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Quantum gravity: Meaning and measurement

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ABSTRACT

A discussion of the meaning of a physical concept cannot be separated from discussion of the conditions for its ideal measurement. We assert that quantization is no more than the invocation of the quantum of action in the explanation of some process or phenomenon, and does not imply an assertion of the fundamental nature of such a process. This leads to an ecumenical approach to the problem of quantization of the gravitational field. There can be many valid approaches, each of which should be judged by the domain of its applicability to various phenomena. If two approaches have overlapping domains, the relation between them then itself becomes a subject of study. We advocate an approach to general relativity based on the unimodular group, which emphasizes the physical significance and measurability of the conformal and projective structures. A discussion of the method of matched asymptotic expansions, and of the weakness of terrestrial sources compared with astrophysical and cosmological sources, leads us to suggest theoretical studies of gravitational radiation based on retrodiction (observation) rather than prediction (experimentation).

1. Introduction

How can we combine the background-independent, dynamical approach to all space–time structures of general relativity with the quantum theory, which is based on fixed, absolute background space–time structures? That is the fundamental challenge of quantum gravity.

Most approaches to quantum gravity concentrate on the development of a formalism, and only then take up the question of physical applications of this formalism. But this division neglects one of the most important lessons that can be drawn from the history and philosophy of science. No one has stated this lesson more eloquently than Gaston Bachelard:

> In order to embody new experimental evidence, it is necessary to deform the original concepts, study the conditions of applicability of these concepts, and above all incorporate the conditions of applicability of a concept into the very meaning of the concept. … The classic division that separates a theory from its application ignores this necessity to incorporate the conditions of applicability into the very essence of the theory (Bachelard, 1938, p. 61; transl. by J.S.).

We shall discuss some aspects of the problem of quantization of the gravitational field equations in the light of the need to combine the mathematical definition of physically meaningful candidates for quantization with the description of conditions for their measurement in principle, or as we shall say, ideal measurement. Again we may draw inspiration from the words of Bachelard:

> I believe myself that mathematical thought forms the basis of physical explanation and that the conditions of abstract thought from now on are inseparable from the conditions of scientific experiment (Bachelard, 1938, p. 131, translation from Lecourt, 1972, p. 57).

What we shall present here is not a single theory, but a research program. As Imre Lakatos states in his ground-breaking paper “Falsification and the Methodology of Scientific Research Programmes”,

> Sophisticated falsificationism thus shifts the problem of how to appraise theories to the problem of how to appraise series of theories. Not an isolated theory, but only a series of theories can be said to be scientific or unscientific: to apply then

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> the term "scientific" to one single theory is a category mistake. The time-honored empirical criterion for a satisfactory theory was agreement with the observed facts. Our empirical criterion for a series of theories is that it should produce new facts. The idea of growth and the concept of empirical character are soldered into one (Lakatos, 1970).

2. What is quantization?

Given a physical theory, what elements of it to quantize is not an obvious question. First of all, one must decide what quantization means. One of us has emphasized that quantization consists of some procedure used to take account of the existence of h, the quantum of action:

> Quantization is just a way accounting for the effects of h, the quantum of action, on any process involving some system, or rather on theoretical models of such a system, fundamental or composite; in the latter case, the collective behavior of a set of more fundamental entities is quantized. Successful quantization of some classical formalism does not mean that one has achieved a deeper understanding of reality – or better, an understanding of a deeper level of reality. It means that one has successfully understood the effects of the quantum of action on the phenomena (processes) described by the formalism.
>
> The search for a method of quantizing space–time structures associated with the Einstein equations is quite distinct from the search for an underlying theory of *all* "fundamental" interactions. An attempt to quantize one set of space–time structures does not negate, and need not replace, attempts to quantize another set of space–time structures. Everything depends on the utility of the results in explaining some physical processes (Stachel, in press).

There are many such examples of different approaches to quantization of the same physical process, each successful within its range of applicability (Stachel, in press). Rather than leading to a contradiction, this leads to a new and interesting question: what is the relation between such two approaches? For example, Crenshaw has shown that there is a "limited equivalence between microscopic and macroscopic quantizations of the electromagnetic field in a dielectric" (Crenshaw, 2003). Another example is the relation between loop quantization and the usual field quantization of the electromagnetic field – if the loops are "thickened", the two are equivalent (Ashtekar & Rovelli, 1992).

3. Measurability analysis

The formal quantization procedure adopted may not be unique, and may even involve quantities, such as gauge-dependent variables, that are not measurable even in principle. But the physically significant upshot must be to single out a class of physical quantities that are measurable in principle. Following Peter Bergmann, we shall call this the problem of measurability analysis:

> Measurability analysis identifies those dynamic field variables that are susceptible to observation and measurement ("observables"), and investigates to what extent limitations inherent in their experimental determination are consistent with the uncertainties predicted by the formal theory (Bergmann & Smith, 1982).

Measurability analysis identifies those concepts that a theory defines as meaningful within some context and investigates to what extent the values associated with these concepts are ideally measurable in the defining context. It is just as applicable to classical as it is to quantum theories. For example, one can study the differing conditions of applicability of concepts such as hardness and viscosity in the context of the fluid and solid states of matter in classical thermodynamics (Stachel, 1986). One must always establish a qualitative and quantitative *consonance* between the concept of some *entity*, to which physical significance is ascribed, and an ideal *measurement procedure* for that entity.

Indeed, it seems essential to first investigate the conditions of applicability of a concept in a classical context, if it has one, before studying any modifications in the quantum context. If it is a strictly quantum concept, h must enter *both* its definition *and* measurement procedure. This division between classical and quantum concepts is not without its own problems. For example, it is often claimed that spin is a purely quantum concept, but it has been shown that a spin vector can be attached to a classical particle (Stachel & Plebanski, 1977).

When applied to a quantum theory, measurability analysis aims to predict the effect of the quantum of action on measurements: first on individual measurements and then, perhaps even more importantly, on conjoint measurements of pairs of such quantities. This should not be confused with the so-called "measurement problem" in quantum mechanics. We take the position that the task of any quantum theory is to predict the outcome of a process by calculating a probability amplitude for the process. The wave function is no more than a mathematical tool that is sometimes useful in such a calculation, and to which no ontological significance should be attributed. But regardless of one's opinion about either, the distinction between the measurement problem and measurability analysis should be clear.

The origin of measurability analysis for quantum mechanics can be traced back to the work of Heisenberg, and for quantum field theory to the work of Bohr and Rosenfeld. Indeed, as Bergmann and Smith emphasized, much can still be learned about the problems of quantum gravity from the Bohr–Rosenfeld (B–R) analysis of the measurability and co-measurability of the components of the electromagnetic field (Bohr & Rosenfeld, 1933, 1950, 1978; Darrigol, 1991). The criterion of consonance between definability and measurability of a physical quantity can play a heuristic role in the search for a viable theory of quantum gravity:

> For well-established theories, this criterion can be tested. For example, in spite of a serious challenge, source-free quantum electrodynamics was shown to pass this test. In the case of quantum gravity, our situation is rather the opposite. In the absence of a fully accepted, rigorous theory, exploration of the limits of measurability of various quantities can serve as a tool to provide clues in the search for such a theory: If we are fairly certain of the results of our measurability analysis, the proposed theory must be fully consistent with these results (Amelino-Camelia & Stachel, 2009).

The first important conclusion that can be drawn from B–R is that the field components at a point are not measurable. Even an ideal measurement involves a finite region of space and takes a finite amount of time. In a word: only averages over some region of space–time are measurable and such a measurement requires a four-volume element. This is just what B–R did in their analysis of the measurability of the components of the electric and magnetic fields.

The second important conclusion that can be drawn from (B–R) is that co-measurability of averages over two time-like-separated regions must be investigated. This suggests that formulations of a theory based on canonical commutation relations on a space-like hypersurface may not be the best starting point for an approach