Science & Education **12:** 495–502, 2003.
© 2003 *Kluwer Academic Publishers. Printed in the Netherlands.*

On the Nature of Quantons

JEAN-MARC LÉVY-LEBLOND
Physique théorique, Université de Nice, F-06108 Nice cedex, France
E-mail: jmll@unice.fr

It is now well over a century since quantum theory was born with the seminal work of Planck on black-body radiation. It took only a quarter of a century for quantum theory to develop a consistent formalism and show an amazing power of explanation and prediction. Yet, strange as it may seem, the conceptual status of fundamental quantum notions still is under dispute, despite decades of arguments. Most elementary textbooks and popularization works about quantum physics remain plagued by archaic wordings and formulations. Mario Bunge for long has advocated the necessity of confronting these misunderstandings. His paper exposes some of his proposals in this direction. It seems as if times were now ripe for such views to gain acceptance, as several recent publications on the epistemological problems of quantum theory bear witness (Auletta 2000). My purpose here is to contribute to the same endeavour, by concentrating on the concepts used for describing the basic entities of quantum theory, while stressing the terminological questions they give rise to (Lévy-Leblond 1999). It is hoped that the ideas (and words) presented here may contribute to clarifying and simplifying the teaching of quantum physics (Lévy-Leblond & Balibar 1990).

Before entering the discussion, it may be useful to offer a brief comment upon the roots of the curious paradox which sees the epitome of modern physics, quantum theory, hampered by a long tardiness. Of course, no new idea, whatever its domain, is born fully grown. Initial formulations of novel conceptions, being still tributary to the old views they are to replace, of necessity are awkward and inappropriate. Any scientific theory, following its inception, then has to undergo a recasting process through which its notions are clarified and its terms improved. An example in point is offered by Maxwellian electromagnetism, which, within a few decades, evolved from a mechanistic presentation (dealing with stresses and motions in a material medium, the ether) to a radically novel theory of fields. The question then is that of the reasons for the delays in the recasting process of quantum theory (and much the same remarks could be developed for relativity theory). One cannot help relating this situation to the deep changes in the organisation of scientific activity during the twentieth century. As in most domains of social life, technicisation, industrialisation and commercialisation have extended their empire to the scientific world; short term productivity and practical applications have been

privileged over critical thinking and intellectual demands. In spite of its apparent triumphs, it may well be the case that contemporary science is not in such a good health and could even show signs of senescence (Lévy-Leblond 1996b).

Neither Waves, Nor Particles, but Quantons!

That the true nature of quantum objects has long been misunderstood is proved by their still all too common description in terms of an alleged "wave-particle duality". It must be remarked first of all that this formulation is at best ambiguous. For it may be understood as meaning either that a quantum object is at once a wave and a particle, or that it is sometimes a wave and sometimes a particle. Neither one of these interpretations in fact make sense. "Wave" and "particle" are not things but concepts, and incompatible ones; as such, they definitely cannot characterise the same entity. While it is true that quantum objects may in some cases look like waves, and in other cases like particles, it is truer still that in most situations, particularly the ones explored by the elaborate modern experiments, they resemble neither one nor the other. The situation here is reminiscent of that encountered by the first explorers of Australia, when they discovered strange animals dwelling in brooks. Viewed from the forefront, they exhibited a duckbill and webbed feet, while, seen from behind, they showed a furry body and tail. They were then dubbed "duckmoles". It was later discovered that this "duck-mole duality" was of limited validity, and that the zoological specificity of these beasts deserved a proper naming, which was chosen as "platypus".[1] Much in the same way, we thus can (and must) safely assert that quantum objects are *neither waves*, *nor particles*, but are to be described by a specific and novel concept, which certainly deserve a name of its own (Lévy-Leblond 1981, 1988). Bunge's proposal to call them "quantons", building on the common terminology (electrons, photons, nucleons, etc.) and extending it to a common categorisation, is most to the point, and it is to be hoped that this terminology gradually gains ground.

For indeed, quantons are novel entities! The best way, perhaps, to stress the originality of the notion is to examine it from the point of view of the discrete/continuous dichotomy. Quantons show discreteness in that they come in units, and can be counted: an atom has an integer number of electrons, and a photographic plate registers the individual impacts of photons. Nevertheless, electrons as well as photons (and all quantons) do show continuous essence as well, since they can be subjected to interferences, superposition, etc. In fact, it should be realised that a physical object must be characterised through the consideration of *two* discrete/continuous dichotomies; one has to consider separately the question of the number of objects and the question of their extension (spatiotemporal properties). Within classical physics, these two questions merge. Classical particles are discrete under both aspects; they come in discontinuous counts and are discretely localised. Classical fields are continuous under both aspects; they have continuous amplitudes and continuous spatial extensions. But quantons exhibit the original combination

of discreteness in number and continuity in extension, as shown by the following table:

	Number	**Extension**
Particles	discrete	discrete
Fields	continuous	continuous
Quantons	discrete	continouous

This double nature of quantons (not a contradictory one, since discreteness and continuity do not refer to the same notions) is the very lesson of quantum physics.[2]

The Unity of Quantics

It is now easier to understand the two partial classical appearances of quantons; if, in a given experimental set-up, the discrete character of their number is preponderant and the continuous character of their extension secondary, they can be *approximately* described as particles. Conversely, if, in another experimental set-up, the discrete character of their number is secondary and the continuous character of their extension preponderant, they can be *approximately* described as waves. The latter case is mostly met for macroscopic systems comprising a large number of quantons, which often may be reasonably treated by a continuous description (as, in classical physics, a flow of sand or grain may be assimilated to a fluid).[3] But in most cases, especially in the very sophisticated modern quantum experiments, quantons certainly look neither as waves nor as particles, and must be accounted for through their intrinsic and unique conceptualisation. As Feynman is supposed to have said, "quantum objets are crazy, but they all have the same craziness". In fact, it is not quantum physics, but classical physics which does exhibit a wave-particle duality (Lévy-Leblond 1977).

It is perhaps worthwhile pointing out here that the deepest revolution in the theorisation of physical objects probably took place, not at the beginning of the twentieth century with the advent of quanta, but earlier, by the second half of the nineteenth century, when there emerged the notion of *field*, which Maxwell brought to fruition. Initially conceived as the description of a disturbance in an underlying medium (such as water for ordinary waves), electromagnetic waves were first supposed to travel in ether. The demise of this medium led to the idea of electromagnetic fields existing *per se*, in the vacuum. The novelty of this ontological status probably was not realised and assimilated deeply enough; yet the very existence of physical entities without bulk, substantiality, nor spatial localisation or form, radically challenged the mechanistic legacy of Newtonian physics.

It may be argued that a part of the misunderstandings which have plagued quantum theory up to now, is due to the older failure to fully assimilate the (classical) notion of field. This is reflected, for instance, in the surviving of the appellation "quantum *mechanics*", despite the symmetrical status of the classical

notions of particle and field with respect to their (unique) successor, the notion of quanton. A simple alternative exists, following the well-established tradition of substantivation for naming the fields of physics; as for acoustics, thermodynamics, electronics (and physics itself!), why do we not simply use the term "quantics" to denote the whole field?[4]

Quantum Properties

Thus, quantons are, by their very nature, spatially extended objects. The mental difficulty experienced in reconciling this idea with that of their numerical discreteness accounts for the negative characterisation commonly given of these objects. So it has become customary to speak of the "non-locality" of quantons, as if they were deprived of the 'normal' property of locality. A better strategy would be to try taming the epistemological difficulty by adopting a more assertive and more intrinsic terminology. A rather natural neologism could be introduced, naming "pantopy" this spatial extensiveness of quantons. It must be stressed that the continuous nature of quantons is not limited to their spatial localisation; it holds as well for all physical magnitudes associated to space-time, such as speed, momentum, and energy. While for classical entities, the physical properties take on unique and determined numerical values, for quantons they are characterised by numerical spectra, extended sets of numerical values.

The possible discretisation of some of these spectra, for instance the energy levels of a bound system, is but a particular case, linked to the spatial confinement of the system (in close analogy with the quantisation of the frequencies of vibrating strings, as noted by Bunge). A physical magnitude of a quanton then is characterised by the spectrum of its possible numerical values ("proper values") and the set of particular states which are associated with a single such value ("proper states"). It may then be shown that both these aspects can be encompassed under the mathematical form of a linear operator in the state space. In other terms, the classical description of a physical property by a unique numerical value must be replaced in quantum theory by this more general mathematical notion. If such a formalisation is accepted, there is no longer any difficulty in attributing objective physical properties to quantons (Lévy-Leblond and Balibar 1990, chapter 2, also Paty 1999).

Of course, this new mathematisation has important original consequences. For "incompatible" couples of physical magnitudes, that is, properties the representative operators of which do not commute, e.g., the spatial position and the momentum, there exists a correlation between the widths of their respective spectra, such that, for instance, the narrower is the spatial distribution, the wider is the momentum distribution. Here again, the usual terminology, that of the (in)famous "uncertainty relations" does not give justice to the situation: the width (or dispersions) of the distributions are not "uncertainties", in that they have nothing to do with some lack of precision in the description of the state of the quanton; they are

objective characterisations of this state.[5] Indeed, far from expressing a limitation in our knowledge, the Heisenberg inequalities (as they could more soberly be called) are of utmost value for our understanding and heuristic treatment of many quantum problems (Lévy-Leblond & Balibar 1990, chapter 3).

Collective Quantum Behaviour

If the quantum specificities pertaining to the description of individual quantons cannot be too strongly stressed, it must now be added that systems of quantons exhibit even more original behaviour. It had already been realised in the early days of quantum theory that identical quantons should show up statistical properties of a totally non-classical nature. Quantons were proved to belong to two mutually exclusive categories, fermions and bosons; while bosons have an intrinsic tendency to gregarity, fermions obey the Pauli exclusion principle. There is absolutely no classical equivalent of this property. Indeed, the respective gregarious tendencies of bosons and exclusive tendencies of fermions have nothing to do with mutual interaction forces between the quantons; it is not a dynamical and contingent property, but an essential and ontic one. Any system comprising several identical quantons is strongly determined by this property; for instance, the fermionic nature of electrons is crucial for the architecture of atoms and molecules.

Let us note in passing that for systems with few quantons, the identity of the components has physical consequences which manifest themselves at the individual level, and do not require or imply statistical considerations. It thus seem rather preposterous to describe the fermionic or bosonic nature of quantons in terms of their "statistics". Here again, a more appropriate wording would seem useful, referring to a specific physical property of the quantons; one could for instance speak of their "permutancy", even or odd, according to the symmetrical (for bosons) or antisymmetrical (for fermions) character of a collective state under permutation.

It remains to stress that, far from being confined to the microscopic realm, the collective nature of identical quantons is crucial to the existence and properties of macroscopic matter as we know it. It has taken an unduly long time to recognise (and the proof still requires quite sophisticated methods) that the very possibility of applying ordinary classical thermodynamics, relying on the extensivity of energy, is ensured only in virtue of the fermionic nature of electrons (Lieb 1984, and, for a pedagogical discussion, Lévy-Leblond & Balibar 1990, chapter 7). More generally, we must now realise that macroscopic is not synonymous with classical. Not only do we build more and more specifically quantum objects of paramount technical importance operating on our ordinary human scale (laser, superconductors, superfluids, etc.), but deep common properties of matter cannot be understood except in quantum terms (Lévy-Leblond 1996a).

Implexity, the Quantum Essence

A full realisation of the specificities pertaining to the very nature of quantons has been rather slow to emerge at the individual level – that of quantons considered one by one. But the delay has been much worse for our understanding of the collective level – beyond, or rather, before the problem of identical quantons. Indeed, the fermion/boson duality is but the expression of the permutational invariance of multiquanton states, abstractly formulated at the level of the Hilbert state space; these states are either totally symmetric (bosons) or totally antisymmetric (fermions). In other words, a collective state cannot be considered as a mere collection of individual states, but shows a peculiar wholeness. The situation contrasts with the classical one, for the state of a system consisting of many classical particles is completely described by the individual states of the particles. Reciprocally, given such a classical collective state, it is always possible to attribute a well-defined state to any of its constituent particles. Such is no longer the case for quantum systems. In the perceptive words of Schrödinger, who was certainly the first to stress what is perhaps the deepest and most original specificity of quantum theory, a full description of a compound system does not entail a full description of its components (Schrödinger 1935).

This highly counter-intuitive situation is intrinsically linked to the superposition principle, that is, to the linear structure of quantum theory, according to which the states of a quanton are described by vectors in a Hilbert space. The states of a multiquanton system then define a new Hilbert space, which is the tensor product of the individual state spaces; now, if (tensor) products of individual states do generate the collective space, a collective state in general is *not* a product of such individual states. It cannot be too strongly stressed how the very notion of tensor product, while mathematically elementary, is heuristically opaque; the reason is probably that, contrarily to the metric structure of a Hilbert space of which we have a rather good intuition starting from our experience in ordinary Euclidean space, the tensor structure has no analogue that we are familiar with (the smallest nontrivial tensor product is four-dimensional . . .). In any case, it took several decades to realise the full extent of the consequences of the tensor structure and the non-factorisability of generic vector states.

Schrödinger coined the word "Verschränkung", usually translated as "entanglement", to describe this 'non-separability' of general quantum states. Yet it may be judged that the use of a word with all too familiar connotations, risks yielding concrete and false pictures. A neologism would seem, here again, a better solution. Since the notion of entangling or intertwining is rendered in Greek by the word *emplexis*, from the verb *plekô*, it is tempting to propose the term "implexity" which has the double advantage of paying regards to David Bohm's insistence on what he called the "implicate order" of quantics, and to take a natural place in an long and familiar series of words, like complexity and perplexity (both of which, after all, already properly characterising the context of quantum theory . . .).

It is all the more surprising that it took so long to face the implications of implexity since the states of identical fermions exhibit it to a maximal degree, which, as has been stressed, is the precise reason why they play an essential role in accounting for the properties of atoms as well as condensed matter. In any case, it is clear by now that, whatever word is used for it, this idea is indeed the core of the argument behind the Einstein-Podolsky-Rosen (pseudo)paradox, its re-exploration by Bell and his ensuing inequalities, the experimental vindication of the quantum predictions by Aspect and others, and the recent flurry of amazing experiments on these basic quantum phenomena, which nowadays lead to practical perspectives in quantum computing and quantum cryptography (Greenberger et al. 1993, Ghose 1999, Zeilinger 1999, Macchiavello et al. 2000).

Notes

[1] Of course, the aboriginal people already had a specific and appropriate name for the animals, that is, I am told, "mallingong".

[2] We let it open here the question of the possible consistence and existence of entities showing continuity as to their number and discreteness as to their extension.

[3] Further considerations about the collective properties of quantons show that only bosons (obeying a gregarity principle) and not fermions (obeying the Pauli exclusion principle) may give rise to such an approximate macroscopic description in terms of waves or fields.

[4] In adopting this title for our textbook (Lévy-Leblond & Balibar 1990), we have in fact followed a terminological innovation spontaneously initiated by our students.

[5] The story of the term "uncertainty" is by itself rather entertaining. It results from the combination of epistemological misunderstandings with doubtful translations ; the original German wording by Heisenberg, was closer in meaning to "indeterminacy", which is certainly better, if not yet fully adequate (Lévy-Leblond & Balibar,1998).

References

Auletta, G.: 2000, *Foundations and Interpretation of Quantum Mechanics*, Singapore, World Scientific.

Ghose, P.: 1999, *Testing Quantum Mechanics on New Grounds*, Cambridge University Press.

Greenberger, D.M., Horne, M.A. & Zeilinger, A.: 1993, 'Multiparticle Interferometry and the Superposition Principle', *Physics Today* **46**(8), 22–29.

Lévy-Leblond, J.-M.: 1977, 'The Picture of the Quantum World: From Duality to Unity', *Int. J. Quant. Chem.* **12**(1), 415.

Lévy-Leblond, J.-M.: 1981, 'Classical Apples and Quantum Potatoes', *Eur. J. Phys.* **2**, 44.

Lévy-Leblond, J.-M.: 1988, 'Neither Waves, Nor Particles, but Quantons', *Nature* **334**, 6177.

Lévy-Leblond, J.-M.: 1996a, 'Quantum Theory at Large', in E. Beltrametti & J.-M. Lévy-Leblond (eds), *Adv. in Quantum Phenomena*, Plenum.

Lévy-Leblond, J.-M.: 1996b, *La pierre de touche (La science à l'essai. . .)*, Gallimard.

Lévy-Leblond, J.-M.: 1999, 'Quantum Words for a Quantum World', in D.M. Greenberger et al. (eds), *Epistemological and Experimental Perspectives on Quantum Physics*, Vienna Circle Institute Yearbook, Springer.

Lévy-Leblond, J.-M. & Balibar, F.: 1990, *Quantics (Rudiments)*, North-Holland.

Lévy-Leblond, J.-M. & Balibar, F.: 1998, 'When Did the Indeterminacy Principle Cecome the Uncertainty Principle?', *Am. J. Phys.* **66**, 278–279.

Lieb, E. H: 1990, 'The Stability of Matter: From Atoms to Stars', 1989 Gibbs Lecture, *Bull. Amer. Math. Soc.* **22**, 1–49.

Macchiavello, C., Palma, G. M. & Zeilinger, A. (eds): 2000, *Quantum Computation and Quantum Information Theory*, World Scientific, Singapore.

Paty, M.: 1999, 'Are Quantum Systems Physical Objects with Physical Properties?', *Eur. J. Phys.* **20**, 373–388.

Schrödinger, E.: 1935, 'Die gegenwärtige Situation in der Quantenmechanik', *Die Naturwissenschaften*, pp. 807–812, 823–828, 844–849.

Zeilinger, A.: 1999, 'Experiment and the Foundation of Quantum Physics', *Rev. Mod. Phys.* **71**(2), S288–S297.