Quantum mechanics and realistic ontology
Historical and critical remarks

Paolo PECERE

ABSTRACT. Quantum mechanics appeared, far more than 20 years ago, as an efficient theory whose epistemological outlook was far from clear, which could be improved and even disputed in its formalism; therefore new experiments are being designed, in order to establish its validity on firmer grounds, or to declare a full-fledged scientific revolution. My observations today regard the epistemological problems of quantum mechanics, rather than the physical issues which are still unsettled, , particularly the question: are new theories going to alter our view of objectivity, knowledge and experience?

KEYWORDS: *quantum mechanics, epistemology, realism, realistic ontology*

Introduction

Quantum mechanics constitutes one of the most successful theories of modern physics in terms of predictive accuracy; it successfully solved, the main problems that affected atomic physics at the beginning of the XX century stimulated the experimental discoveries of post-war atomic physics and is still regarded as one of the main pillars of our physical knowledge of the world. Nonetheless, the ultimate validity of the theory has been harshly contested since the early years of ist history, even by physicists who contributed to its development, such as Einstein, Schrödinger and De Broglie. For instance, Einstein stated his view of the incompleteness of what he called "statistical quantum theory":

All my esteemed colleagues Born, Pauli, Heitler, Born, and Margenau (…) are all firmly convinced that the riddle of the double nature of all corpuscles (corpuscular and ondulatory character) has in essence found its final solution in *statistical quantum theory*. On the strength of the successes of the theory they consider it proved that a theoretically complete description of a system, can, in essence, involve only statistical assertions concerning the measurable quantities of this system (…) I am, in fact, firmly convinced that this theory operates with an incomplete description of physical systems.[1]

In the early '50s Werner Heisenberg, among the creators of the theory, took up the leadership of the so called "Copenhagen Interpretation", with the bold claim that QM could not be internally reformed, and had to be regarded moreover as the ultimate theory in the field of atomic physics. The issue of completeness was stressed by Heisenberg himself in a late comment on Einstein's critical view: «Einstein agreed with Born that the […] mathematical formalism of quantum mechanics correctly represents the phenomena of the [electronic] shells of the atom». But «Einstein did not want to acknowledge that quantum mechanics represented a finally valid [*endgültig*], and even less a complete, description of these phenomena».[2]

Heisenberg's firm defence of the "Copenhagen Interpretation", in spite of the different views supported by the leading quantum physicists, was partly a fruit of the renewed criticism of standard Quantum theory which began in the Postwar period.[3] Indeed, since the early '50s, new interpretations and alternative theories have appeared. As a result of these alternatives and of John Bell's severe criticism of the consistency of the standard interpretation regarding the measurement process, the debate within the community of physicists has led to a growing recognition of the revisability of the theory. Quantum mechanics has appeared, far more than 20 years ago, as an efficient theory whose epistemological outlook is far from clear, which can be improved and even disputed in its formalism; therefore new experiments are being designed in order to establish its validity on firmer grounds, or to declare a full-fledged scientific revolution. My observations today regard, rather than the physical issues which are still unsettled, the epistemological problems of quantum mechanics, particularly the question: whether new theories may alter our view of objectivity, knowledge and experience.

Standard Quantum mechanics: paradoxes and the Copenhagen Interpretation

I will discuss some philosophical issues about objective reality, visualization and determinism as well as the way their solution, proposed in the early days of quantum theory in a positivistic perspective, underwent heavy criticism from a realistic point of view. In order to understand these issues, it is necessary to give a very short exposition of those aspects of quantum mechanics (QM) which stimulated most philosophical arguments.

As it is well known, quantum physics started in the early XX century from the recognition of discontinuities in the interaction between matter and radiation. The visual representation of the atom, as composed by the nucleus and electrons rotating along elliptical orbits, was not compatible with classical electromagnetical theory. In 1912, Bohr proposed a new model of the atom, where only determinate orbits were "permitted" for electrons, and there was no room for understanding what happened when an electron "jumped" to a different orbit after an energy exchange. Bohr's model implies a restriction of the "visualizability" of physical processes, which was typical of classical mechanics. This loss in visualizability was retained in Heisenberg's new "quantum mechanics" (1925), which is introduced by a programmatic statement of positivistic attitude:

This present paper seeks to establish a basis for a theoretical quantum mechanics founded exclusively upon the relationships between quantities which in principle are observable.[4]

At the same time, as Heisenberg made clear in his 1927 paper on the "intuitive content" (*Anschaulichkeit*) of the theory, the process of measurement, according to the new theory, implies a limitation in the simultaneous determination of physical properties ("observables"), such as position and momentum ($\Delta x \Delta p \geq \hbar/2\pi$). Such relations are known as "uncertainty relations", and are implied according to Heisenberg. We have to give up the standard concept of causality, since we cannot know the present with sufficient accuracy in order to predict the future.

A second aspect of the theory, which radically differs from classical physics, is derived from the probabilistic interpretation of the wave function (Born 1927). The new quantum mechanics, formulated in years 1925-1927 by Heisenberg and Schrödinger, involves in his standard formulation a distinction between the equation of motion and the process of measurement, which is unknown in classical mechanics. By the wave function ψ we do not predict the mechanical properties at a given time (such as position and momentum), but the probability of measurement results. After each measurement, however, the wave function begins to evolve from the point were the "particle" has been found. After J. Von Neumann's influential exposition of the theory (1932), this is called the "collapse of the wave function" and was considered as an instantaneous effect of the measurement, which again cannot be further analyzed by the theory and is taken as a postulate.

The third problem to be mentioned, which was put forward by Einstein-Podolski and Rosen, and discussed in two seminal papers by Schrödinger in 1935, is the existence of "entangled states", that is joint states of physical systems which cannot be separated inside the theory but can get a definite value only by measurement. Here is how Schrödinger presented the novelty of the new physical concept:

When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before, viz. by endowing each of them with a representative of its own. By the interaction, the two representatives [the quantum states] have become entangled.[5]

In discussing the process of measurement, Schrödinger elaborated a famous paradox concerning the correlation between microscopic and macroscopic states in the process of measurement. The measurement of the alternative states of an atom in a box, which is initially in a state of superposition, is connected to the release of poison in the box, where a cat has been enclosed. According to QM, the macroscopic state of the cat is entangled with the microscopic state of the atom; therefore, we cannot tell if the cat is dead or alive unless we open the box and therefore measure the system. This paradoxical situation was usually contrasted by quantum physicists by way of a distinction between microscopic and macroscopic states, whose exact definition, however, had not been developed.

To sum up, these different aspects of QM put severe constraints on our objective knowledge of physical states, as it was conceived in classical physics. The main point of trouble is the process of measurement itself. According to the uncertainty relations, we have to give up the ideally unbounded precision of measurement. The collapse of the wave function and the disentanglement of states, moreover, qualify the process of measurement not only as the empirical acquisition of data, but as a necessary condition for the determination of physical states. These features of the theory certainly inspired Bohr for his elaboration of the "principle of complementarity", according to which in QM we can give a "unambiguous" description of the quantum world – in an analogy to classical physics – only by adopting different and alternative experimental contexts, whereas we have to give up the idea of atomic reality as being determined independently from the ways of our representation of macroscopic reality. Yet, as it has been repeatedly observed by recent quantum physicists, the limit between the microscopic and macroscopic world remain unclear and need a better elaboration.[6]

Anyway, while Bohr's views were difficult to understand and are still under discussion, Heisenberg drew distinct philosophical conclusions from the above featurers of QM. First, he interpreted the uncertainty relations as a confutation of the classical causality principle; second, he viewed the reduction of the wave packet as a result of the interaction between the observer and the physical system, developing a subjectivistic interpretation of QM. As a result of the latter view, he gave up any visualization of the quantum world, and in the '50s introduced the view of quantum properties as "potentialities", which are noticed through observation. These views, together with the idea of the ultimate validity of the theory, were central to Heisenberg's defence of the "Copenhagen Interpretation" in his widely read book *Physics and Philosophy* of 1958. The philosophical framework of Heisenberg's mature views was not anymore positivistic, but depends on a peculiar elaboration of the neokantian idea of "relativized a priori" principles, associated with scientific theories; nonetheless, Heisenberg still mantained that (standard) quantum mechanics was to be considered as a "closed theory", whose validity for the quantum domain was not to be challenged by any alternative theory.

Before considering the realistic opposition to such philosophical interpretation of QM, let us consider one classical example of the problematic nature of the theory, the two-slit experiment. A source of particles is separated from a photographic plate by a metal frame with two very close slits. The particles are directed toward the slits, and their final position on the plate is registered. Now, according to classical physics, by alternatively closing the two slits, we should get the same statistical distribution of particles as if both slits are open. The result of the experiment, however, is that we get a different distribution, which – by increasing the number of test particles – shows the shape of wave interferences. This leads to the hypothesis that matter is actually distributed in space as a wave, a view originally upheld by Schrödinger. Yet, the final positions of the particles distinctly show a particle-like behaviour (this led to Born's statistical interpretation of the wave function). On the whole, it seems that the particles passing through the first slit behave differently, according to the opening or closing of the second slit, even though the latter cannot physically influence the particles themselves.

This result was interpreted by Bohr as an example of the complementarity of knowledge; on the contrary, it was, and still is considered by many physicists and philosophers as strong evidence that the theory has to be reformed.

The realistic opposition (1932-1957)

Although himself influenced by positivism in his earlier work, Einstein was a staunch critic of QM from the beginning. As we have seen, it was not the efficacy and importance of the theory, but its *ultimate* validity which was contested by Einstein - who, after all, considered even his own theory of general relativity as incomplete. In 1935 Einstein, together with Podolski and Rosen, published a groundbreaking article, where the *incompleteness* of QM was argued. By considering two entangled systems, the authors argued that one could calculate the value of any chosen property in one system by observing the second one and without interfering with the former one. QM, on the other hand, states the impossibility of attributing definite values of *any* property to physical systems, *before the process of their measurement*. This means, according to Einstein-Podolski-Rosen (EPR), that QM is incomplete and has to be refined by a more powerful theory.[7]

EPR's argument is grounded on a concept of 'reality' as independent from the "perturbation" produced by the measurement process, and was as such contrasted by Bohr as question begging. Nonetheless, Einstein constantly upheld the need for a realistic and complete theory of the quantum phenomena, which QM did not satisfy, even though he shared this view with a tiny minority of physicists. This criticism of Einstein, on the other hand, deeply influenced Popper's early epistemological reflections. Elaborating on some of Einstein's epistemological statements about relativity theory, Popper argued in his influential *Logic of Scientific Discovery* (1934) that scientific theories do not arise from induction, but are advanced as free, even speculative claims about an independent reality, which cannot always be the object of direct observation. In striking contrast with the positivism of the thinkers of the "Vienna Circle", with whom he was in strict connection., Popper embraced the idea of "realistic metaphysics" or "ontology".

QM constituted a crucial point for the statement of this contrast. The interpretation and justification of the new theory by the physicists in Copenhagen and Göttingen was highly appreciated in positivistic philosophical circles, as it seemed to imply a scientific confirmation of their epistemological views. Drawing, again, on the position held by Einstein, Popper advanced in his book a statistical interpretation of QM. According to this view, QM merely describes the statistical behavior of ensembles of particles, and does not provide a description of the individual evolution of their states. As such, it does not supersede classical mechanics but can be likened to statistical mechanics in classical physics, which is the study of large numbers of particles. A new fundamental theory, able to explain and describe the properties of quantum particles, is possible, but is still lacking.

So far Popper's ideas closely reflected the views of Einstein, but in the following years the philosopher would develop a different view about the status of QM. As Einstein kept working on a unified field theory, which had to restore a complete description of physical reality in a deterministic theory, Popper – while recognizing the open status of physical research – developed in the early '50s a probabilistic interpretation of QM. According to this interpretation, the probabilistic nature of quantum theory depends on the physical existence of stochastic "propensities", which lead the evolution of particle states toward slightly unpredictable results. A major advantage of this view lies, according to Popper, in the recovery of a classical view of objectivity: particles and their paths can be visualized; the reduction of the wave packet is not a physical process, but a subjective modification in our information about physical systems; the uncertainty relationships and entanglement are to be referred to as statistical predictions, not to the actual properties of particles, though our knowledge about them can be temporarily limited. In the end, the interpretation of QM is just a matter of understanding probability theory, taking the very concept of probability as an objective feature of physical processes (grounded in "propensities") and not as the result of a subjective limitation of the information which is available to us.

Popper's original approach to QM – presented in the '50s in a number of essays as well as in the three-volume *Postscript to the Logic of Scientific Discovery*, which would appear only in 1982 - exerted a fundamental influence on the next generations of philosophers, contrasting widely rooted and elaborated views about QM and firmly stating the need for a realistic interpretation. Yet, Popper did not elaborate a full-fledged physical theory, different in its formalism from standard QM and alternative to it; nor did he think that such a theory was necessary at all. The propensity interpretation of QM, as an alternative to the Copenhagen Interpretation, had to be in itself sufficient in order to get rid of the paradoxical aspects of the theory. However, Popper's view was not able to remove all the faults that it helped to identify from the theory. For instance, Popper offered no convincing solution of the double slit experiment; he simply claimed that there is an influence of the experimental set up on statistical predictions, without being able to explain the striking, wave-like interference patterns on the photographic plate, by means of a realistic physical theory.[8]

It is surprising, then, that Popper did not react positively to the alternative theory published in 1952 by David Bohm. This was a full-fledged, consistent and predicatively equivalent, yet an alternative theory to QM, which modified the very formalism of standard QM and was able to dispose of the "positivistic" features of the theory by postulating hidden variables (in order to preserve classical trajectories for particles) and a dualistic particle-wave ontology. Bohm's mechanics realized and developed in detail an idea presented as early as 1927 – and later abandoned – by Louis De Broglie, introducing a "pilot wave" associated with particles and responsible for interference effects. In the two-slit experiment, for instance, the modification of the experimental set-up modifies the evolution of the pilot wave, and therefore the behavior of the single particles. The classical visualization is preserved: particles are supposed to move along strangely curved paths, which produce interference pictures.

This result of an alternative, the hidden variables theory – a result that was considered by the defenders of the standard view as a logical impossibility – eliminated many mysteries about the role of the observer and the influence of the measurement process on physical reality. Moreover, *Bohm's "quantum force" (the pilot wave) could take the place of Popper's propensities in explaining the probabilistic behavior of particles in a classical representation*. It is all the more striking, therefore, that Bohmian' mechanics receives a cold reception in Popper's writings of this period.

Popper and Bohm even had the occasion of directly discussing each other's views, although not personally. Bohm left the US in 1951 after being arrested for refusing to collaborate with the McCarthy anticommunist Commission and being therefore dismissed at Princeton. In 1957 he arrived in Bristol as a research fellow, and there he was invited to participate at the Colston Symposium "Observation and Interpetation", held on 1-4 April 1957. He presented the basic ideas of his new theory in his paper: "A proposed explanation of quantum theory in terms of hidden variables at a sub-quantum-mechanical level". Popper presented a paper on "The propensity interpretation of the calculus of probability, and the quantum theory", but he could not attend the Congress and had his former pupil Paul Feyerabend read his paper. The whole congress, with the intervention of Popper, Feyerabend, Bohm and his pupil Vigier, was dominated by a critical view of the orthodox theory; the latter was defended against objections by a quite isolated Leon Rosenfeld. In the same year Bohm published his first theoretical work, *Causality and chance in modern physics*, which had to receive in 1960 a quite positive review by Feyerabend, who was engaged, following his former teacher Popper, in the research for a realistic revival in epistemology. In spite of these favorable circumstances, the agreement between Bohm and Popper was very limited from the outset.

In the discussion about Popper's paper, Bohm objected to Popperj's belief that the propensity interpretation of probability "does not solve any problem of quantum mechanics. The wave-particle duality is just as difficult when you regard it through propensities as when you regard it in any other way". This is precisely the limit of Popper's view that has been remarked on before. Popper – in the reply written for the Congress' proceedings – did not reply on this point but expressed doubts regarding Bohm's derivation of probability in a deterministic world view.[9] This gives a clue to understand why the champion of realistic ontology did not accept the realistic quantum theory proposed by Bohm.

Why did Popper reject Bohmian Mechanics?

Bohm presented his theory as an attempt to restore a "deterministic" and complete view of physics, of the kind supported by Einstein and Schrödinger.[10] By postulating a sub-quantum-mechanical level, Bohm was able to argue that uncertainty depends on hidden deterministic processes and does not involve any role for the observer. Yet, the new determistic mechanics was obtained at the high cost of giving up major principles of the realistic view, as it was upheld by Einstein. First of all, as we have seen, entanglement and the collapse of the wave function, according to Bohm's mechanics, are real processes, which imply instantaneous, i.e. non-linear physical processes. In the two-slits experiment, for instance, the closing of a shutter *instantly* modifies the propagation of the pilot wave, influencing the paths of quantum particles regardless of the distance. This means that one of the principles of Einsteinian realism, the prohibition of action at distance, is violated. This feature of the new theory is known as non-locality, and it is precisely one of the points of dissatisfaction expressed by Popper in his remarks on Bohm's theory. In particular, Popper shared Einstein's doubts against Bohm's hypothesis that the reduction of the wave packet introduces a "superluminal" interaction, and unrightly claimed that it "even retains Heisenberg's 'interference of the subject with the object' – although it tries to interpret this interfence objectively".[11]

On this point Bohm's and Einstein's views actually differed, and indeed the relativistic generalization of Bohmian mechanics is still a disputed point in physical theory. Moreover, Bohm being a former supporter of the Copenhagen Interpretation, Popper apparently connected the new non-local theory with the alleged "subjective" explanations of the measurement process in the standard interpretation. To sum up, non-locality was certainly one of the reasons why Popper, although he was well disposed towards a speculative and incomplete new hypotheses, did not support Bohmian mechanics.

But the main point of divergence lies in the deterministic character of this new theory. Popper devoted a large section of his *Postscript to the Logic of Scientific Discovery* to the critique of scientific determinism (this section had to be published in 1982 as vol. 2 of the *Postscript*: *The Open Universe: an Argument for Indeterminism*). His criticism of the deterministic interpretation of both classical and quantum mechanics, grounded on the propensity theory of probability, was considered by Popper as a cornerstone of his justification of human creativity and free will. Commenting on the well known Kantian anthitesis between determinism and free will, Popper argued as follows. Kant was a follower of scientific determinism, and therefore, in order to make room for free will and morality, had to distinguish between nature as the totality of (deterministic) the *phenomena* and the supersensibile (indeterministic) substratum of *noumena.* By arguing against determinism inside physical theory, Popper supported the "uniqueness" of the World. "Kant's worries were therefore unnecessary".[12]

It is very important to put this anti-Kantian argument in the context of Popper's overall views about nature and free will. Indeed, the link between indeterminism and free will was openly contested by the great historian and philosopher Ernst Cassirer in his *Determinismus und Indeterminismus in der modernen Physik* (1937), which contains the most articulated and influential Kantian interpretation of quantum physics of this period. Cassirer emphasized a distinction, already put by Kant himself, between causality as a connection of phenomena according to a rule and Laplacean determinism. He argued therefore – drawing on writings of the Austrian physicist Franz Exner and his pupil Schrödinger – that the probabilistic feature of quantum theory does not contradict the law of causality. Moreover, in the last pages of his book, commenting on some very famous lines of Plato's *Phaedo*, Cassirer stated that the transition from casual determination of events in the physical domain and the determination of free action in the sphere of human values stand under completely different points of views, and that the idea of a foundation of free will in the quantum domain is a "metabasis eis allo genos". Therefore, Cassirer concluded:

Quantum mechanics has never abandoned the idea of causality; it has rather given a different [probabilistic] treatment of causality. If the idea of moral freedom was put in danger by the idea of causality, Quantum mechanics could not be of any help […]

We cannot give up the higher concept of determination in the construction either of the physical world, or of the ethical world. But the determination in the domain of Being is subject to different categories than in the domain of Duty. These categories do not contradict each other, because they belong to completely different "dimensions" of thinking.[13]

These pages received high praise by physicists such as Max von Laue and, notably, Max Born. The latter cited Cassirer's arguments about causality and determinism in his *Natural Philosophy of Cause and Chance* (1949), and supported Cassirers's pluralistic ontology, exposed in the latter's *Philosophy of Symbolic Forms*.[14] It must be remarked, finally, that Born's agreement with Cassirer can be read among a wider convergence between the followers of Bohr's complementarity and the pluralistic Neokantism of Cassirer, which was grounded on different issues, such as the rejection of visualization as a necessary condition for physical knowledge and the symbolic character of physical knowledge. Though this agreement was far from complete and the "Kantian" thread in the earlier quantum epistemology presents a quite complicated story – which we cannot expound in detail here – Popper must have been aware of the intersection between Kant's transcendental dualism and complementarity. As a matter of fact, he would not consider the pluralistic view of the Kantian philosopher Cassirer, who was a supporter of Bohr and of standard QM.

Nonetheless, in the *Postscript*, Popper held a quite similar view to Cassirer's, as he admitted that we are fre,e not in that we are able to act randomly, but because there is a limit in the rational prediction of events, notably of works of art and science themselves.[15]

We are 'free' […] not because we are subject to chance rather than to strict natural laws, but because the progressive rationalization of the world – the attempt to catch the world in the net of knowledge–has limits […].

Outstanding among the reasons for my conviction [about indeterminism] is the intuitive argument that the creation of a new work, such as Mozart's G minor symphony, cannot be predicted, in all its details, by a physicist, or a physiologist, who studies Mozart's body in detail – especially his brain – and his physical environment.[16]

Indeed, the core of the book contains different arguments against scientific determinism, none of which is drawn from the propensity interpretation of QM, and in an article from 1973 (included as an *Addendum* in the book) Popper made clear that "indeterminism is not enough" for the foundation of creativity and free will.[17] Still, he apparently considered it necessary to have an indeterministic physical theory, in order to leave room for free will. In this article Popper introduced a brand new ontological framework, which he was to discuss more at length in another article about scientific reductionism and the incompleteness of science (also included as an *Addendum* in *The Open Universe*)[18] and in his book on the mind-body problem, written with the neurophysiologist John Eccles, *The Self and its Brain* (1977). In these works Popper presented several arguments against scientific reductionism and defended interactionism, that is, the view according to which psychological reality is different from physical reality and can causally interact with the latter. Therefore he gave up the monistic tendency of the *Postscript* and presented a pluralistic ontology, by drawing a distinction among the World of physical events ("World 1"), the World of psychological events ("World 2") and the World of cultural products ("World 3"), considered as three distinct ontological domains which can causally interact. This new framework had to support, again, in indeterministic metaphysics. However, even in this late period of Popper's thought the arguments about indeterminism overlap. He claims that the indeterministic feature of QM contradicts the reduction or identification of phychological states to physical states. At the same time, along a quite different line of argument, it is the recognition of cultural causation which is contrasted to monistic views. In the end, it is far from clear whether the adoption of an indeterministic theory of physics constitutes a necessary condition for the philosophical defense of free will.

Following his own method of looking for scientific and falsificable theories in order to corroborate metaphysical claims, among them his own "metaphysical realism", Popper consistently devoted many efforts to the interpretation of Quantum theory; nonetheless, instead of taking into serious consideration a bold, realistic and full-fledged theory, such as Bohmian mechanics, Popper heavily relied on his own indeterministic, purely philosophical interpretation. His connection of "metaphysical realism" with quantum mechanics, in the '50s and after, shows more autonomy and independence of pure philosophical argumentation and philosophical concerns than in his earlier works. Still, even in this phase, Popper continued to rely on an indeterministic commitment in physics.

Conclusions

The overlapping of metaphysical and physical arguments in Popper's realism, and his rejection of Bohmian mechanics, suggest some remarks about a subtler articulation of the issue of realism.

'Reality', 'realism', 'reductionism'

One should draw a distinction between 'reality', as the ultimate aim of knowledge, and the specific forms of 'Reality' considered from the point of view of physical knowledge, outer perception, psychological introspection, art, etc. Such a distinction was notably drawn by Cassirer in his articulation of the different symbolic forms, such as expression, perception and scientific knowledge. Popper himself, though he was not fond of idealistic philosophy, shared the anti-reductionistic trend of such pluralism, and even articulated a similar ontological distinction with his concepts of World 1 (the world of physical processes), World 2 (the world of psychological processes) and World 3 (the world of cultural products, such as theories and works of art). In both approaches, the idea of a singular, independent reality, underlying all the phenomena of human experience remains an abstraction, whose content is provided according to different "forms", or dimensions of experience itself, whose difference cannot be eliminated even by a successful scientific reduction.

Along this line, we cannot identify the content of a scientific theory with a description of 'Reality' in the wider sense. This contrasts a now scarcely represented radical reduction program, which was strongly supported by the Viennese specialists in the field, and whose last impressive monument are the first two volumes of the incomplete *Encyclopedia of the Unified Science*, published in Chicago in 1955 and 1971.

Physical reality and scientific theories

One should also distinguish between 'physical reality', as the aim of scientific knowledge, and the descriptions of the latter in different scientific theories. From the point of view of a realistic ontology, physical reality is considered as an independent being, and this supports the search for (to quote the title of Popper's seminal paper of 1967) a "quantum theory without the observer".

Besides this general constraint, a pure philosophical argument cannot decide for the rejection or acceptance of a specific theory, on the grounds, say, of a critical appraisal of non-locality or stochastic elements in quantum theories (in Bohmian mechanics and GRW models, respectively). This choice should depend strictly on physical arguments, such as empirical adequacy, predictive power, structural simplicity, andconsistency with other parts of physical theory. (For example, by carefully considering Bell's disequality and Aspect's experiments we feel more confident about the non-locality and hidden variables theories. By testing the conservation of energy and the possible influence of gravitation on stochastic "noise" we can collect evidence in support or against GRW models etc.)

Physical Theory, Biological and Cultural Phenomena

Regarding the intricate connection between physical theory and psychological experience, our first point suggests that we should reject radical reductionist programs, or at least avoid selecting among scientific hypotheses on the light of reductionism. Indeed, even if we admit some causal interaction between physical and psychological reality, or even if we support an identity between matter and mind, we cannot derive from this assumption any selection among most aspects of different physical theories, such as determism and locality in QM. For instance, the emergence of order and legality, at a biological or cultural level, could be compatible with both chaotic, intrinsically indeterministic, and complex, yet deterministic accounts of the underlying physical processes (think of the role of mutation in evolution theory, or the existence of subconscious conditions of thinking and acting in neuroscience and psychoanalysis).

Ontology

Therefore realistic ontology – in spite of its name, which originates in XVII-XVIII century scholastic metaphysics – cannot be articulated into a single theoretical framework and cannot be grounded on a single successful physical theory (such as QM); it must be articulated in different special ontologies, according to well rooted traditions in European philosophy (Kantism and Husserlian phenomenology), whose relevance for the reappraisal of contemporary quantum theory has yet to be appreciated.

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