Continuous and Discrete Aspects of Nature

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Abstract

The aim of this essay is to try to provide an open-minded look at some of the problems in fundamental physics which resulted from the idea of quantization. The sole reason for this attempt is to examine whether those problems might have been caused by an implicit exclusion of the correct, but radical and counter-intuitive research directions. Three topics will be discussed – (i) the nature of the quantum object, (ii) quantum gravity, and (iii) whether or not the Planck scale implies discreteness of spacetime itself.

1 Introduction

It is often stated that modern physics can be regarded as a triumph of the ancient idea of atomism. And indeed the apparent continuity of matter and electromagnetic radiation at the macroscopic scale of the world is now regarded only as an emergent phenomenon. At the quantum scale both matter and radiation are granular – electrons, quarks, and photons, for example, are regarded as indivisible entities without further structure. At first sight it seems Nature exhibits a simple interplay between continuity and discreteness – at a given level reality is continuous, but at a more fundamental level, it is discrete.

However, this apparent simplicity is quite illusory. First, it turned out that the twentieth century 'atoms' have a very bizarre behaviour. Quantum objects – for example, photons (the quanta of the electromagnetic field) and electrons (the quanta of the electron field) – demonstrate both continuous (wave-like) and discrete (particle-like) features. Single photons and single electrons behave like a wave when they pass through both slits of a double-slit interference experiment, but are always registered like particle-like entities (every single photon or electron hits the screen behind the double slits at a specific location). Electrons can also perform 'tunnelling' and 'quantum jumps' in atoms (which almost succeeded in making Schrödinger regret his involvement in the development of quantum mechanics).

Second, although the fields of three of the four fundamental forces in Nature – the electromagnetic force (mediated by the photon), the weak force (mediated by the W and Z 'particles'), and the strong force (mediated by the gluon) – have been successfully quantized, the quantization of the fourth fundamental interaction – gravity – turned out to be notoriously problematic. Unlike the electromagnetic field, which is regarded as continuous at the macroscopic scale (as described by the classical Maxwell electrodynamics) but quantized at the quantum scale, the gravitational field stubbornly refuses to get quantized.

Third, the existence of a Planck scale is often interpreted to imply that spacetime itself is not continuous at that scale. Such an interpretation seems to be fully in line with the enormous success of quantum physics in the twentieth century, which appears to suggest that everything should be quantized. However, in the case of spacetime, assuming that it is continuous at all scales – an assumption that is usually regarded conservative – might turn out to be radical.

Section 2 addresses the question of the nature of quantum objects and asks whether an *implicit* assumption – that the quantum object exists *continuously* in time – might have been responsible for the apparent quantum paradoxes. Section 3 asks another heretical question – whether the failure to arrive at a theory of quantum gravity might have been caused by taking for granted that gravity is a fundamental interaction of the type of the other three fundamental interactions. Section 4 deals with the question of the status of spacetime at the Planck scale and points out a serious conceptual difficulty that any attempt to quantize spacetime should overcome.

2 On the Nature of the Quantum Object

As quantum theory gives us only probabilities of experimental outcomes it is often stated that it tells us nothing about the nature of the quantum objects involved in the experiments and therefore the question "What is the quantum object?" is incorrect or metaphysical at best. Such a position is rather paradoxical because at the same time particle physics is studying the properties of quantum objects and trying to discover new 'particles' predicted by the Standard Model (most recently – the famous Higgs boson). I think everyone would agree that we will never gain deep understanding of the world if legitimate physical questions – such as those of the nature of the entities living at the quantum scale – are ignored by labelling them metaphysical or philosophical.

What is ultimately responsible for all apparent quantum paradoxes is the wave-particle duality of quantum objects. Feynman notably acknowledged the weirdness of quantum phenomena – "I can safely say that nobody understands quantum mechanics" [1, p. 129]. From time to time Feynman's admission is downplayed by saying that he was joking. Ironically, that could have been precisely the case – Feynman might have really joked, especially given the fact that one can only joke about a problem so intractable that all attempts to find a solution have failed so far.

To demonstrate that indeed nobody understands quantum mechanics let us consider the same interference experiment – the double slit experiment – which Feynman discussed and "which has been designed to contain all of the mystery of quantum mechanics" [1, p. 130]. This experiment has been performed with *single* electrons and photons (one electron or photon at a time) and an interference pattern has been observed [2]-[5]. This can be only explained by the wave-like behaviour of *individual* electrons and photons – every *single electron and photon goes through both slits at the same time and then interferes with itself* before hitting the screen behind the slits at a specific *location*.

The mystery is so disturbingly obvious – how can a photon or an electron, which is registered as a *localized* entity (and only where the bright fringes of the interference pattern are formed) go through *both* slits? Feynman's advice is [1, p. 129]:

> Do not keep saying to yourself, if you can possibly avoid it, 'But how can it be like that?' because you will get 'down the drain', into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that.

Feynman appears to have given up the hope that we will be able to solve the mystery and understand the strange world at the quantum scale. But to help anyone who studied the quantum phenomena he suggested that a working strategy would be to merely accept their absurdity [6]:

> The theory of quantum electrodynamics describes Nature as absurd from the point of view of common sense. And it agrees fully with experiment. So I hope you can accept Nature as She is – absurd.

Feynman's advice might be a good temporary strategy to continue the quest for understanding of the quantum world, but no real advancement would be possible without a genuine understanding of the intimate mechanism of quantum phenomena. Another good strategy is to carry out rigorous conceptual analyses of the existing theoretical and experimental evidence, one of whose aims is to identify some implicit assumptions, which might have been leading to apparent paradoxes. Although there have been some signs of a doubtful tendency in fundamental physics in recent decades – that such analyses are rather old-fashioned – the history of physics (especially the contributions of Galileo, Newton, Einstein, and the founders of quantum physics) has convincingly demonstrated that conceptual analyses are physics at its best.

Let us see how a brief conceptual analysis of the interference experiments with single photons (or electrons) can help us identify what appears to be an important implicit assumption, which may hold the key for a breakthrough in our true understanding of the quantum phenomena. Let me start with Dirac's brilliant conceptual analysis of interference of photons, which helped him arrive at the conclusion that every single photon of a photon beam should participate in both components of the split beam and should interfere only with itself [7]:

> Suppose we have a beam of light consisting of a large number of photons split up into two components of equal intensity. On the assumption that the intensity of a beam is connected with the probable number of photons in it, we should have half the total number of photons going into each component. If the two components are now made to interfere, we should require a photon in one component to be able to interfere with one in the other. Sometimes these two photons would have to annihilate one another and other times they would have to produce four photons. This would contradict the conservation of energy. The new theory, which connects the wave function with probabilities for one photon, gets over the difficulty

> by making each photon go partly into each of the two components. Each photon then interferes only with itself. Interference between two different photons never occurs.

Although there have been attempts to question Dirac's conclusion – that a photon can interfere only with itself – there exists undeniable experimental evidence supporting that mystery. Even the evidence from our daily experience is overwhelming – no mobile telephones and no radio and TV broadcast would be possible if *different* photons did interfere. We, as species, would not have survived if Dirac's analysis and conclusion were wrong because in such a case photons reflected by different objects would interfere before hitting our eyes' retina and we would be unable to see the world properly.

So the mystery that every photon and electron in the interference experiments with single photons and electrons passes through both slits and interferes only with itself is an experimental fact. The question is whether it is really a mystery which we should merely accept and give up any attempts to solve it. Let us start with what is undeniable – every electron, for example, (i) goes through both slits, and (ii) is registered as a localized entity. What appears to cause the mystery is the belief that such a localized entity somehow goes through both slits. However, that belief is based on the implicit assumption that if the electron hits the screed behind the slits as a localized entity, it was such an entity before that as well. More specifically, the implicit assumption is that an electron exists as a localized entity at *all* moments of time, i.e. that an electron exists *continuously* in time as a localized entity. In other words, the mystery is caused by the belief that an electron is after all a particle (since it *appears* to be registered as such), which continuously exists in time, but somehow passes through the two slits.

If we replace the identified implicit assumption (continuous existence in time) and replace it with its (now obvious) alternative – that an electron exists *discontinuously* in time as a localized object – the mystery disappears at once since the appearing and disappearing constituents of the *same* electron can go through all slits at their disposal and then reunite (the electron interferes with *itself*), but always hit the screen as localized (particle-like) entities.

The idea of bringing the concept of atomism (more specifically of discreteness) to its logical completion – discreteness not only in space, but in time as well – was proposed in the eighties (see [8]) but unfortunately remained unnoticed. I think it is worth examining this radical idea by testing its predictions [8] and eventually deducing new ones. Its careful examination is especially warranted by the fact that the assumption that electrons (and quantum objects in general) do not exist continuously in time appears to provide unexpected but reasonable conceptual answers to probably all quantum puzzles. Here, in addition to the double-slit-type experiments, I will list only three examples (for a little more detailed conceptual account of the idea that quantum objects may exist discontinuously in time see [9, Ch. 10]):

- The mysterious Compton frequency of the electron $f_C = m_e c^2/h \approx 10^{20} s^{-1}$ can be interpreted as the frequency of appearance / disappearance of the electron's constituents.

- Superposition, quantum jumps, and tunnelling can be consistently explained by the assumption that what was regarded as a spatially indivisible electron might in fact have a structure in time (rather in spacetime).
- The idea of discontinuously existing quantum objects also provides a surprisingly coherent explanation of what has been regarded as a serious problem of modern physics – the apparent contradiction between the deterministic theory of relativity and the probabilistic quantum theory. Although special relativity is not fully applicable at the quantum scale (since its equations of motion manifestly fail to describe the behaviour of the quantum objects), spacetime is still the arena at that scale. If not only Minkowski's mathematical four-dimensional representation [10] of Einstein's special relativity, but also his view of the Universe as an absolute four-dimensional world (spacetime), are fully taken into account [9], [11], the apparent contradiction between relativity and quantum physics is resolved. An electron, for example, is represented in spacetime not by a classical (non-quantum) worldline, but by 'points' (the 'points' of its 'disintegrated' worldline), which are probabilistically scattered all over a spacetime region where the electron wavefunction is different from zero. So the behaviour of an electron can be described only in terms of probability, but on the other hand the whole history of the electron in time (the probabilistic distribution of all of its constituents, representing the electron at all moments of its history) is *forever given* in spacetime as a 'frozen', or perhaps more appropriately, as a 'predetermined' probabilistic distribution.

3 Can Gravity be Quantized?

To see that there is a serious conceptual (foundational) problem to quantize the gravitational interaction, it is not even necessary to discuss the specific problems which the attempts to create a theory of quantum gravity encounter (for a recent account of the different approaches to quantum gravity see [13]).

According to Einstein's general relativity gravity is not a particle field – it is a manifestation of the non-Euclidean geometry of spacetime. One might be tempted to say that gravity is still a field but geometric. However, even this cannot be defended since the concept of a field implies some interaction, whereas what is called 'gravitational interaction' in general relativity has nothing in common with the other fundamental interactions.

In Einstein's general relativity the planets do not interact in any way with the Sun since they move by inertia – their worldlines (or rather worldtubes) are geodesics (representing inertial motion), but due to the curvature of spacetime caused by the Sun's mass the planets' worldtubes are helixes around the worldtube of the Sun (which in the ordinary three-dimensional language means that the planets orbit the Sun while moving by inertia). As motion by inertia does not imply any interaction one cannot properly talk about gravitational interaction in general relativity.

Then the obvious question is how gravity can be quantized given the fact that there is nothing to quantize – gravity is not a particle field and there is no gravitational energy-momentum (reflected in the fact that the mathematical formalism of general relativity does not contain an energy-momentum tensor in full agreement with the physical interpretation that gravity is curvature of spacetime).

Perhaps the strongest evidence that gravity is a manifestation of the non-Euclidean geometry of spacetime as described by Einstein's general relativity is the *experimental fact* that bodies falling toward the Earth's surface *offer no resistance to their fall.* Einstein regarded the realization of this fact – that "if a person falls freely he will not feel his own weight" [12] – as the 'happiest thought' of his life.

The experimental fact that bodies falling toward the Earth's surface move by inertia (non-resistantly) is most important for the question posed in the title of this section, because any alternative representations of general relativity aimed at making it amenable to quantization will contradict this experimental fact, if they regard gravity as some *physical* field giving rise to a gravitational *force.* One might object to such a contradiction by saying that the gravitational force acting on a falling body is balanced by some inertial force. Such an objection would be an unfortunate misunderstanding because in such a case the falling body would still resist its fall in contradiction with the experimental evidence. When one sits in a car making a turn, the centripetal force acting on his body is balanced by the inertial centrifugal force, but the person's body still resists its acceleration (changing the direction of its velocity) and that resistance is precisely the centrifugal (inertial) force, which should be overcome by the centripetal force in order that the car makes a turn. In general, when a body is accelerated by a force, the force is balanced by the inertial force coming from the the body, which resists its acceleration (the body's inertial mass is the measure of that resistance). Therefore, the experimental fact that a falling body does not resist its fall does prove that the body is subjected to *no* gravitational force, which would be necessary only if the body resisted its fall (in order to overcome that resistance).

Although the fact revealed by general relativity – that there is no gravitational interaction – and its immediate implication that gravity is not a fundamental interaction of the type of the other fundamental interactions, might be too heretical to some, I think it should be seriously examined. The need for such an examination is demonstrated not only by the experimental evidence, but also by the failure so far to construct a quantum theory of gravity.

In fact, there is one more reason of why I think such a radical option should be given proper consideration. Sometimes some physicists say "Oh, this is simply a matter of description. We can equally well describe gravitational interaction in terms of spacetime curvature and in terms of a gravitational force." Unfortunately, such an approach is a sure recipe for making no progress. The physics behind the two descriptions is fundamentally different – as gravity is either a force or a manifestation of the curvature of spacetime we should find predictions that would allow us to distinguish between the two descriptions *experimentally.* And we do have at our disposal such a piece of experimental evidence – if gravity were a force a falling body would resist its fall (its being subjected to the gravitational force causing its fall), but it does not.

A thorough examination of whether or not gravity is a fundamental interaction would also make it possible to properly approach the open question of how matter curves spacetime and to determine what kind of interaction is involved in that phenomenon.

4 Can Spacetime be Quantized?

Over a hundred years ago (in 1899) Max Planck noticed (see [14]) that the combination of three fundamental constants c, G, and h (the speed of light, the gravitational constant, and the Planck constant) yield some characteristic values for length and time (with $\hbar = h/2\pi$):

$$L_P = \left(\frac{\hbar G}{c^3}\right)^{1/2} = 1.6 \times 10^{-35} m$$

$$T_P = \left(\frac{\hbar G}{c^5}\right)^{1/2} = 0.5 \times 10^{-43} s$$

and also for mass and therefore for energy as well. In recent years, especially in view of the so far unsuccessful attempts to create a quantum theory of gravity, there have been speculations that the existence of a Planck scale would imply that spacetime itself might be granular at that scale.

There are many issues involved in any comprehensive study of the physical meaning of the Planck scale and its possible implications – (i) whether L_P and T_P reflect anything from the real world, (ii) if the Planck scale does reflect an objective physical scale, what its physical meaning is (in fact, there are at least two possibilities that can be deduced from the Planck length, for example: "the Planck length should be a sort of fundamental minimum – either a minimum physically meaningful length or the length at which spacetime displays inescapable quantum properties, that is, the classical spacetime continuum concept loses validity" [14]), etc.

If it turns out that the granularity of spacetime at the Planck scale is a serious option perhaps two of the immediate questions which will require special attention will be:

- The pressure to resolve the debate on the nature of spacetime – whether spacetime is something (an entity) or it is only a mathematical continuum representing relations between physical objects – will be sharply increased. The natural argument will be – in order to be quantized, spacetime should be something. A similar argument comes from general relativity – in order to be curved, spacetime should be something. Those who hold that spacetime is a non-entity will have a hard time defending such a view. Moreover, no answer has ever been given to the old question in the case of space (which fully applies to spacetime as well) – if space is nothingness, what separates physical bodies (planets, for example)?
- The status of the theory of relativity (particularly special relativity) will need a thorough re-examination to see whether it breaks down at the Planck scale or should be extended (see [15]).

Here, however, I will briefly discuss a conceptual argument, which I think should be addressed by anyone involved in the attempts to explore the world at the Planck scale. I would like to stress that this is a real and relevant argument and cannot be brushed aside by merely calling it metaphysical or philosophical.

Whenever we talk about discreteness it is implicitly assumed that what is discrete exists in an underlying continuous reality – spacetime has been regarded as such a reality (before Minkowski's four-dimensional representation of special relativity space was believed to be such a continuous reality). The profound question is whether we can have granularity of a *physical* entity without presupposing the existence of a continuous *physical* background. I will revisit an ancient argument, which deals with this question in its most general form, and which turns out to be amazingly relevant to the very possibility of quantizing spacetime itself.

The ancient argument was formulated by the Eleatic philosopher Parmenides over twenty five centuries ago. The Eleatics believed that being (what exists) is continuous and that nothing can come into or go out of being because it would contradict a basic postulate – being exists, non-being does not exist – which can be deduced from what we perceive: "there are signs aplenty that, being, it is ungenerated and indestructible, whole, of one kind and unwavering, and complete. Nor was it ever, nor will it be since now it is, altogether, one continuous" [16].

The Eleatic argument that what exists should be continuous is strikingly simple and powerful (we can be truly proud of our smart ancestors!) – if being were not continuous, it could be separated either by being or non-being, which is impossible since being cannot separate being (as, for example, water does not separate water), whereas non-being does not exist. Stated a bit differently, the Eleatics had been saying something unbelievably profound – what is common in the uncountable variety of objects in the world is their *existence*; nothing can separate one area of the existing world from another area and in this sense being is indeed continuous (the Eleatic argument implies that spacetime should be an existing physical entity).

By the same argument, if spacetime were not continuous, but granular, what would separate the different quanta of spacetime? Should we assume that there exists an ultimate underlying reality which is continuous? And if so, how would it differ from spacetime?

Conclusion

The purpose of this essay is to show that studying the interplay between continuous and discrete aspects of Nature requires a careful approach since in fundamental physics that interplay might turn out to be quite unexpected. This is done by discussing three topics – (i) what the quantum object might be, (ii) whether quantum gravity is in principle possible, and (iii) whether the Planck scale should be interpreted to necessitate quantization of spacetime itself – and suggesting that some of the problems in these examples might have been caused by implicitly excluding the correct, but radical and counter-intuitive ideas.

References

[1] R.P. Feynman, *The Character of Physical Law* (MIT Press, Massachusetts 1967)

[2] P. Grangier, G. Roger and A. Aspect, Experimental evidence for a photon anticorrelation effect on a beam splitter: a new light on single-photon interferences, *Europhys. Lett.* **1** (1986) 173–179

[3] W. Rueckner and P. Titcomb, A lecture demonstration of single photon interference, *Am. J. Phys.* **64** (1996) 184–188

[4] A. Tonomura, J. Endo, T. Matsuda, T. Kawasaki, and H. Exawa, Demonstration of single-electron buildup of an interference pattern, *Am. J. Phys.* **57** (1989) 117–120

[5] G. Greenstein and A.G. Zajonc, *The Quantum Challenge* (Jones and Bartlett, Sudbury, Massachusetts 1997)

[6] R.P. Feynman, *QED: The Strange Theory of Light and Matter* (Princeton University Press, Princeton 1985) p 10

[7] P.A.M. Dirac, *Principles of quantum mechanics*, 4ed. (Oxford University Press, Oxford 1958) p 9

[8] A. H. Anastassov, Self-Contained Phase-Space Formulation of Quantum Mechanics as Statistics of Virtual Particles, *Annuaire de l'Universite de Sofia "St. Kliment Ohridski", Faculte de Physique* **81** (1993) 135–163

[9] V. Petkov, *Relativity and the Nature of Spacetime*, 2nd ed. (Springer, Heidelberg 2009)

[10] H. Minkowski, Space and Time. New translation by D. Lehmkuhl in: V. Petkov (ed.) *Minkowski Spacetime: A Hundred Years Later* (Springer, Heidelberg 2010) pp xiv–xlii

[11] V. Petkov, On the Reality of Minkowski Space, *Foundations of Physics* **37** (2007) 1499–1502

[12] A. Pais, *Subtle Is the Lord: The Science and the Life of Albert Einstein* (Oxford University Press, Oxford 2005) p 179

[13] D. Oriti (ed.), *Approaches to Quantum Gravity: Toward a New Understanding of Space, Time and Matter* (Cambridge University Press, Cambridge 2009)

[14] R.J. Adler, Six easy roads to the Planck scale, *Am. J. Phys.* **78** (2010) 925–932

[15] G. Amelino-Camelia, Doubly-Special Relativity: Facts, Myths and Some Key Open Issues, *Symmetry* **2** (2010) 230–271

[16] J. Barnes, *Early Greek Philosophy* (Penguin Classics, London 2001), 2nd ed., p 82