as a directly observable quantity[56].

Before considering experimentation, we would like to underline some aspects of our hypothesis:

Scholium 3. Newton's third law, the "action-reaction" or "interaction" law, results classically from the symmetry of physical laws. It does exist at the macroscopic level and, in a certain way, at the quantical level, even if the field formalism does not make it obvious. With our hypothesis, gravitation might not respect this law inside each potential world (in-world action), but only between potential worlds (trans-world action). Thus, gravitation would not be an interaction in the same way as electroweak and strong forces.

Scholium 4. Without gravitation, potential worlds do not mingle because quantical interference maintains them phenomenologically separate. On the other hand, gravitation, as it is now understood, is not linear with respect to wave-function, thus inaccessible potential worlds should gravitationally interact.

Scholium 5. If our hypothesis is correct, for trans-world reasoning, the most adequate representation of alternative worlds is RSI — except that when gravitation joins the game the phenomenological world isolation of RSI vanishes. On the other hand, for in-world reasoning, the best heuristic support is PWI — again, when gravitation is out of the game.

D. Crucial experiment

We presented the main tool of our proposed experiment in section II.D: the qubal, or quantical simple binary alternative. Its general ambition is similar to Schroedinger's cat or Wigner's friend but with a clearly formulated and experimentable quantical protocol. In this experiment, we would have a qubal with results "1" and "2" determining the position of a heavy massive body M. In branch 1 of the alternative, that is if result 1 appears, body M will be put in place r_1 at some date t (previously defined). In branch 2, that is if result 2 appears, mass M will be put in place r_2 at the same date t. If we except gravitation, any observer in branch 1 can note then that M is in position r_1, by view or contact, for example; if our hypothesis is valid, it will not be the case with gravity.

Let us suppose this qubal has Born coefficients a_1 and a_2. Classically, measurable gravity strength ("acceleration") given by M would be g_1 in case 1, and g_2 in case

[56] There have been many attempts to prove Born's rule, but they are still controversial, even in RSI context. An experimental confirmation of our hypothesis would change the purport of these attempts. It would also bring some support to Lev Vaidman's terminology for Born's rule coefficients: *measure of existence*, for a world in a many-worlds interpretation (1998).

2. The experimental context body may be, for example, a 1 t quarry stone moved from a distance to a point 1 m away from a gravimeter in case 1, and remaining distant in case 2 [57]. With a rough evaluation $g_2 \ll g_1$, and $g_1 = G.M/d_1^2 \simeq 7.10^{-11} \times 10^3/1^2 = 7.10^{-8}\,\mathrm{m.s^{-2}} = 7\,\mu\mathrm{Gal}$. This value comes in the range of today's microgravimetry apparatuses. If our hypothesis is correct, and if effect follows the von Neumann chain, received gravity strength would be $g \simeq |a|^2 g_1$. If the qubal is symmetric, with equal probabilities of the two branches, then $g \simeq \frac{1}{2} g_1$.

What can we learn from this experiment? Before the turn of the 20th century, physicists thought that molecules would never be observed. For that reason, some authors, like Ernst Mach or Wilhelm Ostwald, rejected atomism (Cohen-Tanoudji and Spiro, 2013, p. 51). The situation has some similarities with that of potential worlds. For RSI, all potential worlds are physically real; for PWI one is real and the others merely virtual. Would such a protocol be confirmed by experiments, our potential worlds modal interpretation, convergence of RSI and PWI, would be well established as an interpretation framework. Still, this result is highly counter-intuitive, perhaps for good reasons, and thus may well fail. Would this happen, it would be an indication that inaccessible worlds (in sec. II.C sense) are phenomenologically impervious, and so that distinctions between RSI and PWI are essentially metaphysical. Physical discussion could nevertheless remain on the sound grounds of quantum modal logic and potential worlds.

Concerning gravitation, an experimental success would urge us to revise large scale gravitational reasoning and take into account the gravitation received from alternate potential worlds. We will shortly explore some possible consequences of such an effect in the following sections. These hypothetical consequences are incentives to experiment our hypothesis, since it would then link several current difficulties. On the contrary, a failure of this experiment could suggest that gravity may be ultimately linear in some wave-function representation, and be an invitation to elaborate quantical theories of gravitation.

IV. EXPLORATION OF CONSEQUENCES

We will now explore some possible consequences of our hypothesis of trans-world gravitation.

[57] One can also mention the extremely heavy bodies of the building industry: bridge elements, building parts, or even entire buildings (on May 22nd, 2012, a 6 200 t historical building was moved 60 m away in Zurich, Switzerland).

A. Potential worlds and cosmic inflation

The idea of cosmic inflation was developed in the early 1980's by Alan Guth (1981). It is generally thought to be a phase transition of the early universe, and is still in want of an explanation. It could be linked to a term similar to the cosmological constant in the energy-momentum stress tensor, and/or be an early effect of a scalar field. Cosmic inflation is modeled as a metric expansion of the universe. It is considered to be exponential and to correspond to 26 orders of magnitude, at least — considerably more in some models. Its duration is extremely hypothetical; in some theories, inflation is even perpetual in some parts of the universe. The main justification for this idea is that it solves the horizon and flatness problems[58]. The main observational evidence in favor of inflation is the CMB, which is very homogeneous, and the variations of which are interpreted as inhomogeneities corresponding to quantical fluctuations scaled-up by the inflation process.

How could we address this question within our framework? Some models of perpetual cosmic inflation predict that it produces causally independent universes; this situation is called cosmic multiverse. Some independent publication, notably (Nomura, 2011), suggest that the multiverse may be linked, or even corresponds to, the multiple worlds of QM. This proposal relies heavily on the idea that anything that is possible (in the model, but sometimes in one's imagination) will happen[59]. We will take another path.

Cosmology suggests that there are two main effects of gravitation — or space-time curvature, whatever the cause: the first one is attractive and directed, the other is (metrically) expansive and isotropic. In a symmetric situation, the balance of forces nullifies the first effect. In an early stage of the universe, before the separation of relative states (or potential worlds), such a situation occurs, leaving unbalanced the expansive component of gravitation only. Cosmic inflation is a measure of the universe's gravitational symmetry. Without our hypothesis, this symmetry is very soon destroyed and inflation is often supposed to last something like 10^{-33} s or 10^{-32} s. If our hypothesis corresponds to the experiment, the universe perceived by gravitation is much more symmetrical and homogeneous than the same universe seen by electromagnetic radiations: quantical fluctuations produce no gravitational asymmetry and so inflation may

[58] The horizon problem is that of the relative large scale homogeneity and isotropy of the universe. The flatness problem is that of the almost critical density of a flat space-time in GR. See, *e.g.* (Cohen-Tanoudji and Spiro, 2013). Observations, especially from the *Planck* satellite, confirm that the space-time curvature is under 0.005 (Planck Collaboration, 2016, p. 37–38).

[59] See, *e.g.*, the beginning of (Nomura, 2011). Sure, there is no experimental support for this — and cannot be any, by definition.

last longer. In such a situation, inflation would cease, or become negligible, when trans-world received gravitation (*i.e.* gravitation given by alternate worlds) becomes relatively small, compared to in-world inhomogeneities.

Quantitatively, we only know that this situation happens before the decoupling epoch (the CMB wall), at redshift $z \approx 1000$. To investigate further, one has to evaluate the quantitative incidence of the two effects. First, the cosmological horizon, similarly to a black-hole horizon, causally separates potential worlds, diminishing gravitational influence on each other, thus causing inhomogeneities to be unbalanced. Secondly, worlds differentiate by an effect of decoherence, causing some sort of "distance" between worlds, which we will call *modal proximity*. Let us elaborate a little further on that matter in the next section.

B. Modal proximity and mass discrepancy

1. The discrepancy between the visible and dynamical mass

As early as 1933, Fritz Zwicky noticed a large discrepancy between matter visible due to its electromagnetical emissions and dynamical mass according to observable gravitational effects[60]. This is the origin of the generic term "dark matter". "[By 1980] Astronomers in general thought in terms of rather conventionnal dark matter — cold gas, very low-mass stars, failed stars (or super planets), stellar remnants such as cold white dwarfs, neutron stars, or low-mass black holes". This conventionnal dark matter is generally called "baryonic dark matter", since most of its energy content is made of baryons. Part of this dark matter, mainly X-ray emitting gas in galaxy clusters, has now become visible; part is still invisible, but its proportion in the universe's energy content is quite precisely estimated. The WMAP satellite observations of the CMB fluctuation spectrum are in excellent agreement with a flat universe as it is today ($\Omega_{\text{total}} = 1.099 \pm 0.1$) and with the "concordance model of the Universe": $\sim 5\%$ baryonic matter, 25% cold dark matter, 70% dark energy. Observations and theoretical models of the early universe have set a constraint for baryonic matter quantity: $\Omega_b = 4\% \cdots 5\%$, so "only one-tenth of the baryons are actually shining"[61]. "The remainder of the mass-energy content of the Universe is thought to consist partly of dark matter that is unidentified, and primarily of dark energy of even more uncertain nature. The dark matter fills the Universe, promotes structure formation and accounts for the discrepancy between the visible and dynamical mass of bound astronomical systems such as galaxies and clusters; it is the major constituent of such systems." In 2009, and still today, "the candidate dark matter particles have not been detected independently of their presumed gravitational effects". Robert Sanders (2010) concludes that "the existence of dark matter remains hypothetical and is dependent upon the assumed law of gravity or inertia on astronomical scales. So it is not at all outrageous to consider the possibility that our understanding of gravity is incomplete."

2. Dark matter and modal proximity

Now, consider some potential world $\mathcal{W}$, branching in potential worlds $\mathcal{W}_0$ and $\mathcal{W}_1$ after a qubal. Whatever the observer's world, received gravitation is the sum of gravitation of matter in these two worlds, each one counted with its Born coefficient. Next, let us imagine a sequel of n qubals, leading to 2^n potential worlds, $\mathcal{W}_{i_1 i_2 \cdots i_n}$. Let us suppose, by symmetry, that the observer's world is $\mathcal{W}_{00\cdots 0}$. The longer the initial 0-sequence, the closer is a potential world to the observer's. To simplify formulation, if qubals are symmetrical, each world has coefficient 2^{-n}, but, as seen from observer's world, it's effectively $2^{-(n-\ell)}$, with ℓ the initial common history length. Let us define the *modal proximity* of a world to be the product of Born coefficients after branching from the observer's world. Modally close worlds, that is worlds with a recent shared history (*i.e.* a small ℓ), are generally more similar and have a higher modal proximity. Modally distant worlds have a lower modal proximity and may have a different distribution of matter.

Note that for general reasoning we have defined worlds on a very wide basis, encompassing all matter, but, in practice, we can use potential world model on subsystems of the universe, in as much as we can suppose them isolated enough. This allows us to define a modal proximity for individual objects. With Newtonian approximation, a body M in a potential world gives gravitation in proportion to its modal proximity and inverse squared distance.

If our trans-world gravitation hypothesis is correct, we receive gravitation from all worlds, from matter present in our world and from matter existing in alternate potential worlds. In a way, gravitation is the contribution of our world and of some sort of *gravitational shadow of alternate worlds*. In other words, this gravitational shadow acts as if it were matter (*i.e.* energy content) interacting with other matter by no other means than gravitation. Thus, it does contribute to "dark matter", even if modal proximity is quickly decreasing with qubals.

Now, let us imagine the early fluctuations that initiated the build-up of a galaxy. In modally close alternate

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[60] In this section, quotations and historical facts about dark matter and MOND without explicit reference are from (Sanders, 2010).

[61] Luminous part: $\Omega_v \approx 3‰$, X-ray emitting gas of galaxy clusters: $\Omega_g \approx 2.5‰$, so shining baryonic matter: $\Omega_v + \Omega_g \approx 5‰$. Other components can also be estimated; CMB: $\Omega_{\text{CMB}} = 5 \times 10^{-5}$, neutrinos: $\Omega_\nu \approx 3‰ \cdots 10\%$. See (Sanders, 2010) for references.

worlds, counterparts of this galaxy may have vastly different orientations and positions. In fact, if universe structures are distant descendants of quantum fluctuations, the alternate worlds should reflect that any interaction may correspond to multiple potential outcomes in multiple directions and that any subquantum trajectory line may correspond to multiple moments of interaction. At the galaxy scale, one can imagine that gravitation given by alternate worlds' counterparts produce something like a "dark matter" halo, interacting purely by means of gravitation, and with no instability problem. This may account for galactic stability and, perhaps, for the observed flat terminal rotation velocity curves of spiral galaxies[62].

Being more speculative, this might explain why large-scale structures look so much like potential interaction diagrams: alternate world galaxies populate a galaxy filament, in the modal vicinity of an initial potential particle diagram.

3. MOND and cinematic interpretation of relativity

In 1983, Mordehai Milgrom published an alternative proposal to non-baryonic dark matter: a modification of Newton's second law of motion or of Newton's law of gravitation itself[63]. In this phenomenal theory, Newtonian gravitational acceleration, $a = \frac{GM}{R^2}$, becomes $\frac{a^2}{a_0} = \frac{GM}{R^2}$ in the case of tiny accelerations: $a \ll a_0$. As of today this *Modified Newtonian dynamics* (MOND) has no theoretical foundation, but it is greatly resilient to experimental evidence. Furthermore, it explains much more phenomena than the cold dark matter model. The terminal velocity of spiral galaxies is straightforward[64]: $v^4/R^2 a_0 = GM/R^2$, so $v = \sqrt[4]{GMa_0}$. Supposing a uniform mass-to-light ratio in spiral galaxies, one can derive the Tully–Fisher relation (1977), now known to be a very good correlation between the luminosity and the terminal rotation velocity, $L \propto V^4$, and settle an experimental value for reference acceleration $a_0 \approx 10^{-10}\,\mathrm{m.s}^{-2}$. MOND also explains why surface-brightness does not exceed Freeman's limit. Last but not least, MOND accounts for the Faber–Jackson relation (1976) concerning all near-isothermal pressure-supported systems, $M \propto \sigma^4$, where σ is velocity dispersion, measured by spectral line width.

Being again very speculative, let us put forward an idea which could lead to some theoretical justification of MOND. Classical Pound–Rebka–Snider experiments confirmed that radial gravitational redshift is quantitatively equivalent to a frontal Doppler–Fizeau effect. Now, let us turn to our cinematic interpretation of special relativity and represent any quantical particle as a superposition of potential particles all displaced at the same pace magnitude (corresponding to velocity c). Each momentum is something like $\vec{p} = \frac{h}{c}\nu\vec{n}$. If it undergoes the same gravitational frequency shift as photons, $\frac{\sqrt{1-\frac{R_S}{r}}}{\sqrt{1-\frac{R_S}{r'}}} \approx 1 + \frac{R_S}{2r'} - \frac{R_S}{2r}$, one can imagine that centerward potential particles are blueshifted and outward ones are redshifted. The effect would be in the order of $\frac{\delta r}{r^2} . \frac{GM}{2c} . \frac{h}{c}\nu$, and would induce a gravitational strength in the order of $\frac{GM}{r^2}$ for higher level massive particles. One can also imagine a similar reasoning with (non-directional) redshift due to the universe expansion, $\frac{H_0.d}{c}$. If we consider radial potential particles, both effects could compensate for $\frac{H_0.\delta r}{c} \approx \frac{\delta r}{r^2} . \frac{GM}{2c^2}$, *i.e.* $H_0 c \approx \frac{GM}{2r^2}$. Sure, not all potential particles are radial: one would have to build a coherent theory out of these ideas. Heuristically, if this effect is confirmed, one can expect that something will happen to the gravitation when gravitational strength goes down to the order of magnitude of $H_0.c \approx 7 \times 10^{-10}\,\mathrm{m.s}^{-2}$ — that is the MOND order of magnitude. We could foresee a combination of these two phenomena, gravitation being dominant for high accelerations and becoming something like $\sqrt{\frac{GM}{r^2}.H_0 c}$ for small ones. This is still very speculative, but might account for the MOND phenomenal theory — which we should probably call more accurately the *Milgrom effect*.

On the galactic and sub-galactic scales, MOND explains well the observed mass discrepancy. On a larger scale, it reduces it from $\sim 6 \cdots 7$ to $\sim 2 \cdots 3$, but does not eliminate it (Sanders, 2010). So, even if the Milgrom effect is confirmed, this does not rule out the need for some sort of non-baryonic "dark matter".

Finally, the observation of the "Bullet" galaxy cluster (1E 0657–558, $z = 0.296$) showed that "[a]ny nonstandard gravitational force that scales with baryonic mass" is insufficient to account for the decoupling between the visible mass (galaxies and X-ray emitting plasma) and the map of gravitational strength (projected along the line-of-sight) by weak gravitational lensing methodology (Clowe et al., 2006)[65]. More precisely, this map suggests that "unobserved matter, whatever it is, behaves

[62] Velocity measures of gas galactic fringe in spiral galaxies show that this velocity tends to be constant, and not to decrease in a Keplerian manner (the equilibrium between centripetal and gravitational accelerations gives $v^2/R = GM/R^2$, therefore $v \propto 1/\sqrt{R}$ where $M(R)$ is constant). Cf. e.g. (Sanders, 2010).

[63] The facts in this paragraph sum up Sanders (Sanders, 2010), chap. 10.

[64] Moreover, "It even appears that details in the rotation curves are matched by the predicted MOND rotation curves" (Sanders, 2010, p. 141).

[65] Douglas Clowe *et al.* (2006) also mention that "other merging clusters, MS 1054–03 (Jee et al., 2005) and A520 (in preparation), exhibit similar offsets between the peaks of the lensing and baryonic mass, although based on lensing reconstructions with lower spatial resolution and less clear-cut cluster geometry."

like the stars and not like the hot diffuse gas — it is dissipationless" (Sanders, 2010, p. 144). This is precisely what we could expect if this "matter" is the result of the shadow gravitation given by galaxies of alternate potential worlds.

C. The cosmological constant and trans-world gravitation

1. The cosmological constant problem

For each quantum field theory, even a space totally devoid of particles (its idealized zero point state) still contains virtual particles: this is called its *vacuum*. QED vacuum, for example, is the current preferred interpretation cause for the Casimir effect. The question is: do these vacua contribute to weight? It is generally believed they do, in the form of the cosmological constant Λ (eq. 4), but this belief does not come without trouble. In their historical survey, Svend Erik Rugh and Henrik Zinkernagel (2002) "distinguish at least three different meanings to the notion of a cosmological constant problem: 1. A 'physics' problem: QFT vacuum $\leftrightarrow$ Λ [...] 2. An 'expected scale' problem for Λ [...] 3. An 'astronomical' problem of observing Λ". We will focus here on second point, named the "vacuum catastrophe" by Ronald J. Adler *et al.* (1995), noticing that "numerous papers have been written about it".

Zero point energy density is, theoretically, evaluated by counting QFT modes and applying a cutoff to elude divergence. This (strong) divergence is not *per se* an extraordinary difficulty — and it is physically somewhat understood; the "vacuum catastrophe", named after the historical "ultraviolet catastrophe", is the fact that even with a reasonable cutoff, the zero point energy density is evaluated to be way bigger than astronomical observations — and this fact is not at all understood. If we limit ourselves to the electroweak theory and set a 100 GeV cutoff, $\rho_{\text{vac}}^{\text{EW}} \sim 10^{46}\,\text{erg.cm}^{-3} = 10^{45}\,\text{J.m}^{-3}$. "This is already a huge amount of vacuum energy attributed to the QED ground state which exceeds the observational bound on the total vacuum energy density in QFT by $\sim$ 55 orders of magnitude" (Rugh and Zinkernagel, 2002, p. 676)[66]. If we set the cutoff at the Planck energy level, the same evaluation rises up to $\sim$ 120 orders of magnitude. "This is probably the worst theoretical prediction in the history of physics!"[67] Moreover, this is only for QED; accounts of other quantum field theories are extremely complicated: introducing the BEH mechanism requires a massive choice, so to say, and the overall procedure is very model dependent[68]. Finally, we should add that a huge value for the cosmological constant is coherent with the inflationary model[69].

The theoretical connection of zero point energy density and gravitation is, for the time being, highly speculative as, on the one hand, energy in QM, as in classical physics, is defined only to a constant, and, on the other hand, gravitation in GR is given by any form of energy, with an absolute value. In the future, any expected connection between QFTs and GR will have to deal with this gap[70]. At present, we know no experimental result linking gravitation and any QFT, so it is only speculative whether or not we can assimilate energy in the sense of QFTs to energy in the sense of GR. We can broaden the question, taking into account one of the best predictions of physics: gravitation is so faint, compared to "other forces" that one can compute the magnetic moment of the electron up to eleven exact digits without taking gravitation into account at all.

2. Trans-world analysis of vacuum

Can our framework shed some light on this situation? It can certainly raise some questions. Does QFT vacua exert their effects in each potential world or are these vacua trans-world phenomena? Is vacuum gravitation "diluted" with time or is it essentially time-independent? If we consider given and received gravitation, it would certainly be a surprise if QFT vacua would not give gravitation, but what could be the meaning of receiving gravitation for a fundamental state? Even more fundamentally, are the QFT vacua to be thought of as objects or as mere reification of relations between objects?

Let us first come back to the physical meaning of concepts. Reflection about motion started to be questioned rationally, in the Ancient times, by conceiving the empty space. Later, Galileo used this notion for his relativity principle, and Newton considered it a necessary basis for establishing his laws. Some notion of "free space" is also fundamental for relativity: we supposed it, implicitly, when expressing facts 1 and 2, above. Blaise Pascal, a philosopher and experimenter, made a clear distinction between empty space (*vide*, emptied space, space devoid of matter) and nothingness (*néant*): nothingness has no quality, contrary to empty space. The

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[66] Gravitational observations (in the context of a model) constrain $\rho \lesssim 10^{-9}\,\text{J/m}^3$ — see e.g. (Adler et al., 1995; Rugh and Zinkernagel, 2002).

[67] M. P. Hobson, G. P. Efstathiou, A. N. Lasenby, *General Relativity: An introduction for physicists*, Cambridge University Press, 2006, p. 187.

[68] Even in the case of QED, far better understood than QCD, the procedure is not sound: the energy density estimation depends on the cutoff — which is based on a belief — and on the regularization of a delta-function by a volume — the symmetries of which have a major incidence on the computation.

[69] The original idea of Alan Guth (1981) was that a huge vacuum energy drove the inflation.

[70] In his historical survey (1989), Steven Weinberg introduces it as a "veritable crisis".

interpretation of his experimental setups would be different today, but we can still keep the fundamental difference between a space *physically* devoid of matter and an *ideal* space-time with no content. Sticking to experimental facts, we know now that intergalactic space contains $\sim 10^{-12}\,\mathrm{m}^{-3}$ molecules. Even the extreme empty space between galactic clusters contains at least the cosmic microwave background. Closer to us, extreme laboratory empty space would certainly also contain the cosmic neutrino background[71]. So, everywhere, there is matter — or, to be more exact, a probability of the presence of matter. Vacua do not exist as physical states of a place.

In our framework, any quantical particle is a swarm of potential particles, the list of which is mostly the choice of a representation. In a way, a vacuum contributes to all quantical particles. Vacua are often presented as fluctuations in time of void space. This representation is not actually coherent: the vacuum state corresponds to the lowest energy eigenspace of the free Hamiltonian of a QFT, so it is not much a fluctuation in time (it does not change), but a variation between potential worlds. Thus, vacua should be best viewed as trans-world phenomena, and one can therefore expect that they dilute themselves with the increasing modal proximity between all worlds. If this is the case, 120 orders of magnitude would indeed not be that big, corresponding, roughly, to $log_2 10^{120} \approx 400$ symmetrical qubals. Since they are not really objects, QFT vacua do not gravitate, *stricto sensu*; the participating particles give and receive gravitation, but not the vacua themselves.

V. CONCLUSION

This paper has sketched out an assembly of puzzle pieces between Quantum Mechanics, Special Relativity, gravitation and cosmology, but a lot is still missing. To recall only some:

- The first thing to do would be to experiment and *test our hypothesis of trans-world gravitation* to better understand possible articulations of gravitation and quantical physics.

- If our hypothesis is confirmed, our framework anticipates that gravitation received from inaccessible worlds would manifest itself as *shadow gravitation* in our world and explain at least part of the inflation and "dark matter" phenomena. To go further, it is necessary to *build cosmological scenarios* and see how much of these phenomena the shadow gravitation could explain. On the contrary, would our hypothesis be invalidated, one would have to explain how gravitation could be confined to potential worlds, *i.e.* respect EVERETT's relative state separation — or, at least, behaves as if it did.

- On the theoretical side, *the cinematic justification of Special Relativity should be explored further.* We investigated only a displacement pace factor on the wave function. An interval factor might be likewise investigated.

- Finally, one has to design hypotheses about the geometry of the sub-space and its links with gravitation. A mechanism *à la* PERELMAN would be an interesting scenario of emergence of the sub-space; it could also give some clues to sub-quantical gravitation. This line of research line can be traced back to Richard S. HAMILTON's research which introduced the Ricci flow (1982) and drew a parallel with the heat equation. This parallel may have a more profound physical meaning.

[71] Estimated $\sim 5.10^{-5}\,\mathrm{m}^{-3}$ at 1.9 K on a theoretical basis (Cohen-Tanoudji and Spiro, 2013, p. 412).

REFERENCES

Ronald J. Adler, Brendan Casey, and Ovid C. Jacob. Vacuum catastrophe: An elementary exposition of the cosmological constant problem. *American Journal of Physics*, 63(7):620–626, 1995. doi:10.1119/1.17850. 19

ATLAS collaboration. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Physics Letters B*, 716(1):1–29, 2012. doi:10.1016/j.physletb.2012.08.020. 11

Françoise Balibar. *Galilée, Newton lus par Einstein.* Presses Universitaires de France, 2002. 2

Yoav Ben-Dov. *Versions de la mécanique quantique sans réduction de la fonction d'onde : la théorie d'Everett et l'onde-pilote.* PhD thesis, Université Paris XIII, March 1988. Michel Paty (dir.). 5, 8, 10

Yoav Ben-Dov. Everett's theory and the "many-worlds" interpretation. *Am. J. Phys.*, 58(9):829–832, 1990. 5

Garrett Birkhoff and John von Neumann. The logic of quantum mechanics. *Annals of Mathematics*, 37(4):823–843, 1936. doi:10.2307/1968621. 3, 7

David Bohm. A proposed explanation of quantum theory in terms of hidden variables at a sub quantum mechanical level. *Colston Papers*, 1957. 10

Douglas Clowe, Maruša Bradač, Anthony H. Gonzalez, Maxim Markevitch, Scott W. Randall, Christine Jones, and Dennis Zaritsky. A direct empirical proof of the existence of dark matter. *The Astrophysical Journal Letters*, 648(2): L109–L113, aug 2006. doi:10.1086/508162. 18

Gilles Cohen-Tanoudji and Michel Spiro. *Le boson et le chapeau mexicain.* Gallimard, 2013. 10, 16, 20

Nicolas Copernic. *Des révolutions des orbes célestes.* Diderot multimédia, 1998. Fr. trans. A. Koyré. 2

Yannis Delmas-Rigoutsos. A double deduction system for Quantum Logic based on Natural Deduction. *Journal of Philosophical Logic*, 26(1):57–67, 1997. URL http://www.jstor.org/stable/30226598. 3, 7, 8

Bernard d'Espagnat. *Le réel voilé. Analyse des concepts quantiques*. Fayard, 1994. English transl. *Veiled Reality: An Analysis of Quantum Mechanical Concepts*, Westview Press, 2003. 8, 13

Albert Einstein. Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig? *Annalen der Physik*, 323(13):639–641, 1905. doi:10.1002/andp.19053231314. 13

Albert Einstein, B. Podolsky, and N. Rosen. Can quantum-mechanical description of reality be considered complete? *Physical Review, Ser. 2*, 47:777–780, 1935. 3

Ch. Eisele, A. Yu. Nevsky, and S. Schiller. Laboratory test of the isotropy of light propagation at the 10^{-17} level. *Physical Review Letters*, 103:090401, Aug 2009. doi: 10.1103/PhysRevLett.103.090401. 10

Hugh Everett. *The Theory of the Universal Wave-function*. PhD thesis, Princeton University, 1955. URL https://www.pbs.org/wgbh/nova/manyworlds/pdf/dissertation.pdf. 5, 6, 7, 8

Hugh Everett. 'Relative state' formulation of quantum mechanics. *Reviews of Modern Physics*, 29(3):454–462, 1957. doi:10.1103/RevModPhys.29.454. 2, 5

Richard P. Feynman. Space-time approach to non-relativistic Quantum Mechanics. *Reviews of Modern Physics*, 20(2): 367–387, 1948. doi:10.1103/RevModPhys.20.367. 9

Richard P. Feynman. Space-time approach to quantum electrodynamics. *Physical Review*, 76:769–789, 1949. doi: 10.1103/PhysRev.76.769. 9

Galileo Galilei. *Dialogue sur les deux grands systèmes du monde*. coll. Points sciences. Seuil, 1992. 2

Peter F. Gibbins. A user-friendly quantum logic. *Logique et Analyse*, 112:353–362, 1985. 7

Alan H. Guth. Inflationary universe: A possible solution to the horizon and flatness problems. *Physical Review D*, 23: 347–356, 1981. doi:10.1103/PhysRevD.23.347. 16, 19

W. Heisenberg. *Physics and Philosophy: The Revolution in Modern Science*. Harper Torchbooks. George Allen & Unwin, 1958. ISBN 9780045300167. URL https://books.google.fr/books?id=VVGnSwAACAAJ. 3, 5

Robert Locqueneux. *Une Histoire des idées en physique*. Cahiers d'Histoire et de Philosophie des Sciences. Vuibert, 2009. 13

Isaac Newton. *Philosophiae Naturalis Principia Mathematica*. Pepys, London, 1687. 13

Yasunori Nomura. Physical theories, eternal inflation, and the quantum universe. *Journal of High Energy Physics*, 2011(11):63, Nov 2011. ISSN 1029-8479. doi: 10.1007/JHEP11(2011)063. URL https://arxiv.org/abs/1104.2324. 16

Constantin Piron. Axiomatique quantique. *Helvetica Physica Acta*, 37:439–468, 1964. 7

Planck Collaboration. Planck 2015 results. XIII. Cosmological parameters. *Astronomy & Astrophysics. 594: A13.*, 2016. doi:10.1051/0004-6361/201525830. URL https://arxiv.org/abs/1502.01589. 16

Karl R Popper. The propensity interpretation of probability. *The British journal for the philosophy of science*, 10(37): 25–42, 1959. 8

Howard P Robertson. Postulate versus observation in the special theory of relativity. *Reviews of modern Physics*, 21 (3):378, 1949. doi:10.1103/revmodphys.21.378. 10, 11

Svend E Rugh and Henrik Zinkernagel. The quantum vacuum and the cosmological constant problem. *Studies In History and Philosophy of Modern Physics*, 33(4):663–705, 2002. 19

Andrei D. Sakharov. Вакуумные квантовые флуктуации в искривленном пространстве и теория гравитации. *Proceedings of the USSR Academy of Sciences*, 177(1):70–71, 1967. Translated as (Sakharov, 1991). 13

Andrei D. Sakharov. Vacuum quantum fluctuations in curved space and the theory of gravitation. *Soviet Physics Uspekhi*, 34(5):394, 1991. doi:10.1070/PU1991v034n05ABEH002498. URL http://www.turpion.org/php/paper.phtml?journal_id=pu&paper_id=2498. 21

Robert H. Sanders. *The Dark Matter Problem: A Historical Perspective*. Cambridge University Press, 2010. 17, 18, 19

Erwin Schrödinger. Die gegenwärtige Situation in der Quantenmechanik. *Naturwissenschaften*, 23(48, 49, 50):807–812, 823–828, 844–849, 1935. doi:10.1007/BF01491891, 10.1007/BF01491914, 10.1007/BF01491987. Eng. tr. John D. Trimmer in (Wheeler and Zurek, 1983), p. 152–167. 9

Daniel F. Styer, Miranda S. Balkin, Kathryn M. Becker, Matthew R. Burns, Christopher E. Dudley, Scott T. Forth, Jeremy S. Gaumer, Mark A. Kramer, David C. Oertel, Leonard H. Park, Marie T. Rinkoski, Clait T. Smith, and Timothy D. Wotherspoon. Nine formulations of quantum mechanics. *American Journal of Physics*, 70(3):288–297, 2002. doi:10.1119/1.1445404. 4

Pierre Touboul, Gilles Métris, Manuel Rodrigues, Yves André, Quentin Baghi, Joël Bergé, Damien Boulanger, Stefanie Bremer, Patrice Carle, Ratana Chhun, Bruno Christophe, Valerio Cipolla, Thibault Damour, Pascale Danto, Hansjoerg Dittus, Pierre Fayet, Bernard Foulon, Claude Gageant, Pierre-Yves Guidotti, Daniel Hagedorn, Emilie Hardy, Phuong-Anh Huynh, Henri Inchauspe, Patrick Kayser, Stéphanie Lala, Claus Lämmerzahl, Vincent Lebat, Pierre Leseur, Françoise Liorzou, Meike List, Frank Löffler, Isabelle Panet, Benjamin Pouilloux, Pascal Prieur, Alexandre Rebray, Serge Reynaud, Benny Rievers, Alain Robert, Hanns Selig, Laura Serron, Timothy Sumner, Nicolas Tanguy, and Pieter Visser. MICROSCOPE mission: First results of a space test of the equivalence principle. *Physical Review Letters*, 119:231101, Dec 2017. doi: 10.1103/PhysRevLett.119.231101. 13

Lev Vaidman. On schizophrenic experiences of the neutron or why we should believe in the many-worlds interpretation of quantum theory. *International Studies in the Philosophy of Science*, 12(3):245–261, 1998. doi: 10.1080/02698599808573600. 15

Johann von Neumann. *Mathematische Grundlagen der Quantenmechanik*. Springer, 1932. Eng. trans. (von Neumann, 1955). 5, 21

John von Neumann. *Mathematical Foundations of Quantum Mechanics*. Princeton University Press, 1955. (von Neumann, 1932) eng. trans. R. T. Beyer. 4, 6, 21

Steven Weinberg. The cosmological constant problem. *Reviews of modern physics*, 61(1):1, 1989. doi: 10.1103/RevModPhys.61.1. 19

John A. Wheeler and Wojciech H. Zurek. *Quantum Theory and Measurement*. 1983. 9, 21

Clifford M. Will. The confrontation between general relativity and experiment. *Living Reviews in Relativity*, 17(1):4, Jun 2014. ISSN 1433-8351. doi:10.12942/lrr-2014-4. 14

Wojciech H. Zurek. Decoherence and the transition from quantum to classical. *Physics Today*, 44:36–44, 1991. doi: 10.1063/1.881293. 6

Wojciech H. Zurek. Decoherence, einselection, and the quantum origins of the classical. *Reviews of Modern Physics*, 75 (3):715–775, may 2003. doi:10.1103/revmodphys.75.715. 6