The Problem of the Physical Interpretation of Theoretical Quantities and the Intelligibility of the Quantum Domain

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La interpretación de las magnitudes físicas y el problema de la inteligibilidad del mundo cuantico.

SETTING UP THE PROBLEM

The problem of interpretation in science has possibly known its apogee (or climax) with the advent of quantum mechanics, when a highly mathematically formalized theory, which had shown an up-to-then unequalled efficiency by giving account of the phenomena of the "unseen" and new atomic domain, seemed at the same time to need an interpretation if one wanted to get the exact physical meaning of its statements. The quantities used in the theoretical formalism and in the equations had lost the mathematical form and the physical meaning they usually had in previous physical theories and were endowed with another, more abstract, one ; probabilities and statistics appeared to be at the root of the theoretical description ; and reference to obervation seemed to be inherent to the latter. The problem of the interpretation of quantum mechanics appeared to be a rather complex one, as it called not only for limited or "localized" physical interpretations of mathematical quantities (as one had in the past, for example with differential, "infinitesimal", variables), but also for more general considerations which implied philosophical conceptions about nature and about the knowledge of it.

As exaggerated this dimension of interpretation might have been, it reveals, in a somewhat extreme form, an interesting problem which is universally encountered in the process of the advancement of scientific knowledge : any new element of knowledge, when appearing, asks for its understanding, i.e. to be made intelligible, and "interpretation" is a way to attend this demand. Various types of interpretation may be found in the course of scientific inquiry and also in the various stages of development of a given scientific field. In quantum physics, the intelligibility and interpretation problem is not restricted to the one of the quantum mechanical stage, well known because of its famous debates (dominated by the Bohr-Einstein controversy about quantum mechanics and physical reality). We shall investigate, in what follows, how interpretation problems were actually present at the various stages of the constitution of quantum physics, under different species, and try to clarify the relationships between the type of interpretation, the change in conceptual content, and the status of the theoretical description.

From the historical point of view, one may consider that the knowledge of what we now legitimately call the "quantum domain" has been obtained from a three stages elaboration, corresponding to three degrees, so to speak, of conceptual and theoretical integration together with the acquisition of experimental data, each stage displaying significant aspects of the problem of the intelligibility of this field of physical knowledge.

In the first period (from 1900 to 1916), quantum physics was being constituted as a new domain of physical phenomena and systems showing a specificity of their own, and corresponding to a proper field of knowledge, irreductible to the previous theories. This specificity was expressed through new concepts which required, in order to be fully intelligible, a consistent "quantum" theory, with the "first quantum theory" (called "semi-classical") as a first approximation.

The second period (1917-1926) extends from this first theory up to the establishment of quantum mechanics, through elaborating ideas, concepts and theoretical schemes that were theoretically more precise and experimentally more embracing (such as "wave-particle duality", "undistinguishability of identical particles", "quantum kind" of probabilistic behaviour, etc.). But the theoretical approach based on this knowledge showed a two-speeds efficiency for the mathematical formalizations on the one hand (which were powerful) and the physical corresponding description on the other hand (which was unclear), whereas the overall success in giving account of the quantum phenomena seemed to ascertain that one had finally obtained the good "quantum theory in the proper sense" of the kind that had been looked for.

The third period (since 1927 to nowadays) includes the "interpretation" of quantum mechanics as a "frame-work theory" as well as its theoretical developments regarding the dynamics of quantum processes. The interpretation which was considered necessary by then to get at a full intelligibility of the quantum domain was not expressed only in terms of a new physical content for the mathematical entities, as precedented in earlier physical theories : it dealt also with philosophical presuppositions of scientific and physical knowledge such as the status of observation with regard to knowledge and to reality, i.e. the subject-object distinction, and claimed also a failure of causality and determinism.

To each of these stages of the development of quantum physics, one is confronted to the problem of *knowledge*, as description and as explanation, and to the problem of the *intelligibility* that one acquires about it. For each one, the knowledge obtained at and the intelligibility of it do not coincide, at least in a first moment, and it is from this difference that the need of an interpretation arises. The three stages of the elaboration of quantum physics exhibit different types of demands for interpretation, or various patterns of interpretation, related with the process of concepts transformations. In the two first stages, the interpretation problem seems to have remained confined inside purely physical concerns, leading as an effect to a more and more refined and constraining theoretical elaboration. When the powerful quantum theory obtained at the end of the process showed to be self-consistent and stable, it happened that the interpretation problem as considered henceafter suffered a change of nature. We may ask which is the relationship between this new type of interpretation and the kind of physical concepts of the theory. It seemed that something new was needed that was so fundamentally different from the previous physico-theoretical approaches that it was necessary to reconsider the philosophical roots of physical knowledge themselves. We may ask ourselves also whether this difference was a natural (or necessary) one, or whether it was due to a particular historical context. In which case we might ask the question of which type of interpretation would correspond "naturally" to a fully self-consistent theory.

THE EXPLORATORY PERIOD : CONSTITUTION OF A NEW CONCEPTUAL DOMAIN FOR PHYSICS

Let us elaborate further on the three periods or stages of the elaboration of quantum physics. As we said, the first period has been that of exploration, starting from the confrontation of the then available ("classical") theoretical material with the experimental data that stemmed out, since around 1900, of inner atomic matter and radiation processes. Informations were obtained about the physical features of these processes that appeared to be at odds with the usual concepts of physics and with the classical theories of mechanics, electromagnetism and thermodynamics (with kinetic theory and statistical mechanics). This stage extended up to the end of the year 1916, when a first comprehensive, albeit still “semi-classical”, theory of quantum phenomena was proposed by Einstein.

One may qualify this period as that of the constitution of the quantum domain as such, concerning phenomena and physical systems whose qualifications of “microscopic”, or even “atomic and radiation”, strictly speaking, are inadequate to point at its exact peculiarity. It appeared that only its qualification as a “quantum” (domain) was able to express what was at stake, i.e. a conceptual and theoretical breakdown symbolized by the Planck-Einstein's quantum of action, and which had been characterized (by Einstein already in 1906 and by Ehrenfest in 1912) as needing to give up the classical electromagnetic theory of radiation and even, as Poincaré stated it early in 1912, the use of differential equations in the physico-mathematical processing[1]. The ingredients of the new physical theory, i.e. the new concepts and relationships, whose necessity had been initially acknowledged as “something missing”, were progressively elaborated.

A new domain had revealed and the question was : up to where and how deep. Knowledge was acquired, but it was not fully understood. In other words, this new knowledge was being identified as something radically new, but a thorough and deep understanding of it was not available. The physical content corresponding to the results obtained experimentally was not embedded in a comprehensive theory ; but, despite this, some original concepts were emerging, such as quantum of action, energy-frequency and momentum-wave-length relationships for light, atomic quantum numbers and, sometime later (in 1924-1926, in the second period), undistinguishability of identical particles, Pauli exclusion principle, etc., as well as some specific statements about discreteness of quantum processes, related on one side to the use of differential equations and, on another side, to the use and meaning of probabilities.

So many (and unusual) *elements of knowledge* were obviously tied together, and what we may call *intelligibility* of them, although lacking on the whole, was being gained by steps, since the newly appearing quantum features shed some light on the previous ones. For instance, Einstein's recognition, in 1906-1909, of something of a particle aspect in the behaviour of electromagnetic wave-light (in a distribution of fluctuations) deepened the physical meaning of the quantum energy discontinuity for radiation-matter energy exchanges found in december 1900 by Planck, and extended to the radiation energy itself by Einstein in 1905. Similarly Einstein's extension of the quantum of action from radiation to atomic properties, in 1907, through the calculation of specific warmths, showed that the quantum characterization was a general property of the overall domain of microprocesses, atomic as well as radiative ones[2].

Bohr's consideration, in 1913, of the atomic energy properties in terms of discrete levels, was another extension of the quantum algorithm[3]. A further extension and wider understanding was obtained when Einstein formulated, at the end of 1916, his first synthetic, semi-classical, theory of quanta, which is the culminating point of the period[4]. He took, as first elements, Planck's quantum of action and Bohr's discrete atomic levels with their relative state frequencies, which yielded the probability of transition per unit of time between two states. Expressing the condition of thermodynamic equilibrium, at a given temperature, between the radiations and the molecular states distribution, he obtained as a result Planck's radiation law and Bohr's frequencies relation (e_m - e_n = hn_{mn}). An intermediate step was to admit that the radiation, that had already been given a discrete energy ($E = hv$), was endowed also with a discrete momentum (p = h/l), which entailed the fully corpuscular character of light, although it maintained its wave character[5], which obliged to admit a wave-particle (dualist) behaviour for electromagnetic radiation (light and other waves and rays, X, g). The radiation momentum was, therefore, justified, if not directly proven, by the result obtained.

As a conclusion, all the quantum features known up-to-then were integrated into a consistent theoretical scheme, allowing to deduce from it the transition probabilities (per unit of time) for emission and absorbtion of an electromagnetic radiation of given energy or frequency, as a function of the transition amplitudes of the atomic states [6]. Note that, in formulating his theory, Einstein did not base it on the classical electromagnetic wave concepts. However, the price to pay for this relative self-consistency of the theory was to admit the transition amplitudes as empirically given, and to let to chance (i.e. through a statistical distribution) the direction of the emitted radiation.

The theory was therefore still lacking from the point of view of a full rational understanding, which pointed toward the need of a more specifically quantum theory. As a matter of fact, the radiation momentum result and the relations between transition amplitudes for atomic levels have been afterward the basis of all further progress in quantum theory, i.e. the starting point for the second and third stages.

In the course of this first stage of elaboration of the quantum knowledge, we may consider that this knowledge consisted of concepts breaking with the previous ones (discontinuous versus continous, light momentum, etc.) and of an embracing theory that was, however, not fully satisfactory, beacause it was letting space to empirical complements as observational statements that had no rational or theoretical explanation.

Let us notice, at that point, that we have used several words which are epistemologically and philosophically problematic and which would require some elucidation : namely *knowledge* (empirical, conceptual, theoretical), and *intelligibility*. I let aside, for the moment, such an elucidation, which would be helped by a further and deeper analysis of the physical problems involved and by the manner in which the scientists of the field considered these problems. Even if they did not often use at this stage the word "interpretation", we may consider that their worries were about how to *interprete* the new elements of knowlege that had come to them. In any case they wanted to understand them in a way or another.

For instance, quantum discontinuity was known, identified and recognized as such, and it became clear after some time that it would be understood only when a theory for it would have been formulated. The requirement of intelligibility pointed at the necessity of getting a new theoretical scheme which would have to incorporate the quantum features known up to then. Such was the claim of Einstein, who considered that in order to get at such a theory it would be necessary, first, to know the peculiarities of the quantum properties. The stake was not yet interpretation, but more knowledge, for without enough knowledge there is no interpretation of this knowledge, and no need of it.

However, at the same time, some kind of interpretation was implied in these statements, but it was in a negative sense : the "quantum knowledge" obtained up to then showed (as Einstein and Ehrenfest said) that *the classical theory* was no more valid in the quantum domain. Poincaré went even further, concluding that *differential equations* in general were no more of use in it. The "interpretation" involved in these considerations of the "quantum facts" was closer to what we call "*proof of unsufficiency*" than what we use to call "interpretation". But the step that goes from the "elements of knowledge" to the statement on the unsufficiency of present theories, or theoretical schemes, illustrates that further than *knowledge* stands a deeper instance with respect to which this knowledge is received and "interpreted" in terms homogeneous to the *understanding*, so as to be assimilated by it in a straightforward way. This instance is *intelligibility*. In the discussed case, it pointed at the necessity of a further theoretical elaboration, and of knowing the general principles of physics on which such a theory could be established. Some of these principles were already known, according to Einstein, and would serve as a sound basis for elaborating the future theory, and understand the quantum features (or established facts) [7]. New other ones would have to be found.

There was another way, at the same stage, to call for interpretation in a somewhat different meaning : when, for instance, it was asked how to connect the microscopic picture (take Bohr's atomic model of quantified levels and the radiation of a given frequency exchanged between two of these levels) with the observed and (classical) theoretically admitted result about the intensities of the spectrum lines. Bohr had the idea of a "correspondence principle" to connect them, and it was, clearly, a general statement going far beyond the mere experiment-theory interplay : it was indeed a condition of mutual consistency for the classical and the quantum pictures in their commond domain of validity, and in a circumstance where there was no independent and self-consistent theory of the quantum domain. The knowledge of the quantum domain was thought to depend on the classical representation, and a correspondence rule was required to situate the quantum features, hypothese and concepts, with reference to the knowledge of the "non quantum" domain (or classical one) and its theoretical synthesis, in the limit where the statements of the latter remained valid. Here, such "interpretation" is a conceptual complement for the "quantum knowledge" which substituted what was missing in it to give a full account of the phenomena.

Notwithstanding the differences in the two situations, physicists were in both cases facing questions of *interpretation* of the present (quantum) knowledge related to the fact that *they did not have a fully intelligible picture* of it. This meaning of "interpretation" is connected with the "unachieved" character of the theoretical scheme, and points at a further, "better achieved", theory for the same domain. On the contrary, in a situation where one disposes of a fully "achieved" theory, such as classical analytic mechanics, or special or general relativity theory, all "physical interpretations" that can be formulated are statements which remain inner to the theory, be they of definition (of physical quantities and variables with their mathematical expressions), or expressing relationships, which are already implied by those of the theoretical quantities[8].

Let us make explicit that, in any type of situation, "*interpretations*" are statements about the given elements of knowledge that are able to provide us with an *overall intelligibility* (at least provisonal).

The case of "achieved theories", which may be also "complete" ones (but I cannot enter in this distinction here[9]), makes us sensible to the "ideal of interpretation" for such theories, which is such that the physical interpretation of their magnitudes or of their relationships are given from inside the theoretical structure itself. Only then can one claim a full intelligibility of the physical domain under consideration. It is because of this implicit ideal that interpretation, in the case of unachieved theories or theories in the making, points towards the need of better theoretical achievement. As Einstein said of his first theory of quanta, emphatizing its weaknesses (the wave particle connexion which escaped our understanding, and the probabilistic character of elementary processes) : "these properties of elementary processes let appear as unavoidable the formulation of a true quantum theory"[10]. By "true", he meant founded on its proper, *sui generis*, exigencies, which we understand as : fully rational and intelligible.

PROPER QUANTUM CONCEPTS AND PRINCIPLES, IN VIEW OF A SELF-CONSISTENT QUANTUM THEORY

The second stage of the developments of the quantum ideas was that of the obtention, starting from the first theory just evoked, of deeper features of quantum phenomena and systems, which led to the elaboration of a "quantum theory" properly speaking (wave or quantum mechanics), endowed with fuller inner consistency, in which theses features were incorporated ; but it happens that these features appear still, retrospectively, to be the most fundamental ones from the physical point of view. I refer to the *wave particle duality* for radiation and matter and, even more fundamentally, to the *undistinguishability* of identical quantum states and their specific probabilistic behavior, i.e. according to bosons or to fermions statistics. Both properties are intertwinned and are another way of expressing the quantum of action.

The particle aspect of radiation superimposed to its wave one, although it appeared established from Einstein's 1916 quantum theory, had direct implications which were asking confirmation : Compton's experiment (1923) showed that an electromagnetic radiation (X or g ray) impinging on an atomic electron was to be treated as a collision process between corpuscles (photon and electron), with the conservation laws for the kinematic variables (momentum and energy, or relativistic quadrimomentum). An alternative theoretical hypothesis wanting to preserve continuity in atomic and radiation processes, through a purely statistical consideration involving energy non conservation for (individual) elementary processes, proposed by Bohr, Kramer and Slater (1924) was subsequently contradicted by the result of a more refined experiment performed by Geiger and Bothe (1925), which exhibited an angular correlation of a corpuscular type between the outgoing photon and electron[11]. It showed at the same time that elementary quantum processes were individual processes : a question on which Einstein always insisted, but which remained ambiguous in the "Copenhagen interpretation".

The double *wave-particle* property of electromagnetic radiation was generalized to particles of matter by Louis de Broglie in the same period, so that it appeared as a fundamental property of quantum systems to be taken into account and also to be accounted for, as there was still no explanation of it. De Broglie understood this property in the frame of an intuition of his own, a particle inside its associated wave (a picture whose systematization would lead him to his "double solution" interpretation or theory, alternative to the standard quantum theory). Einstein did not interprete it, as he thought that models would be inadequate, but saw in it some fundamental deep aspect of quantum systems. In a way, quantum-mechanics would offer an interpretation of it, as Einstein stated in a retrospectively in his *Autobiographical notes* : with the existence of light quanta as definitely established, he wrote, "this double nature of radiation (and of material corpuscles) is a major property of reality, which has been *interpreted* ["*gedeutet hat*", in the original] by quantum-mechanics in an ingenuous and amazingly successful fashion"[12]. Actually, quantum mechanics took it it as one of the base of its theoretical formalism. It was, as a matter of fact, the starting point of Schrödinger's elaboration of his wave mechanics, although he would meet in the end with a conceptual difficulty : the theoretical formalism he elaborated (Shrödinger's equation), while providing exceptionally powerful results, excluded the initial "interpretation" of the state function as a the amplitude of a physical wave[13].

Another unusual character coming also from calculations on quantum processes, and which had as well to be referred to some physical property, was the "*undistinguishability*" of identical quantum particles or systems, which arouse from Bose and Einstein's, and a short time later from Pauli, Fermi and Dirac's works on sets of quantum systems (photons and monoatomic gas for the former, electrons for the latter). This property, considered for photons, was intimately related with Planck's law of radiation, as it corresponded to a different counting of elements in energy cells from the usual one for classical particles (as in the case of Boltzmann's gas). Considered for atoms, it was directly connected to the wave-particle behaviour.

Various types of "interpretations" of such unusual property were considered. Schrödinger, guided by his "wave view of the world", saw in it an evidence against the corpuscular representation, and considered gas molecules as energy excitation, devoid of individuality. Later on he would speak of “entanglement”, a concept re-actualized afterwards by the quantum correlations of EPR type (in 1935), and he referred it to considerations akin to some “metaphysics” of the superposition principle of quantum mechanics[14]. Einstein, although he evoked the eventuality of some propension, for such molecules, to be in the same cell as another one, or of some “mutual influence of the molecules” [15], did not give an interpretation, strictly speaking, in these terms. Actually, he saw in this property at the same time a formal and a factual one : the formal property (undistinguishability and its specific rule of counting, showing a statistical dependence) had theoretical consequences (the spectrum distribution adequate to observation), and the right interpretation of it would be given in a future theory which would have to incorporate it : in this sense, such a property enlightened the future needed theory.

During this stage, as it is well known, various parallel (but actually converging) attempts at integrating these new fundamental features of quantum phenomena into a unifying theoretical scheme were made, by Schrödinger, by Born, Heisenberg and Jordan, and by Dirac[16]. The quantum theory thus obtained by construction (wave and quantum mechanics, shown to lead to equivalent results) manifested its usefulness and theoretical power, but seemed at a first glance to have gone in a formal direction well beyond its purely physical purposes[17]. In the beginning, physical interpretations for its theoretical elements were looked for, essentially to picture out the meaning of the wave or state function (which could by no means describe a wave in the usual, classical, sense), such as Madelung's hydrodynamical interpretation, de Broglie's double solution, Born's probabilist interpretation[18]. There is a difference between them, as the two former suggest some specific model added physically to the theory in its strict formulation, whereas Born's probabilist interpretation of the wave function is merely of the kind of a definition : it affords to the “wave function” (or state function, *y*) the meaning of an “amplitude of probability”, a new concept having no known meaning in mathematics, and being given one in physics, namely : the squared modulus of it is the probability for the system to be (or to be found) in the state *y*.

Born's probabilist interpretation of the state functon was generally retained because of its “economical” character which accepted quantum mechanics without addition, and was incorporated among the “principles” of the new theory. Together with it was the “superposition principle”, which, precisely, forbade to consider the state function as a “physical object” in the ordinary sense : it was taken as purely mathematical, and the theory was thought of being a closed formalism that needed to be interpreted in view of physics : this would be the kind of “interpretation” of the third stage of our story. Up to it, the need of interpretations had been essentially considered as related to the *unachieved* character of the theory, and as pointing *toward a deeper theoretical scheme*, a quantum theory of its own, that would eliminate any recourse to classical theories, and eventually any reference to it. Quantum mechanics was proclaimed, in 1927, to be such a true quantum theory. It had however to maintain the use of classical quantities, according to Bohr's interpretation, due to its reference to observation through macroscopic devices ; but this was not maintaining a classical theory, since the classical quantities were confined into a limited domain of validity, imposed by the quantum conditions[19].

Another type of interpretation of the theoretical quantum relations is Heisenberg's explanation of the “uncertainty ” or “indetermination” relations that had come out of the theoretical formalism as a consequence of the anti-commutation relations between the operators standing for “incompatible” observable magnitudes (for instance, position and impulsion)[20]. These, as operators, actually, were not (directly) observable, but their eigenvalues were, and they were considered as the physical ones, affected with the corresponding probabilities. Heisenberg's unequality relations were in terms of these “classical-type” quantities, considered through the observation process, implying an interaction with the obervation device which introduced a perturbation, unassignable (due to the finiteness of the quantum of action), making impossible to get at an exact supposed original value, prior to the interaction. This was clearly an *interpretation in classical terms of a quantum property* : it was intended to justify the limits of validity of the classical concepts in the quantum domain. But with it we have entered already the third stage of the elaboration of quantum physics.

THE QUANTUM THEORETICAL SCHEME, ITS DEVELOPMENTS AND INTERPRETATIONS

The third stage is that of the *self-consistent quantum theory* that wave or quantum mechanics have been generally considered to be since then. As a physical theory, quantum mechanics yielded a stable frame of symbolic entities formalized mathematically (state vectors defined in a Hilbert space, differential or matrix linear operators acting on them, etc.), with rules of correspondence with physical outcomes : these outcomes were chosen as the results of measurements, which define the choice of an "observational interpretation" (that of the Copenhagen school). Such standard or dominant interpretation imposed itself in the "quantum" scientific community through Bohr's influential position and convincing ability[21].

One might actually distinguish the theory itself from its interpretation problem : the theory (as theoretical scheme) worked well, but the physicists were not able to state exactly what it meant "physically". They could get predictions from it, and observe them as verified (for example, the "tunnel effect"), but they could not state clearly to what the theoretical "formal" quantities and the probabilities attached to them should be referred. To them, there was no imaginable physical objects and properties of the kind quantum theoretical quantities would describe directly. (Even Born, Heisenberg, Jordan and Dirac thought so, although they had invented these theoretical forms). Clearly the need for an interpretation of the overall theoretical scheme was sustained by the feeling of a lack of intelligibility, not by some weakness of the theoretical scheme itself.

The theory had been obtained by integrating all the formal exigencies required by the phenomenal properties already considered (as those evoked above) into a theoretical structure inspired by the hamiltonian form of the classical physical theories. As a result, theoretical relationships were obtained between the variables. These relationships expressed the quantum physical properties, but in an apparently abstract way, as the variables used were not of a commonly conceived physical type. The quantum variables with their relationships were considered together as an algorithm useful for calculations but which needed to be deciphered to be put in relation with an actual physical description. This decoding was exactly to what pretended the "formalism interpretation".

To sum up, quantum mechanics was a theory presenting itself under the appearence of a mathematical formalism which was able to give account of the known physical phenomena of the domain, but under the condition that one modifies the physical meaning usually attached to the theoretical quantities appearing in the state equations, and that one adopts conventional rules for the correspondence between the theory and the observed phenomena (this being the "first level" of the interpretation). The interpretation problem was therefore conceived as more complex than in the preceding stages, as it did not any more point toward a deeper theory, for the main theory was already in hands : and, as a matter of fact, further dynamical theories (such as the quantum theory of fields) were developed with success inside the theoretical frame of quantum mechanics.

Interpretation, according to this new meaning, was proposed to give a translation in classical physical terms (which were those of the macroscopic instruments of observation) of the consequences of the abstract relationships of the "formalism". Such a physical interpretation implied a modification of the kind of "object" that was supposed to be described by physics. The rules of correspondence were thought to gain a full meaning if they were surrounded by a more general view about physical knowlege, breaking down with the previous one, and concerning mainly the subject-object relationship (this being the "second level" of the interpretation). The "Copenhagen" bohrian interpretation introduced the idea of a *subject-object indivision* that made impossible any direct representation of quantum systems : to it, such systems could be *described* and *thought* only through their *observational conditions* and there was no such thing as a "real physical system" existing of its own, with its individuality, of the type Einstein persisted to think of. Such was the dominant claim, and hence the "debate of the century" between Bohr and Einstein[22].

We shall not enter into details about this new kind of interpretation, which mixed a theoretical (physical) and a philosophical concern, as it is rather known[23]. Let us observe that most of the participants in the debate, proponents of one interpretation or another, shared the common purpose to make the quantum mechanical well established knowledge a fully intelligible one. The question is about the type of intelligibility which was claimed by the various parts, and it may be formulated as : which *kind of rationality* was at stake with the various possible interpretations.

We shall only propose here, as a conclusion, some elements of reflection about the cost of the interpretation from a rational point of view. It seems that to modify drastically our conception of knowledge by having the subject-object distinction vanish is of a too high cost, particularly if one considers the other domains of kowledge where this distinction is still considered of value ; and the more so that in practice physicists keep this separation and consider quantum systems as *objects* which they can *think of* and *act on*. For this, they simply jump over the classical intermediaries and think directly their quantum systems with the help of the theoretical quantities of the "formalism", which they see, at least from a practical point of view, as expressing the proper quantum physical concepts, and they actually are effective in it. We have argued elsewhere that they are fully justified to do it by the quantum phenomena themselves[24].

Let us add to this an argument related to the "inner interpretation", which we have mentionned above, for closed classical theories. A satisfactory theory, for many physicists, is a theory in which the physical meaning of the concepts or quantities is given from inside the theory itself, by the theoretical structure, i.e. by the theoretical relationships (this is a general claim by Hertz, by Einstein, even by Heisenberg, and by others). Why would it not be possible to consider quantum mechanics under such a point of view ? This, for sure, would correspond to its less costly interpretation, to its rational achievement. It has seemed up to now difficult, because a direct physical meaning had not been attached to the quantities of the theoretical formalism, qualified of abstract and purely mathematical, as they have mathematical forms that are not numbers or numerical functions, and as they do not correspond directly to observational results.

But nothing obliges *a priori* physical concepts and quantities to be directly given by observation (they can be reconstructed from it), nor to be expressed by numbers or numerical functions ; what we know, above all and more deeply, is that the meaning of quantities (the physical meaning in our case) is given in their mutual relationships. The theoretical quantum quantities make no exception in this sense, as we know that *all fundamental quantum properties can be formulated as straightforward consequences of the relationships of the quantum "formalism"*. A simple extension of meaning of what to accept as physical quantities to the forms of the quantum theoretical ones would make the interpretation problem of quantum mechanics a simpler and a *purely physical* one, free from heavy and undue philosophical upheavals. And this would relieve all the more the question of the *intelligibility of the quantum knowledge*.

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Notes

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[1]See Max Planck's 1900 paper : "Zur Theorie des Gesetzes der Energieverteilung im Normalspektrum", repr. in Planck's *Physikalische Abhandlungen und Vorträge*, 3 vols., Vieweg, Braunschweig, 1958 ; Albert Einstein's 1905 paper : "Ueber einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesischtspunkt", repr. in A.E., *The Collected Papers of Albert Einstein* (CP), Princeton University Press, 2, p. 150-166 ; 1906 paper : "Zur Theorie der Lichterzeugung und Lichtabsorption", CP, 2, p. 350-357 ; 1909 paper : "Zum gegenwärtigen stand des Strahlungsprobleme", CP, p. 185-193 ; 1912 paper : "Zum gegenwärtigen Stande des Problems des spezifischen Wärme", CP, 3, p. 521-548 ; Paul Ehrenfest's 1912 paper : "Zur Frage der Entbehrlichkeit der Lichtäthers", *Physikalische Zeitschrift* 13, 1912, 317-319 (repr. in P.E., *Collected scientific papers*, edited by M. Klein, North Holland, Amsterdam, 1959) (CP, 3, p. 521-548) ; Poincaré's 1912 paper : "Sur la théorie des quanta", *Journal de physique théorique et appliquée*, 5ème série, 2, 1912, 5-34 (repr. in HP, *Oeuvres*, Gauthier-Villars, Paris, 10, p. 626-653. See Max Jammer, *The conceptual development of quantum mechanics*, Mc Graw-Hill, New York, 1966 ; Olivier Darrigol, Statistics and combinatorics in early quantum theory, *Historical Studies in the Physical Sciences*, I : 19 (1), 1988, 17-80 ; II : 21 (2), 1991, 237-298 ; Michel Paty, "Poincaré, Langevin et Einstein", *Epistémologiques. Philosophie, sciences, histoire. Philosophy, science, history* (Paris, São Paulo), 2, n°1, 2002 ; M. Paty, *Einstein, les quanta et le réel. Critique et construction théorique*, forthcoming.

[2] M. Paty, *Einstein, les quanta et le réel, op. cit.*

[3] See Niels Bohr's 1913 three papers : "On the constitution of atoms and molecules", in N. Bohr, *Collected works*, edited by L. Rosenfeld, et J. Rud Nielsen, North Holland, Amsterdam/ Elsevier, New York, vol. 2 *: Works on atomic physics (1912-1917)*, 1981, p. 159-234.

[4] See Einstein's 1916 paper : "Zur Quantentheorie der Strahlung", *Physikalische Gesellschaft Mitteilungen* (Zürich), 1916, 47-62 ; repr. in *Physikalische Zeitschrift* 18, 1917, 121-128.

[5] In these formulas, E and p stand for (particle) energy and momentum, v and l for (wave) frequency and momentum, and h is Planck's constant (with the dimension of an action).

[6] In these formulas, the transition probability per unit of time between two levels, m and n, $dW_{mn'}/dt$, is given as a function of the transition amplitudes of the levels (taken as given), A_{mn} and B_m (respectively, of spontaneous emission and of induced emission and absorbtion), the density of the radiation, r, and the number of molecules (or atoms) in the state considered at equilibrium.

[7] For instance, in his contributions at the 1911 Solvay Conference, Einstein claimed as such principles the energy conservation one and "Boltzmann's principle", as he named the definition of entropy by probability, $S = k \text{ Log } W$ (A. Einstein, "Etat actuel du problème des chaleurs spécifiques, suivi de Discussion du rapport", *in* de Broglie, Maurice et Langevin, Paul (eds.), *La théorie du rayonnement et les quanta. Communications et discussions de la réunion tenue à Bruxelles du 30 octobre au 3 novembre 1911, sous les auspices de M.E. Solvay*, Gauthier-Villars, Paris, 1912, p. 407-450). (S is the entropy, k Boltzmann's constant, W the probability of the considered physical state).

[8] See, for example, M. Paty, *Einstein philosophe. La physique comme pratique philosophique*, Presses Universitaires de France, Paris, 1993, chapter 4.

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[10] A. Einstein, “Zur Quantentheorie der Strahlung”, *op. cit.*, 1916.

[11] For brevity, I refer to my analysis of this episode, with reference to the original publications : M. Paty, *Einstein, les quanta et le réel.*, op. cit., forthcom.

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[14] See M. Paty, “Formalisme et interprétation physique chez Schrödinger”, *op. cit.*, p. 161-190, and reference to the original publications.

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[20] See Heisenberg's 1927 paper in W. Heisenberg, *Gesammelte Werke*, *op.cit.* ; see also W. Heisenberg, *Der Teil und der Ganze. Gespräche in Umkreis der Atomphysik*, Piper, München, 1969. Trad. fr., P. Kessler : *La partie et le tout. Le monde de la physique atomique (Souvenirs, 1920-1965)*, Albin Michel, Paris, 1972 ; 1990.

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Correspondance 1916-1955, comment. M. Born, Seuil, Paris, 1972. See M. Paty, *Einstein, les quanta et le réel*, *op. cit.*

[23] More in M. Paty, *Einstein, les quanta et le réel*, *op. cit.*

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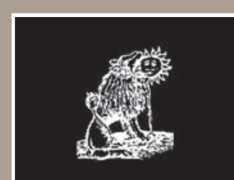

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