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## QUANTUM SPACETIME AND THE PROBLEM OF TIME IN QUANTUM GRAVITY

**Abstract.** Search for a unification of Einstein's general relativity and quantum theory in quantum gravity theory is the most important and most difficult research programme in fundamental physics since early 1980's. In this article we present motivation for the unification and some of main difficulties which prevent contemporary physicists from achieving the aim. We focus our attention on the conceptual problems regarding the notions of time, space and spacetime in quantum gravity. After explaining of why gravity should be quantized (section 1) we present the modern notions of time and spacetime according to general relativity (in section 2) and then compare them in section 3 with the concepts of time and space as they are necessary in quantum mechanics in order for the probabilistic interpretation of the theory to work. Since the concepts in both the theories are different and reconciling them in quantum gravity is extremely hard, we present in section 4 attempts to achieve a less ambitious aim, a fully quantum theory of matter in a classical gravitational field. The current idea that the conceptual problems of foundations of quantum theory may be solved with the help of quantum theory of the Universe is discussed in the last section.

**Keywords:** relativity theory — quantum theory — time — spacetime — quantum gravity — quantum cosmology.

### 1. WHY TO QUANTIZE GRAVITY?

Undoubtedly different people perceive time in different ways depending on their culture and personality. However as a physicist I deeply believe that the irreducible core of all distinct forms of time which exist in natural sciences and the humanities, prose and poetry, philosophy and art, is provided by the physical time. The notion of physical time was deeply modified in the first half of the 20<sup>th</sup> century due to Einstein's relativity theory and now, at the turn of the millennia, the notion faces again a necessity of a radical modification. An analogous modification is expected to meet the concept of physical space. In both cases the modifications will occur in the framework of quantum gravity.

What is quantum gravity? The term refers both to the whole of quantum-mechanical effects in gravitational interactions and a theory describing these effects. Quantum gravity is a curious branch of physics since up to the end of 20<sup>th</sup> century no such quantum effects have ever been observed nor does a theory of them exist. In a sense it is an empty notion. Yet the search for a theory of quantum gravity has been the main line of research in fundamental physics for the last two decades of that century and there is rather little doubt that it will be the leading factor for the development of physics in the forthcoming decades. And it should be explained to philosophers (while for physicists it is quite obvious) that the quest for a theory of unobserved phenomena does not conflict with physics being an empirical science.

Physicists seek for a theory of quantum gravity because they deeply believe in unity of the Nature and the whole history of physics supports that belief. Gravity is a universal property of matter since all forms of matter (all particles and fields) interact gravitationally — in practice a material object may be defined as one that is both affected by gravitational forces of other objects and exerts such forces upon all of them, while the three other fundamental interactions of matter, i.e. electromagnetic, weak and strong ones, are only exerted by specific species of elementary particles. There is only one more feature of matter that is universal: all matter obeys quantum-mechanical laws. Empirically it is beyond any doubt that all microscopic systems have quantum nature. Whether or not macroscopic bodies obey quantum laws, i.e. whether there is a fundamentally classic (non quantum-mechanical) world, is a subtle issue and the debate on it has not been completed. As I will show below, there are strong arguments in favor of the universal validity of quantum laws for all physical objects, even those which are traditionally regarded as classical, and this standpoint is now shared by most physicists. The conviction about the physical unity of the Nature makes it inconceivable to assume that gravity might be an exception, that the gravitational interaction (being a fundamental one) might be devoid of quantum structure and be the only strictly classical entity in the world. Of course, if gravity is not a fundamental (that is, elementary) force and is composed of other forces, then it is not so evident that it should be quantized. For instance one should not quantize the van der Waals forces acting between molecules. Nobody, however, has been successful in decomposing gravity into other known or unknown forces. Furthermore, even if gravity is a composite entity described by Einstein's General Relativity, there are convincing arguments showing that the picture of quantum matter generating a smooth classical gravitational field may be inconsistent. It seems thus unavoidable to quantize gravity, i.e. to replace the physical picture of the gravitational field as a smooth entity filling the space by that of a swarm of discrete quanta of the field, named gravitons. This picture arises from a strict analogy between gravity and electromagnetism: by quantizing the classical electromagnetic field one assigns elementary particles (being quantum excitations of the field) to it — photons; one expects that a similar effect occurs in the case of gravity. Actually this analogy may be, as we shall see, misleading or even false, but for the moment one may use it to visualize what is meant by quantum gravitational field.

It is not surprising that quantum nature of gravity, if real, remains concealed in all known laboratory and astronomical effects. In all these effects gravitational forces are weak, we have not observed yet any process where gravity is strong. It is likely that even in the regime of strong gravity it will not be easy to discern its quantum structure. By analogy: it is rather hard to show that an intense beam of light actually consists of photons and it took several years in the beginning of 20<sup>th</sup> century to prove it. Furthermore, physicists are not quite sure of how to recognise quantum effects in a strong gravitational field (besides showing that the field is actually discontinuous and is made of gravitons — and this picture, as mentioned above, may be false).

It is currently believed that the domain of quantum gravity is determined by the Planck scale, i.e. quantum effects should become conspicuous for gravitational

processes occurring in the scale of Planck units. To describe quantum gravity one needs to use three fundamental constants of physics: Newton's gravitational constant  $G$  indicating that the interaction is gravitational, light velocity  $c$  since the interaction is relativistic and Planck constant  $h$  responsible for its quantum nature. Out of these 3 constants one can define quantities bearing dimension of any physical quantity by taking appropriate powers of the constants. These quantities serve as the natural system of units for fundamental physics. The traditional units of length, time and mass, namely the meter, the second and the gram, were introduced on purely historical grounds and have no motivation in fundamental physics. The Planck units made of  $h$ ,  $c$  and  $G$ , when applied to ordinary atomic and nuclear physics, are either very small or extremely huge, indicating that they determine the natural scale only for quantum effects including gravity. Gravity, however, is negligibly weak in phenomena studied by ordinary quantum physics. Consider a collision of two electrons, each carrying relativistic energy of order of Planck energy  $E_P = (hc^5/G)^{1/2} = 10^{19}$  GeV; for elementary particles it is a huge energy as it equals to the kinetic energy of an airliner of mass 60 tons flying at velocity 900 km/h. For quantum gravity effects, however, it is insufficient to have Planck energy in a collision: disastrous collisions of airliners have occurred but no quantum effects ever appeared. To this aim the colliding particles must approach each other at a very small distance of order of Planck length  $L_P = (hG/c^3)^{1/2} = 10^{-33}$  cm, that is  $10^{20}$  times smaller than the proton diameter. This means that only point particles (like electrons or photons) are relevant, all extended objects like protons or whole atoms will not do. One may therefore expect that quantum gravity will dominate over classical (i.e. non-quantum) gravity for electrons with energy of order  $E_P$  colliding 'head-on' (at the moment of closest approach their distance should not much exceed  $L_P$ ). This clearly means that quantum gravity is very exotic for the known physics. In fact, using modern technology, to accelerate an electron to an energy comparable with  $E_P$  would need an accelerator of the size of the Milky Way! And there are no such energetic particles arriving to the Earth in the cosmic radiation. At present we can imagine only one place in the Universe where quantum gravity may actually be essential: in a vicinity of a spacetime curvature singularity, i.e. in the very early Universe just after the Big Bang and deep inside black holes, far below their event horizons. These regions are inaccessible for observations.

Since there is no empirical evidence at all for quantum gravity, its theory must be constructed on purely conceptual, theoretical grounds and internal consistency and mathematical elegance are the only guides for the theoreticians. Although the quantum structure of matter is regarded as the underlying one, physicists are unable to construct a quantum theory of some processes *ab initio*. A classical theory of the processes is essential at the outset. A procedure termed 'quantization' is applied to that classical theory which transforms it into a quantum theory. Ordinary (i.e. non-relativistic) quantum mechanics arises by quantizing classical mechanics and quantum electrodynamics arises by quantizing classical Maxwell theory of electromagnetism. If the physical object is a field rather than a mechanical system, there exists a generic scheme of quantizing a classical field theory, named quantum field theory, which correctly works for all known fields in the Nature — with the exception of gravity. In most approaches to quantum gravity Einsteinian

General Relativity (GR) is used as a starting point. In the 1990's it became very popular to replace GR by string theory; according to it the elementary objects are not point particles but very tiny loops (closed strings). Vibrations (or excitations) of a string appear as fundamental interactions and one of the vibrations represents gravity (described by Einstein field equations of GR). In this way gravity gets united with other interactions. At the end of 20<sup>th</sup> century most researchers were attempting to quantize gravity *via* quantizing string theory. However string theory has many hard problems and relativists criticise some of its assumptions. Relativists believe that GR is a more appropriate theory to be quantized.

By definition, quantum gravity should be a consistent union of GR (or possibly another classical theory of gravity) and quantum field theory (the latter is meant as a procedure of quantizing a given classical field theory). These two theories are the cornerstones of all physics and finding out their harmonious union would be highly desirable. However they are very distinct. Quantum field theory (QFT) describes elementary particles in their interactions (besides gravity) as material objects existing in a given fixed spacetime — spacetime of Special Relativity (SR). This spacetime is mathematically described by Minkowski space and I will identify the two notions. Minkowski space acts as a rigid stage upon which all physics is performed (physicists say that it is a 'fixed background' for any physical process) and it remains insensitive to any process occurring in it. This is a very good approximation to the genuine spacetime of the world around us. According to GR, however, in the presence of gravity the stage is no more fixed and rigid. It should be identified with the gravitational field itself and becomes a variable entity governed by dynamical laws, analogously to its matter content. Physical processes include both matter and spacetime, since matter interacts gravitationally and gravitational field is spacetime. The influence is mutual: matter affects spacetime and spacetime affects matter. In GR there is no fixed background with respect to which one describes dynamical processes; everything is dynamical and cannot be prescribed from the outset. This picture of the stage actively reacting to what is occurring on it is appropriate in the realm of strong gravitational fields; otherwise the approximation of SR is entirely sufficient. One then sees that QFT and GR deal with different things. What is more important, QFT is based on SR. As I will discuss in more detail later, Minkowski space is essential for QFT. In particular, quantum theory is based on the concept of time taken from SR. In some of its most essential features it coincides with the Newtonian concept of time. This means that QFT and GR in their standard formulations are incompatible. They become compatible and fit together only in the limit of vanishing gravitational interactions where GR becomes trivial and is reduced to SR. The fundamental problem of quantum gravity may be then stated as follows: *any theory of quantum gravity should describe extremely strong gravitational fields as quantum effects while quantum theory is based on concepts of time and space which are valid only for negligibly weak gravity.* From this incompatibility of the theories one infers that a theory of quantum gravity (being a consistent unification of classical gravity and quantum theory) must be radically novel. The question arises which characteristic features of each of these theories must vanish at the unification and what new concepts and categories will

appear. More specifically: what is quantum spacetime, and in particular, what is time in quantum gravity?

The idea that gravity has ultimately a quantum nature was first expressed by Einstein in 1918 in a paper on gravitational waves. For the next 30 years there appeared only few occasional works on the subject and it was only in 1950 that Paul Dirac began systematic investigations of quantization of GR. During the next half century after his pioneering works most of eminent physicists working in elementary particle physics, QFT or GR endeavoured to construct a theory of quantum gravity applying various approaches. It would be safe to state that this enormous effort of a considerable number of highest quality scholars has produced up to now a very modest outcome. At first the researchers have encountered very hard mathematical difficulties. All mathematical problems already known in QFT turned out much harder in quantum gravity. Furthermore a lot of new problems have been found. Whilst dealing with these difficulties it turned out that in most cases they arise from underlying conceptual problems. Gradually it was realized that almost all physical concepts, which are precise and reliable in ordinary quantum physics and GR, lose their precise character and actually make no sense when carried over to the domain of quantum gravity. This is the case of spacetime and time evolution of a physical system, probability, wave function (quantum state vector) and quantum measurement. There is no stable ground on which theory of quantum gravity may be based. All the attempts employing the methods developed within QFT have failed. The two most promising approaches, which are based on string theory and on the so-called loop quantum gravity (developing ideas introduced in 1987 by Abhay Ashtekar) still remain in their initial stages and are coping with a multitude of difficulties. They are very far from making any physical predictions that might in principle be experimentally tested. Using anthropomorphic terms one would say that gravity (particularly Einstein's GR) effectively protects itself from being quantized.

The best example of the difficulties is the problem of time (and closely related to it the problem of space). What is time in modern physics? As mentioned, the concept of physical time is provided by GR. In the next section I present it and in section 3 the troubles that the concept generates when quantum physics is taken into account are discussed. The rather elaborated treatment of the concept of time in GR is necessary to elucidate the problems dealt with in the last three sections.

## 2. TIME AND SPACE IN GENERAL RELATIVITY.

In GR time is not a fundamental entity, as it was according to Newton in non-relativistic physics ('absolute, true and mathematical time, of itself, and from its own nature, flows equably without relation to anything external and by another name is called duration...' — *Principia*). Time is a secondary concept defined on a fundamental object — spacetime, and since GR is a geometrically formulated theory of gravity (or better: a physically interpreted curved spacetime geometry) this concept refers to gravity and is expressed in terms of purely geometric quantities. It should be stressed at the outset that in contrast with Newtonian physics and SR, general relativity does not introduce a unique spacetime model but an infinite set of

A Collection of Polish Works on Philosophical Problems  
of Time and Spacetime

Eilstein, H. (Ed.)

2002, VII, 160 p. 3 illus., Hardcover

ISBN: 978-1-4020-0670-8