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PHYSICS

Don't Ask Pythagoras about the Quantum

MASSIMO PAURI

Physics Department, Theoretical Division, University of Parma, Parco Area Scienze, 7/A – Parma
43100, Italy; E-mail: massimo.pauri@fis.unipr.it

The essay of Mario Bunge shows a broad and demanding outlook of quantum theory, with particular emphasis on the assertion of two main theses (historical continuity of 'quantizations' and realistic bearing of the theory), together with several scattered remarks on minor points. I agree with many of Bunge's remarks on minor points, I have a different but definitely not antagonistic stance about his realist view of the quantum world, but I disagree – and I believe for deep and maybe unhealable ontological reasons – with his major claim, which is summarized in the conclusion of the Essay:

To sum up, quantum physics is twenty-five century old, not just one. Moreover, and this is crucial, the trademark of the new physics is not quantization, since this is also a property of things as ordinary as drums, elastic beams, electrically charged clouds, and batteries (p. 463, this issue).

Nearly all of my contentions are consequences of the position I take on the main issue, which I shall first address.¹

In brief – contrary to Mario Bunge's main thesis – I claim that the discovery of the *quantum of action* (Planck 1900) and the formulation of quantum theory represent a milestone of absolute novelty in the history of knowledge and, in particular, in the history of atomism. With the advent of quantum theory it happened for the first time that a major scientific discovery directly disproved a general view of the world, namely the very terms in which the historical tradition of atomism developed. The discovery of the *quantum* constitutes a factual response to the more than two-thousand year-old philosophical question about continuity, discreteness, and divisibility of matter. Quantum theory tells us that matter (in the more general sense of matter-energy) possesses neither a continuous nor a discrete structure, but a peculiar quantum structure instead. Mario Bunge is perfectly right in saying that quantum theory does not represent a triumph over the plenism of Aristotle and Descartes, but, on my reading, the crucial point is that quantum theory gives a definitive blow to the very atomistic conception of Nature. So I believe that asserting in addition: "The resulting view resembles somewhat Descartes's, which was also a synthesis of Aristotelian plenism and Democritean atomism" [computability aside] (p. 456, this issue), is rather misleading. For these reasons, which I shall

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examine in deeper detail in what follows, I cannot see any continuity at all in the manifestations of specific “quantizations” appearing here and there in the history of mathematics and physics and the *quantization* – better called *atomization* – of action which is the basic ontological fact of modern quantum theory.

According to Bunge’s account

In fact, the first to discover quanta² was not Planck in 1900, but Pythagoras in the 6th century B.C. He did so while studying vibrating strings such as a harp’s. Indeed, he found that the frequencies of such a string are integral multiples of a basic frequency or harmonic (p. 445).

I consider this statement to be incorrect. The configuration of a vibrating string is completely defined and described in space and it evolves in time in a continuous way. The notion of a string’s frequencies surfaces through a mathematical analysis of its configuration (in ‘momentum space’), however it adds nothing new, i.e., nothing which is not already contained in the spatiotemporal description of the string. In this sense, the existence of a fundamental frequency is not essential or irreducible. As a matter of fact, this sort of ‘quantization’ is linked to a given physical system (the string) and depends on specific and absolutely contingent particulars of it, like its length and mass density: in other words, it is not *universal*, in any sense.

Now, the fundamental historical event I mentioned before has been the discovery that the action was made up of indivisible units (*quantum*), measured by the Planck constant $\hbar$. It is important to realize that the action is a theoretical entity (of the classical description) which is neither a spatial or temporal entity nor a property of things, and encodes both spatiotemporal and dynamic components. In Bunge’s ontological terms this kind of atomization could be referred to as a *property of sequences of changes of things*.³ In other words, what turned out to be atomized were *processes* instead of *things*: the true atom of contemporary physics is the quantum of action. It should hardly be emphasized that this concerns any kind of physical action and is therefore as universal as it may be.⁴ Also, this is a fact of the world, confirmed by a century of sophisticated experimental work, even if I believe that the consequences of this fundamental achievement of knowledge about the real world have not been drawn and exploited fully in quantum theory so far: certainly not within the formulation of the non-relativistic theory. New fundamental aspects have emerged in the relativistic quantum field theory and further radical conceptual novelties already appear in the relativistic string theory (RQFT). Finally, even more deep consequences could be expected in the searched-for synthesis of quantum theory and general relativity.⁵

Let us consider the whole history of atomism. The paradoxes of the notion of an atom, construed from the beginning as an indivisible element of a homogenous extension, have been widely known since Zeno, through Descartes, and up until Kant. It is crucial to recognize that this paradoxical issue had constantly to do with the nature and intuition of space (possibly intertwined with the issue of the reality of mathematical structures). As is well-known, the most thorough philosophical analysis of the issue, which can also be viewed as the issue of divisibility and the relation *part-whole*, is contained in Kant’s *Second Antinomy of Reason*. In both

the proofs of the thesis and the antithesis, Kant refers to the debate on atomism that took place during the 17th and 18th centuries, mainly due to Descartes, to the English empiricists, to Wolff, Euler, Leibniz and Clarke. With the remarkable exception of Leibniz, the whole historical debate concerned what I would like to call *naïve* or *spatiotemporal* atomism. To grasp the point without entering the sophistications of the Kantian transcendental arguments, it is enough to recall here the spatial argument of Descartes:

D'autant que si petites qu'on suppose ces parties, néanmoins parce qu'il faut qu'elles soient étendues, nous concevons qu'il n'y en a pas une entre elles qui ne puisse être encore divisée en deux ou en un plus grand nombre d'autres plus petites ... (Descartes 1724)

Also, all conflicting positions about atomism, until the 18th century (Leibniz aside), were determined by their relying both on the *spatial interpretation* of the part-whole relation and on the traditional concept of substance, which reduced the composition of material things in terms of a spatial relation of substantial individuals. If, however, atoms are spatially extended, the very possibility of conceptually distinguishing between their parts confers upon them, as it were, some kind of secondary qualities, some kind of differentiating factors that are properly distinctive features of the phenomenal things which atoms are supposed to explain. In other words, although it does not constitute a logical difficulty, it turns out that, if spatially extended, physical atoms cannot be those *simple* entities that they are imagined to be. Partly because of these reasons, both in classical theories and in quantum theory the prevailing view – at the pragmatic level – has always been based on a characterization of the extension of a compounded system in terms of internal interactions among 'elementary' constituents, which are first individuated and then grouped together. According to these interpretations, the part-whole relation is treated partly as spatial and partly as dynamical. And while the 'elementary' constituents of the compound are pragmatically held to be indivisible at a given level of approximation, space itself, as an extension within which the composition is described, is a presupposed background in the traditional Newtonian form of a 'real compositum' and thereby divisible *ad infinitum*.

Now, let us come back to the essence of the quantum revolution: the atomisation of processes. I shall stress only the main aspects of the issue. Let us consider a whole as aggregate of putative parts and an inner dynamical process within it. In traditional classical terms, this process would be conceived as an interaction of parts which exchange energy and momentum across space in the course of time, i.e., a system of parts 'exchanging action'. Now, first of all, the atomization of the action entails that there cannot exist real processes corresponding to exchanges of action smaller than the Planck constant. Even more, the *elementary quantum act* (corresponding to the exchange of a single quantum of action among the putative parts of the whole), cannot be described in any possible *local* way within space-time: in a deep sense, since it is *simple*, literally it *does not belong to* space and time. Actually, were a continuity of spatiotemporal description of the parts conceiv-

able, one would be able to reconstruct processes with arbitrary exchanges of action, since this latter is a continuous function of the physical system configuration.

In conclusion, *stricto sensu*, the parts cannot be described in any local way as entities in spacetime and they lose their traditional individuality: as a matter of fact they are no longer *fully qualified substantial individuals*, i.e., they are not *things* in Bunge's sense. If the parts were things the action could not be atomized!

Furthermore, even if, *prima facie*, no restriction whatsoever seems to be put by process atomization upon the mathematical description of space and time, which, as Mario Bunge correctly remarks, are not touched by (present day) quantum theory, restrictions on the ordinary spatiotemporal language necessarily emerge. Heisenberg inequalities (here too Bunge is perfectly right in criticizing the ambiguity often appearing in the literature about the so-called 'uncertainty' or 'indeterminacy' allegedly entailed by these inequalities) reflect precisely the conceptual tension arising between the symbolic structure that replaces the forbidden spatiotemporal (local and complete) description of the putative parts, on the one hand, and the unavoidable utilization of a causal, spatiotemporal ordinary language at the level of the experimental basis of the theory, on the other hand.

Consider, for example, a single atomic transition between two nearby energy levels of a hydrogen atom induced by some perturbation. Since its spatiotemporal description is *ontologically forbidden* by the quantum principle, the process is represented in the following way: The atom's state vector evolves into a coherent superposition of the atom's state vectors corresponding to the nearby energy levels until an observation of the imperturbed system is eventually performed at time t . During the intermediate period, no objective energy attribution property is possible and the energy values can be referred to only 'potentially'. Thus the transition is treated by means of a linguistic circumstantial compromise in terms of the so-called 'uncertainty' ΔE and Δt of the 'energy values' and the 'moment of transition', in the form of the quantitative limitation $\Delta E \cdot \Delta t \geq \hbar$. In other words, instead of describing the transition, one expresses the probability that the transition has taken place at a certain time, under the constraint of action atomization. Yet, it would be wrong to attribute a duration Δt to the elementary quantum act involved here ('quantum jump') which must be instantaneous (see below).⁶ The implications of process atomization, as well as the relationship between the latter and the *principle of coherent superposition*, are shown here in an exemplary manner.

I therefore believe that, while Bunge is right in asserting that there is no question of uncertainty or indeterminacy of (pre-existing) values of energy, as well as that there is no spread of values of time (which is a classical parameter and not an operator at all), or in denying that these spreads are an effect of measurement, he is wrong when he says (p. 446) that the superposition principle of quantum theory is nothing else than a common feature of linear wave theory⁷ and, even more, when he adds "The expression 'quantum jump' has of course been with us ever since. However, let us not forget the injunction, *to try to analyze every such jump as a continuous albeit swift process*" (p. 448, my italics). Indeed, were this

analysis possible, the whole essence and conceptual structure of quantum theory would be falsified and would collapse. I want to insist on this fundamental point: a non-instantaneous single 'quantum jump' would open the conceptual possibility of a spatiotemporal description of its course, which is irreconcilable with action atomization⁸. As Mario Bunge declares concerning other features of quantum theory, "[it] exhibits counter-intuitive facts, ... and we had better come to terms with [them]". However unpalatable it may appear, the 'quantum jump' must be *instantaneous* because, as it were, it does not belong to the time continuum. Likewise, it entails in general a sudden transition from a non-local spatial description of the quantum state to a spatiotemporal highly localized phenomenon of absorption or revelation of a 'quanton' (to use Bunge's terminology). The absorption or spatiotemporal revelation necessarily takes place in *units*, as the absorption of a photon in a Mach–Zender interferometer exemplarily shows.

Note that the relation between the mathematical description of the quantum state and the revelation process *qua numero* is the very source of the peculiar objective (ontological) chance of quantum theory. The traditional, spatiotemporal, or naïve atomism of 'things' was highly antinomical. Although the atomism of processes is less antinomical, it is not free of unavoidable paradoxes which are still generated by our 'intuition' of space and time as homogeneous extensions. I think we can do nothing other than to "come to terms with them", although, I suspect, such terms are not easily reconcilable with Mario Bunge's basic ontology of things.

Let me add some remarks concerning important achievements of the RQFT. It is true that "As for the virtual particles and virtual photons ... [they] and the shady transitions in which they are allegedly involved are seen to be idle fictions" (Bunge, 1977, p. 159). Indeed it is possible but not necessary to interpret quantum field interactions in terms of intermediate *virtual* entities, but the crucial point is that the picture emerging from relativistic quantum field theory undermines the very distinction between any kind of putative 'parts' and the 'forces' that link them together. This is so, not only because 'quantons' of the same species are indistinguishable from one another (see below) but also because any of them – irrespective of its belonging to the fermion or to the boson species – is 'virtually' made up of every other one. Even if the classical limit of a theory of boson fields is a classical field theory which describes the 'forces' in the conventional formulation, while the classical limit of a theory of fermions fields is a theory of 'particles', away from this limit the difference between fermions and bosons reduces to a difference in statistical properties and, therefore, has no special ontological relevance. I take this unification to be one of the most important and unique achievements of quantum theory, a unification which could be even stronger if the so-called super-symmetry (between fermions and bosons) turned out to be empirically sound. This unification crucially depends on the (partial) synthesis of the quantum principle and special relativity and shows that any claim for a particle ontology is definitely naïve:⁹ this is true in particular for the de Broglie–Bohm view of quantum theory, quite apart from its contextualism (parenthetically, see Bunge, p. 459). Finally, even deeper is

the duality emerging in the quantum-relativistic string theory, where elementary and compounded ‘quantons’ appear to be interchangeable, a fact that originates directly from action atomization and makes the very distinction between the *whole* (as compounded entity) and its *parts* (as composing entities) entirely relative.¹⁰

There is another point having important bearing on the ontology underlying Bunge’s article which is worth examining even if not directly discussed by Bunge: namely the issue of the so-called *identity* or *indiscernibility* of ‘quantons’. It is not explicitly stated by Mario Bunge (see endnote 3) whether he includes spatial location among the properties that individuate things. From his general ontology, I argue that (in consonance with Leibniz but upon quite different ontological motivations) he holds that, by the very fact of having different spatial locations, two entities cannot be (ontologically) identical. Let us see what he says about the indiscernibility issue:

We hold that there are no two identical entities – yet it is common experience that some things are indiscernible or indistinguishable. There is no contradiction here, as two different concepts of difference are involved: the ontological concept of (objective) difference on the one hand, and the epistemological (or pragmatic or psychological) concept of (subjective) differentiability, or discernibility, or ability of somebody to distinguish empirically, e.g., by observation. ... We must therefore distinguish between factual difference and empirical difference or discernibility. ... In microphysics one assumes that particles of the same kind and in the same state (i.e., with no intrinsic difference) count as equal or equivalent and so can be exchanged both in fact and in calculations. This assumption is usually cast with the term ‘indistinguishable’ replacing ‘equal’ or ‘equivalent’ – as if the particles could care about our ability to discern among them. The fact is that we do distinguish among them by their extrinsic (spatiotemporal) properties and so are able to count them. ... In other words, the truth of the matter is that the ‘elementary particles’ are distinct and often distinguishable in practice, but (a) they can be counted as equal or equivalent and (b) when constituting certain wholes they surrender part of their individuality ... there is always a partial loss of ‘identity’ of things when they become components of a system” (Bunge 1977, pp. 90, 91).

I don’t believe that the alternative ontological/epistemological (or factual/empirical), with the corollary notion of “distinguishability in practice”, is what really matters in quantum theory. The indistinguishability asserted of ‘quantons’ is the conceptual impossibility of differentiating between any two of them because of the fact that they are – as it were – theory-dependent natural kinds or types of entities having no differentiating factors over and above the sameness of values of their intrinsic properties like mass, spin, charge etc. And it is not enough to say that we “do distinguish among them by their extrinsic (spatiotemporal) properties and so are able to count them”. As a matter of fact, we are able to *count* them but we cannot *name* them, because it is just the spatiotemporal criterion of individuation that loses its effectiveness at the quantum level.¹¹ Nor is it true that they surrender a part of their individuality because “they become components of a system”. An electron here and an electron on the moon are indistinguishable anyway and partake their states according to the antisymmetrization principle. It is true that when ‘interference’ can be neglected (or FAPP), we recover the same statistical possibilities for quantum states as in classical physics but, of course, from the ontological point of view, ‘interference’ never strictly disappears and this is just

another component of the so-called macro-objectification issue of quantum theory. Therefore the lack in individuality of 'quantons' is different and subtler than that which can be predicated for Bunge's 'things'.

Even more, there is an important upgrading in the surrender of individuality of 'quantons' in passing from the non-relativistic theory to RQFT. For while at the non-relativistic level we can still speak of a definite sort of 'particles' in a certain state, in RQFT 'quantons' (field *quanta* in this case) are simply occurrences of definite excitations states (eigenstates) of quantum fields which are not in general localized at a definite spatiotemporal point and are only properties of the whole quantum system. Above all, they are relative to a chosen basis in a deep sense, for the transition to a different basis (a completely free and arbitrary operation in quantum theory) changes even the sort of the quanta. Finally, there are states, superpositions of states corresponding to definite numbers of quanta, which are characterized by an indefinite number of them. It is therefore also impossible to assert that quantum fields are *composed* or consist of quanta.

In conclusion, it seems very difficult to hold that quanta, or the quantum fields themselves, are things in Bunge's sense. And if our understanding of things is so radically modified, it appears awkward to maintain Bunge's relational conception of space (spacetime) unaltered. This of course should not be mistaken as a defense of the absolutist conception, which becomes even more untenable.

I have not the space here to address the general issue of the realism/phenomenalism debate in a serious way. I am strongly sympathetic to Mario Bunge's realistic attitude in general, but I would like to observe that Mario Bunge himself, after having simply stressed that quantum theory can be viewed realistically, does not go very far with explicit and detailed arguments in favour of his own thesis. I agree in particular with his interpretation of probability as a measure of objective chance instead of our uncertainty or ignorance (p. 462), as well as with his other remarks about the meaning of Heisenberg's inequalities. I also agree, with the view that one should not lightly talk of 'disturbances' caused by the measuring apparatus on a putative, spatiotemporally localized, 'quanton'. At least in part, Bohr's assertion of the inseparability of the apparatus from the observed 'quanton' can be coherently understood in terms of the effect of the objective spatiotemporal restrictions imposed by the experimental setting on the a priori possible spatiotemporal macroscopic manifestations of the quantum domain.¹²

Yet, I think the issue is not so simple and I believe it is not enough to say that quantum theory exhibits "counter-intuitive facts" and that "we had better come to terms with [them]". We should distinguish at least between two main groups of problems: (1) counter-intuitive facts about micro-phenomena must certainly be accepted, because they directly arise from the impossibility of a spatiotemporal (complete and local) description of elementary quantum acts following action atomization. I think that, *pace* all frustrated spatiotemporal local realists, such features – including the disturbing lack of (traditional spatiotemporal) property attribution in certain cases – will be incorporated in any possible future theory.

Spatiotemporal (realistic ?) objectivity of ‘quantons’ must be given up once and for all. (2) The issue of the collapse of the wave function cannot be confined to phenomena concerning micro-entities as it is the case in Aspect-like experiments. Thus, we must better link it more generally to the issue of the macro-objectification which is a deep issue calling into play the objectivity of the macroworld as described by quantum theory. But, since seventy years of debate has not yielded any agreed-upon and satisfactory solution, I think we cannot simply dismiss it as “a process we would like to understand instead of having to accept as a brute fact” (p. 463) or to say that being obliged to take seriously the coherent superposition of macroscopically distinguishable states “amounts to uttering the sentence ‘Blah plus bleh equals blih’ ” (p. 457). Even more since its implications concerning scientific realism are momentous.

We usually think of a whole as an ordinary perceptual thing. Then we can ask: is there a spatiotemporal *limen*, separating things as phenomenal perceptible entities, on the one hand, and quantum entities proper, on the other hand? The crucial point is that quantum theory does not contain any theoretical threshold at all and, what is more, for the very reasons that deny full qualities to the parts, it seems that any such spatiotemporal *limen* cannot exist. This means that quantum theory, as it stands, pretends to be a universal theory. Such a situation seems unacceptable, of course, if nothing else for the philosophical naïvety of the idea of a universal and definitive theory. Yet, as things are now, we cannot safely and simply assert that “concrete material things, such as organisms, robots and social system are [in principle] beyond the reach of the quantum theory” (p. 450) without supplying a technical justification for this assertion. My feeling is that when it comes to the interpretation of quantum theory, the most honest realist purpose becomes seriously strained. And I am convinced that the crux of the matter is our intuition of space (and time) as homogeneous frameworks. The FAPP theorist is not deeply embarrassed, at least until he touches the issue of quantum gravity, since so far the atomization of processes has not put technical limitations upon the mathematical utilization of the spatiotemporal continuum in our quantum theories. However I think that our notion of space and time as extended continua have already been undermined.

In conclusion, I wish to recall that David Bohm, one of the most learned and shrewd realist opposers of the Copenhagen viewpoint about quantum theory, had a deep awareness of the crucial ontological role played by action atomization, independently of the specific technical structure of the theory. In his *Wholeness and the Implicate Order* (Bohm 1980) he argues to the effect that a so-called micro-realistic conception of quantum phenomena entailed the existence of a ‘sub-quantum level’ of reality in which action could not be atomized at all in units of Planck constant. This would mean that the action atomisation of the current theory could only be approximate. But, of course, no empirical findings whatsoever supports this conjecture, which, on the other hand, would open a Pandora’s box of conceptual and physical problems that quantum theory has already exemplarily explained.

Notes

¹ Some of the remarks made in the present Commentary have already appeared in a previous paper of mine (Pauri 2000).

² Bunge exemplifies the quantum as “a basic or indivisible unit, such as the *cent* in the American monetary system, the electric charge of the electron, and the *bit* of information” (p. 447). Let me remark parenthetically that while the cent is an obvious case of conventionality, the quantum of electric charge, which is linked – although only phenomenologically so far, with the exception of Dirac’s theory of monopoles – to the Planck constant, can even appear, contrary to Bunge’s assertion, in fractional units, as in the case of quarks (although not as a property of free particles). A logical link between the *bit* of information and the *quantum* of action could even be conceivable in principle in the context of a future unforeseeable unified theoretical framework but, at present, it is out of question. Among the various cases of – so to speak – *pre-quantum* “quantizations” listed by Mario Bunge, I will address here only the case of the vibrating string, since nearly all of the others examples are conceptually reducible to this latter (“Harpes, drums, crystal, beams, bridges and many other large objects ...”). Admittedly, some significant exceptions are instantiated by “quantizations” appearing in electromagnetic phenomena; yet, these are in fact orthodox *macroscopic quantum effects*.

³ In commenting on the main points of Mario Bunge’s Essay, I am also constantly referring to his wonderful and monumental *Treatise on Basic Philosophy*, in particular Volume 3, *Ontology I: The Furniture of the World* (Bunge 1977). I think that this is correct and useful for the clarity of the argumentation, since it is evident from the wording of many passages of the Essay that Mario Bunge has remained faithful to his original basic ontology in all relevant respects, while our main disagreement is just about quantum ontology. I list here what I believe to be the main points (emphasis mine): (1) “A *fully qualified individual*, if substantial or concrete, will be called a *thing*, ... and a complex thing with coupled components will be termed a system, ...” (p. 26); “A real thing is a *fully qualified individual*, namely an entity or substantial individual endowed with all of its (substantial or nonconceptual) properties, both intrinsic and mutual, permanent or transient. ... It is impossible to define an entity as the set of its properties. Furthermore, even if usually a proper subset of its properties will suffice to distinguish an entity from other entities, nothing short of the totality of properties will constitute and individuate it, i.e., render it ontically distinct from every other entity: what makes a thing what it is, i.e., a distinct individual, is the totality of its properties. Different individuals fail to share some of their properties. ... This concept of a thing synthesizes the notions of substance and of form” (pp. 110, 111). (2) “No two substantial individuals have exactly the same properties. ... By contraposition it follows that, if two entities have exactly the *same properties*, then they are *one*. ... Either of these hypotheses may be called *Leibniz’ law*. [Leibniz takes] identity seriously without mistaking it for mere similarity: the slightest difference between two entities – such as a difference in relative position with respect to a third entity – results in difference” (p. 74). (3) “In absence of things, there should be no spatial relations; and in absence of change there should be no temporal relations. Indeed, it takes at least two things to make sense of ‘here’, ‘there’, ‘to the left’, and the like. And it takes at least two different states of a thing to make sense of ‘before’, ‘after’, ‘meanwhile’, and their kin” (pp. 276, 277). ... Space and time are not self-existing objects but a network of relations among factual items – things and their changes. ... Of course things may be said to have spatiotemporal properties – but the latter boil down to relations among things and events (p. 280). ... What matters to ontology is that space and time are not self-existing (absolute) objects of uncertain ontological status (neither things nor thing properties). The relational view is that *spacetime is the basic structure of the totality of possible facts* (p. 281); ... [Spacetime] has no properties and this because it is itself a property, namely the basic mesh of the sum total of changing things” (p. 317).

⁴ It must be stressed that speaking of energy quantization as a general and typical characteristic of the quantum domain is quite misleading. Energy quantization is not universal, it depends upon specific experimental conditions and it is *derivative* with respect to action atomization: there are

continuous energy spectra and, above all, energy, unlike action, is not a relativistic invariant. It should not be by chance that all kinds of observables that are quantized universally have the physical ‘dimensions’ of an action, like spin and angular momentum, or they are non-spatiotemporal, like the various ‘charges’ and ‘internal’ quantum numbers. The peculiar form of the action phase, $[Et - \mathbf{P} \cdot \mathbf{x}]$, exhibits the non-quantum role of the spatiotemporal parameters within the relation between action, energy and momentum.

⁵ This is the reason why throughout this Commentary, by ‘quantum theory’ I do mean the complex of formulations going from the non-relativistic scheme to the relativistic quantum theory of fields (including some qualitative achievements of the relativistic string theory). I believe that confining the discussion of the main interpretational problems of the theory within the bounds of the non-relativistic approximation – as is often done – is strongly limitative and even misleading. Mario Bunge himself declares that “the basic quantum theory is not quantum mechanics but the so-called second quantification, a field theory” (p. 456). In my opinion, however, he fails to draw all the consequences of this recognition.

⁶ Clearly, actual measurements and preparations of quantum states are possible in practice to the extent that they involve a “macroscopic” number of elementary quantum acts. This is also the reason why quantum measurement theory is so irrelevant to experimental physics: until very recently, no measurement had been limited by quantum noise.

⁷ The essential point being the peculiar physical interpretation of the sub-spaces of Hilbert space and the superposition of their elements in quantum theory.

⁸ Let us recall that recent EPR experiments have been performed over distances of about 50 km with approximately the same degree of accuracy of the original Aspect’s experiments. The lower bound of velocities at which the “collapse” of the wave functions could be said to take place over such distances is about 10^5 times the velocity of light! The “collapse” (viz. the “quantum jump”) is therefore found to be instantaneous to all practical purposes, as the theory predicts. In a quite different context, Dehmelt has (FAPP)-stored [FAPP = For All Practical Purposes] a single electron during 10 months: he observed that the electron which oscillates in the trap makes random quantum jumps. In other experiments it has been established that quantum jumps are sudden and that *it is not possible to associate an energy uncertainty to a putative jump duration* (Dehmelt 1990).

⁹ Not to speak of the lack of invariance of the concept of ‘particle’ upon the transition to accelerate observers or to curved spacetimes (see Pauri and Vallisneri 1999).

¹⁰ “Elementary objects now seem to be made of the very particles they create. More specifically, *duality* makes elementary and composite objects interchangeable: whether a particle or other entity is irreducibly fundamental or is itself made up of even more fundamental entities, *depends on one’s point of view*. Either perspective ultimately yields the same physical result. For example, *tangles of quarks* may give rise to *solitons* that are *monopoles*, *tangles of monopoles* may give rise to *solitons* that are *quarks* . . . *The fundamental scale associated with quantum theory (Planck constant) is intimately entwined with duality*”, L. Susskind, quoted by M. Mukerjee, Scientific American, January 1996 (my italics). Note the misleading and wrong subjectivistic nuance of the above wording “*depends on one’s point of view*”, which should correctly be read “depends on a *methodological* choice”.

¹¹ I would like to add: with important consequences for the traditional relational view of space (spacetime).

¹² An interesting ‘realist’ view of the multidimensional configurational representation of the wave function Ψ emerges, e.g., in the context of *correlated many-body systems*. The *scanning tunnelling microscope* technique allows even to draw on atomic scales the values of $|\Psi|$. Furthermore, in some cases in which the number of ‘particles’ is not fixed, it is possible to observe also the wave function phase (see Enz 1991).

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