language, perfecting the art and science of logical clarity and consistency. Nevertheless, one of the most influential linguistic philosophers of the twentieth century, Ludwig Wittgenstein, ended his first book with the cryptic message: "What we cannot speak about we must pass over in silence" (Wittgenstein, 1961, §7). This tantalizingly mysterious, single-sentence concluding section to a book that attempted to provide a highly logical explanation of how words can have the power to convey meaning has been interpreted in a wide variety of ways.

Could Wittgenstein have been a mystic? This seems rather unlikely, given the great number of words he wrote on wholly non-mystical themes. Yet in the few paragraphs immediately preceding the above quote, he points out that *some* things "cannot be put into words. They *make themselves manifest.* They are what is mystical." (§6.522). He then encourages us "to say nothing except what can be said, i.e. propositions of natural science—i.e. something that has nothing to do with philosophy" (§6.53) and suggests that we correct a person who has attempted to speak metaphysically by demonstrating "that he had failed to give a meaning to certain signs in his propositions." Such a person (presumably Wittgenstein was thinking of his students) would be dissatisfied, feeling we had *failed* in the task of "teaching him philosophy;" yet "*this* method would be the only strictly correct one."

Not being a Wittgenstein scholar, I shall make no attempt in this essay to explain how (or indeed, *whether*) these apparently mystical comments can be made consistent with the rest of Wittgenstein's philosophical corpus. However, I do wish to argue that the prima facie meaning of his words at the close of the *Tractatus* might be intended with the utmost seriousness. Although the philosophical task involves the analysis of words, the *ultimate fulfillment* of this task is an experience not unlike that described by mystics, wherein the words cease and are replaced by an awareness (sometimes called a "vision" or even, paradoxically, a "sound") of wordless silence. As Wittgenstein puts it immediately before the famous concluding sentence of the *Tractatus* "He must transcend these propositions" (§6.54) —i.e., the propositions of Wittgenstein's *own* philosophy, the propositions whose paradoxical purpose is to induce an awareness of the inability of philosophers to gain any knowledge of anything metaphysical, yet whose status cannot themselves be counted as anything other than metaphysical!—"and then he will *see* the world aright." Here Wittgenstein is suggesting that the intended result of this new type of metaphysics is not (as in classical metaphysics) to gain knowledge, but rather, *to induce a certain type of experience.* This experience,

Hekmat va Falsafeh
(Wisdom and Philosophy)
Vol. 2, No. 2, August 2006, pp. 67-76

حکمت و فلسفه
سال دوم، شماره دوم، تابستان ۱۳۸۵

Silence as the Ultimate Fulfillment of the Philosophical Quest

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Abstract
The surprising comment Wittgenstein makes at the end of his Tractatus suggests that, even though the analysis of words is the proper method of doing philosophy, philosophy's ultimate aim may be to experience silence. Whereas Wittgenstein never explains what he meant by his cryptic conclusion, Kant provides numerous clues as to how the same position can be understood in a more complete and systematic way. Distinguishing between the meanings of "silence," "noise" and "sound" provides a helpful way of understanding how philosophers can devote so much effort to analyzing words even though their quest is ultimately fulfilled only in a deep experience of reality that is most adequately expressed in silence.

Keywords: *experience, insight, Kant, linguistic analysis, meaning, metaphysics, mysticism, noise, silence, Wittgenstein.*

* * *

"… one can speak far more of that of which one knows nothing than of that of which one knows something" (Kant, 1902, vol. 29, p.78).

Philosophy is about understanding words and how words come to have meaning. Thus much of the best philosophical thought and writing, especially in the twentieth century, has dealt with the analysis of

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Maxwell, it is only a characteristic of the entity itself (Maxwell, 1976, pp.283-6).

42. It should be born in mind that according to OQT, the measuring device itself, is also subject to the formalism of quantum mechanics if it is itself the object of observation by another piece of macroscopic apparatus.

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proof was mathematically impeccable, he had made a harmless looking technical assumption. Bohm of course had not used this assumption and thus was able to produce a viable version of hidden variable theory. It was John Bell who in 1964 clarified the issue and removed the imposed restriction.

37. H.Margenau for example has called it *latency* while Heisenberg dubbed it *potentia*. In late 1950's, Heisenberg, in an attempt to move away from the phenomenological approach towards quantum mechanics, introduced the notion of *potentia*: "Now, the theoretical interpretation of an experiment starts with the two steps that have been discussed. In the first step we have to describe the arrangement of the experiment, eventually combined with a first observation, in terms of classical physics and translate this description into a probability function. This probability function follows the laws of quantum theory, and its change in the course of time, which is continuous, can be calculated from the initial conditions; this is the second step. The probability function combines objective and subjective elements. It contains statements about possibilities or better tendencies ("*potentia*" in Aristotelian philosophy), and these statements are completely objective; they do not depend on any observer; and it contains statements about our knowledge of the system, which of course are subjective in so far as they may be different for different observers" (Heisenberg, 1958/ 1989, pp.40-1). See also A. Miller, 1984/86, 1985, & 1990.

38. A survey of a number of these proposals is given in A. Shimony (1986).

39. At the outset of his article, Maxwell has made it clear that in his approach, macro systems arise simply as the outcome of interaction between a vast number of micro systems. His main concern is to show that such an interpretation is *in principle*, viable. That there is a *practical* problem in calculating the structure of macro systems out of the configuration of micro systems does not undermine the validity of the model.

40. Note that classical statistical mechanics is not a *fundamentally* probabilistic theory: it presupposes that the dynamical laws are *deterministic*. Probabilism enters into classical statistical mechanics via probabilistic distribution of initial and boundary conditions in relevant ensembles of physical systems (Maxwell, 1988, p.12).

41. The notion of *propensity* was first introduced by Popper (1957). Any propensity P has associated with it a number of possible outcomes $O_1 \ldots O_n$. In specifying the value of a the propensity P at any instant we specify the probability P_r that outcome O_r will occur should the propensity be actualized through the occurrence of a probabilistic event at the instant in question, with r = 1 ... n, and

$$\sum_{r=1}^{n} P_r = 1.$$

Maxwell's notion of propensity, differs from that of Popper. the basic difference boils down to the point that for Popper propensity is a characteristic of the entity + the whole experimental set up, whereas for

by others in Einstein's archive. Their final verdict however, is that Einstein's own argument thought valid, is nonetheless unsound, in that it cannot distinguish, unambiguously, between different quantum systems.
For sympathetic and informative expositions of Einstein's interpretation of Quantum mechanics see L.E.Ballentine (1970, 1972).

30. Einstein, Podolsky, Rosen (1935 / 1970, p.124). The authors had emphasised that their criterion, "while far from exhausting all possible ways of recognizing a physical reality, at least provides us with one such way, whenever the conditions set down in it occur. Regarding not as a necessary, but merely as a sufficient condition of reality, this criterion is in agreement with classical as well as quantum-mechanical ideals of reality." (*ibid*)
31. A.Fine & M. Beller in their [1994] have pointed out that the criterion of reality which Bohr had made as the main target of his criticism was used by Einstein and his colleagues only to clarify that, "when a value is inferred on the unmeasured system, that value constitute an element of reality (i.e., that it must be included in a complete description)."
32. In Fine and Beller's view Bohr and Heisenberg have considered the uncertainty relation as a prohibition not merely on simultaneous measurability, but on the simultaneous existence of sharp values for conjugates variable. In this case, the EPR assignment of simultaneous sharp values for both P and Q would simply be inconsistent with the uncertainty relations (p.6).
33. It should be born in mind that for Bohr the very concept of "phenomenon" refers only to the observations obtained under circumstances whose description includes an account of the whole experimental arrangement.
34. In the fifth Solvay conference, de Broglie delivered a paper entitled "The new dynamic of quanta" in which he presented in an incomplete and diluted form a simplified version of his original ideas concerning a wave-pilot theory. However, this theory did not receive with enthusiasm among the audience. De Broglie himself admitted that it was partly due to this unfavourable reaction that he abandoned his own ideas and espoused the Copenhagen interpretation from then on. Twenty-five years later, however, Bohm's paper, and certain other developments in the general theory of relativity revived his interest in his original causal approach (*Cf.* Jammer, 1966, p.357).
35. "[T]he quantum potential [does] not depend on the intensity of the wave associated with [the quantum objects]; it depends only on the *form* of the wave. And thus, its effect could be large even when the wave has spread out by propagation across large distances" (Bohm, 1987, p.36).
36. Von Neumann in his (1955) after presenting his theorem against the hidden variable theories had emphasised that, "It should be noted that we need not go any further into the mechanism of the hidden parameters since we know that the established results of quantum mechanics can never be rederived with their help" (p.324). As we have noted before, although von Neumann's

of works have appeared on the scene challenging the traditional view. Among these publications, the works by A. Shimony (1983, 1988), and E. Mackinnon (1982), and some recent books on N. Bohr, (e.g., J. Honner 1987 and D. Murdoch 1987) are worth mentioning. Some of these writers, in their enthusiasms for *rehabilitating* those founding fathers have apparently gone too far. For example, H. Krips (1987, p.1) writes: "Neither Heisenberg nor Bohr were anti-realists in the metaphysical sense of denying the existence of an objective external reality lying behind the 'veil of perception', nor did they eschew the scientific realist's commitment to describing that reality within science. In particular they shared with Einstein and the 'realists' a belief in the objective reality of atoms, as well as putting forward atomic theories of matter within science."
Some other writers, (e.g. H. Folse, 1986), in their attempts to make a realist of the authors of Copenhagen version of quantum mechanics have tried to make use of more recent developments in realism/ anti-realism debates. Folse has claimed that Bohr and his colleagues should be called, (in modern jargon), entity-realist, "His [Bohr's] position parallels Cartwright's realist defence of phenomenological laws, and, like Cartwright he eschews building a model to interpret the formalism and then establishing a representational correspondence between the properties of this model and the properties of a reality that lies behind the phenomena" (p.99). This view however, does not seem to be correct given the fact that Cartwright, as we have already seen, advocates the notion of capacity and power for micro-entities and does not subscribe to a Kantian distinction between the noumena and phenomena as Bohr did.

28. In his reply to the famous paper by Einstein, Podolsky, Rosen (1935), *Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?* , Bohr writes, "It is shown that a certain 'criterion of reality' formulated in a recent article with the above title by A.Einstein, B.Podolsky and N.Rosen contains an essential ambiguity when it is applied to quantum phenomena. In this connection a viewpoint termed 'complementarity' is explained from which <u>quantum-mechanical description of physical phenomena would seem to fulfil, within its scope, all rational demands of completeness</u>" (Bohr, 1935, italics in original, emphasis added).

29. The intent of the paper, in Einstein's view, was to present a simple, yet compelling argument for the incompleteness of quantum theory. But as Einstein soon after the publication of the paper confided to Schrödinger that, "For reasons of language [the paper] was written by Podolsky after many discussions ... But, it still has not come out as well as I really wanted; on the contrary, the main point was, so to speak, buried in erudition" (Einstein, 1936). In a recent article, Robert Delete and Reed Guy (1991) have examined the EPR paper from this point of view and have produced a reconstruction of Einstein's own incompleteness argument based on the material researched

be photographed, yet it is not an object; it has no end, and it appears in a different place for each observer.

23. See for example D. Bohm (1957), K. Popper (1967, 1983), B. d'Esagnat (1979/83, 1981/83).
It should be born in mind that the formalism of the theory and different gloss of that formalism are not one and the same thing. Each theory *T* consists of a formalism *F*, a set of correspondence rules *R*, and an explanatory model *M*. The correspondence principle and the model together (or if the former is included in the latter, only the model) are called the interpretation or the semantic of the theory. Now while no pure formalism can be regarded as a physical theory, the semantics which serve to link the formalism to the outside world, may turn out to be incorrect. That is to say, the entities it has postulated may be non-existent, or the envisaged correspondences may be misplaced. From a realist point of view, science by and large progresses by making the formalism *F*, of an empirically successful theory *T*, part of, or at least isomorphic with, a more comprehensive formalism *F** of a more comprehensive theory *T**. The more comprehensive theory *T** may in turn retain part of the semantics of the older theory, or produce a totally new account of the physical reality while providing proper explanation as to where the old interpretation has gone astray.
As we shall see below there are a number of rival interpretations for the present formalism of quantum theory. One can also find radically conflicting accounts even within the frame work of OQM, and in the name of Copenhagen interpretation itself. As M.Stuart (1991, p.601) has pointed out, Rohrlich (1983) maintains that the Copenhagen interpretation has always upheld a realist ontology, whereas Peres (1985) is of the view that the cost of realism within that interpretation is paradoxical. It is also worth noting that in the case of the Copenhagen interpretation, that the predictive success of the theory was established before the finalization of the Copenhagen scheme.
24. For a criticism of van Fraassen's position see A. Paya, 2005.
25. See section IV.
26. "If we understand Einstein in the way that he takes us to, his own realist-sounding language maps out a position closer to *constructive empiricism* than to either 'metaphysical realism' or 'scientific realism'" (Fine, 1986, p.108, italics added). As for Bohr's philosophical inclination, Fine's advocates the traditional view that Bohr has been a positivist (Fine & Beller, 1994), "Bohr's Response to EPR", paper read at the meeting of BSPS, 17 January 1994.
27. The majority of the writers on the philosophical aspects of quantum mechanics in the past few decades have upheld the view concerning the anti-realist tendencies of the members of Copenhagen school. One early exception to this trend has been (the later) Feyerabend (1967/1981b) who (contrary to his earlier views in 1950s and early 1960s), has claimed that Bohr's approach is closer to the realists like Popper. In recent years a number

observation on the event can no longer be ignored. Conversely, quantum mechanics makes possible the treatment of atomic processes by partially forgoing their space-time description and objectification" (Quoted in French & Kennedy, 1985, p.25).

20. Feyerabend (1962, pp.192-3) has pointed out that compatibility of the complementarity principle with experimental results should not be taken as a sign of its correctness but as a possible indicator of it being devoid of empirical content. Furthermore, the *vagueness* in the formulation of this principle has enabled the founders and the followers of the Copenhagen school to take care of objections by "*development* rather than by *reformation*, a procedure which will of course create the impression that the correct answer has been there all the time and that it was overlooked by the critics."

21. Bohr was unhappy about this unpalatable consequence. However, he himself was largely responsible for this undesired outcome. In his Como lecture he had said that: "Our normal [classical] description of physical phenomena is based entirely on the idea that the phenomena may be observed without disturbing them appreciably" (Bohr, 1927, reprinted in Wheeler and Zurek 1983). Schrödinger has commented on this unfortunate influence of Bohr in a letter to Sommerfeld, "... I think the influence erroneous and regrettable which he [Bohr] has himself exercised, owing to his tremendous authority on this more recent development, above all by inventing some catchwords such as complementarity, *direct influence of the observer on what is observed, blurring the limit between subject and object* ...etc. The above mentioned complex of catchwords has been dragged on for two decades already ... and [no one notices] that it has not led to any single tangible success ... In this respect, I always remember Anderson's fairy tale about the 'King's new cloths'" (Quoted in Röseberg, 1990).
Bohr, later on in his life, tried to warn against drawing such a conclusion for the orthodox interpretation. For example, in his contribution to Schilpp's volume on Einstein, after pointing out the importance of the question of terminology in the quantum realm, he writes: "In this connection I warned especially against phrases, often found in physical literature, such as 'disturbing of phenomena by observation' or 'creating physical attributes to atomic objects by measurements' such phrases, which may serve to remind of the apparent paradoxes in quantum theory, are at the same time apt to cause confusion, since words like 'phenomena' and 'observations' just as 'attributes' and 'measurements' are used in a way hardly compatible with common language and practical definition" (Bohr, 1949, p.237). However, despite these cautionary notes, Bohr could not produce a more acceptable approach which would avoid the inherent inconsistencies of the Copenhagen interpretation.

22. N. Herbert (1985, p.162) has given the rainbow as an example of a phenomenon which is objective but not an object. It is objective, e.g. it can

VI. The *principle of Complementarity*: the wave and particle models are complementary. Which model we use is determined by the nature of measurement.

VII. The *Correspondence Principle*: quantum mechanics must converge to classical mechanics in the limit where n (quantum number) is large (Stuart, 1991). Stuart has pointed out that the Copenhagen interpretation is logically inconsistent. In his view the following pairs of postulates are logically incompatible and contradictory, (V,VI), (IV,VI), (IV,V), (II,V), and (I,V). Strong logical inconsistency is certainly not approved by many of other critics of the OQM. We shall discuss the shortcomings of the Copenhagen interpretation in the next section.

17. In a letter to Schrödinger in 1928, Einstein wrote, "The Heisenberg - Bohr tranquillizing philosophy or religion?, is so delicately contrived that, for the time being, it provides a gentle pillow for the true believer from which he cannot very easily be aroused. So let him lie there" (Einstein, 1928, reprinted in Przibram. (ed), 1967, p.31). For the impact of OQT on the physics community see also Selleri (1990).

18. Bohr in his later years has extensively discussed the meaning and significance of the concept '*phenomenon*' for the quantum physics and has tried to find a refined formulation for this term. In 1929 he wrote, "*The finite magnitude of the quantum of action prevents altogethe r a sharp distinction being made between a phenomenon and the agency by which it is observed* (Bohr, 1929 (English translation 1961), p.1, his italic). This formulation, which was a reminiscent of his Como lecture and had obviously quite unpalatable epistemological consequences, was later on refined furthermore. In 1938 Bohr put forward the following definition of the term *phenomenon*, "It is certainly more in accordance with the structure and interpretation of the quantum mechanical symbolism, as well as with the elementary epistemological principles, to reserve the word '*phenomenon*' for the comprehension of the effects observed under given experimental conditions" (1938, reprinted in *New Theories in Physics* 1939, p.11).

In his contribution to Schilpp volume he ascribed the term phenomenon to the *whole* experimental setup, "As a more appropriate way of expression I advocated the application of the word *phenomenon* exclusively to refer to the observations obtained under specified circumstances, including an account of the whole experimental arrangement" (Einstein, 1949, pp.237-8).

19. In his Nobel Prize lecture, in 1932, Heisenberg stated that: "The areas of validity of classical and quantum mechanics can be marked off from each other as follows: Classical physics represents the striving to learn about Nature in which essentially we seek to draw conclusions about objective processes from observations and so ignore the consideration of influence which every observation has on the object to be observed; classical physics, therefore, has its limits at the point from which the influence of the

15. Bohr (1927) reprinted in Wheeler & Zurek, 1983, pp.89-91. Bohr's lecture did not impressed the physicists at the conference. Léon Rosenfeld later said about it, "There was a characteristic remark by Wigner after the Como lecture, 'This lecture will not induce any one of us to change his own meaning about quantum mechanics' (Pais, 1991, p.315). It also should be emphasised that in the course of time Bohr tried again and again to further elaborate his conception concerning the exact meaning of *complementarity*. On one occasion he even changed the term to *reciprocity*, thinking that it is "more efficacious and pedagogical". However, a month later he declared that the new name to be a blunder (p.426). We shall further discuss in the text the significance of this principle for Bohr's philosophy.
Heisenberg in his (1930, p.65) has summed up his discussion of Bohr's complementarity principle in the following diagrammatic way:

	CLASSICAL THEORY Causal Relationships of Phenomena Described in Terms of Space and Time	
	QUANTUM THEORY	
Either Phenomena described in terms of space and time *But* Uncertainty Principle	(Alternatives related statistically)	*Or* Causal relationships expressed by mathematical laws *But* Physical description of phenomena in space - time impossible

16. The main postulates of the Copenhagen interpretation can be summarized as follows:
I. The Completeness principle: quantum mechanical wave function gives a complete specification of what can be known concerning quantum states.
II. The *Superposition principle:* a linear combination of two quantum states is itself a quantum state.
III. The *Uncertainty principle*: observables represented by noncommuting operators cannot simultaneously be measured with arbitrary exactness.
IV. The *Probability Interpretation*: the amplitude of wave function corresponds to a probability amplitude and its absolute square corresponds to a probability density.
V. The *principle of inseparability*: in quantum mechanics, the object under investigation and the apparatus for making measurement make an in-principle inseparable ensemble.

in the text, was not prepared to endorse this view concerning causality and determinism.

13. Heisenberg (1927), reprinted in Wheeler & Zurek ,1983, p.64, italics added. The following quote is also self-explanatory: "We turn now to the concept of 'path of the electron'. By path we understand a series of points in space (in a given reference system) which the electron takes as 'positions' one after the other. As we already know what is to be understood by 'position at a definite time', no new difficulties occur here. Nevertheless, it is easy to recognize that, for example, the often used expression, the '1s orbit of the electron in the hydrogen atom', from our point of view *has no sense*. In order to measure this 1s 'path' we have to illuminate the atom with light whose wavelength is considerably shorter than 10^{-8} cm. However, a single photon of such light is enough to eject the electron completely from its 'path' (so that only a single point of such a path can be defined). Therefore here *the word 'path' has no definable meaning*" (p.65, italics added).

14. In May 1926, Heisenberg, for the second time, came to Copenhagen to succeed Kramers as lektor. He stayed there until June 1927. During this period, one of the major problems which was constantly debated between him and Bohr, was the wave-particle duality. The two principles of uncertainty and complementarity are the fruits of the (sometimes heated) discussions of this rather short time span. As Heisenberg has recollected, "[During these discussions], we discovered that the two of us were trying to resolve the difficulties in rather two different ways. ... He [Bohr] was not so much interested in a special mathematical scheme. Especially he was not so willing to say, 'Well, let us take for instance matrix mechanics and let's just work that out, then we must find all the right answers'. He rather felt, 'Well, there is one mathematical tool — that's matrix mechanics. There is another one — that's wave mechanics. And there may still be other ones. But we must first come to the bottom in the philosophical interpretation" (Heisenberg, 1963 quoted in Pais 1991, p.302). The difference in style, prevented them from coming to a common conclusion, "In the end, shortly after Christmas, we both were in a kind of despair. In some way we couldn't agree and so we were a bit angry about it. ... Both of us became utterly exhausted and rather tense. Hence Bohr decided in February 1927 to go skiing in Norway, and I was quite glad to be left behind in Copenhagen, where I could think undisturbed about the hopelessly complicated problems" (Heisenberg 1971, p.77). During this period, Heisenberg developed his uncertainty principle while Bohr was groping with his (would be) complementarity principle. After his return from Norway, in March and spending some months with Heisenberg, trying to crystallize his views concerning the principle of complementarity, he was at last able to present the first full version of this principle at the Como conference on 16 September 1927.

11. Schrödinger believed that point particles did not exist. He felt that the underlying reality was a continuously distributed field or wave, whose properties and behaviour allowed one to sometimes get the impression that particles existed. His view was compatible with the fact that the continuous classical electromagnetic field possesses inertial and mechanical properties. The Schrödinger matter wave was a true classical continuous wave. He regarded electron as a continuous distribution of charge, the density of which ϱ, was related to the wave amplitude ψ, by the relation $\varrho = |\psi|^2$. This interpretation would imply a completely deterministic behaviour for the waves. Schrödinger's interpretation was tenable only as long as ψ would remain confined within an atom. In free space however, according to Schrödinger's equation, the wave must spread out rapidly over all space without limit. On the other hand, the electron is always actually found within a comparatively small region of space, so that its charge density cannot in general be equal to $\varrho = |\psi|^2$.
12. In his Nobel prize lecture, entitled, *"Statistical Interpretation Of Quantum Mechanics"*, Born has noted that: "Wave mechanics enjoyed much greater popularity than the Göttingen or Cambridge version of quantum mechanics. Wave mechanics operates with a wave function ψ, which — at least in the case of one particle — can be pictured in space, and it employs the mathematical methods of partial differential equations familiar to every physicist. Schrödinger also believed that his wave theory made possible a return to deterministic classical physics; he proposed ... to abandon the particle picture entirely and to speak of electrons not as particles but as a continuous density distribution $|\psi|^2$, or electric density $e|\psi|^2$. To us in Göttingen this interpretation appeared unacceptable in the face of the experimental facts. At that time it was not possible to arrive at a clear interpretation of the ψ function by considering bound electrons. I had therefore been at pains, as early as the end of 1925, to extend the matrix method, which obviously covered only oscillatory processes, in such a way as to be applicable to aperiodic processes. I was at that time the guest of the Massachusetts Institute of Technology in the U.S.A., and there I found in Norbert Wiener a distinguished collaborator. In our joint paper we replaced the matrix by the general concept of an operator and, in this way, made possible the description of aperiodic processes. Yet we missed the true approach, which was reserved for Schrödinger; I immediately took up his method, since it promised to lead to an interpretation of the ψ function. *Once more an idea of Einstein's gave the lead. He had sought to make the duality of particles (light quanta or photons) and waves comprehensible by interpreting the square of the optical wave amplitudes as probability density for the occurrence of photons.* This idea could at once be extended to the ψ function: $|\psi|^2$ must represent the probability destiny for electrons (or other particles)" (Born, 1970, p.94. italics added). Einstein, however, as we shall see

as the foundation of any physical interpretation." However, as it is clear from this very quotation, and as we shall further discuss in the text, Heisenberg is defining positivism in a very narrow sense. The insistence of the Copenhagen interpretation to adhere to observable quantities, places it comfortably in the camp of positivists and instrumentalists. P.Feyerabend, while still a realist, made this remark on Heisenberg's claim, "This [Heisenberg's claim] is true. However this "foundation" is again assumed to be "given" in the sense that it cannot be further analyzed or explained, an attitude which to a certain extent still justifies the term "positivism"" (Feyerabend, 1981, p.226). See also Bohr's criticisms of positivism in his dialogue with Heisenberg and Pauli, in Heisenberg (1971, pp.205-217).

According to Bohm and Groenewold in private communication with Feyerabend (1962, p.259), Bohr has always claimed to be a realist and has been somewhat critical of Heisenberg's positivism. Feyerabend however, having assessed Bohr's various comments, has concluded that Bohr's point of view can be christened as a "*positivism of a higher order*" (1958, p.82, italics in original). Some writers maintain that apart from Bohr, Born, who was Heisenberg supervisor for a while, was also responsible for encouraging Heisenberg towards taking a more positivistic approach to the quantum realm. Encyclopedia Britannica [1964] has put the point in this way, "The impetus to this approach was Born's repeated emphasis that the reason the old quantum theory was then (1925) failing was that it sought to use the same kinematical concepts of space and time within the atom as in ordinary measurable large-scale events. After all, the concepts of space and time have a meaning only when we tell how they can be measured, and obviously at atomic distances we cannot use ordinary measuring rods or clocks. Guided by this philosophy based on the so-called operational viewpoint, Heisenberg discovered the matrix mechanics" (1964, p.926).

9. Schrödinger conjectured that quantum mechanics stands in the same relation to ordinary classical mechanics that physical optics does to geometrical optics. Just as the ray-tracing characteristics of the latter fail in the explaining the phenomena of diffraction and interference, so ordinary mechanics cannot explain atomic phenomena, the reason in each case being that the dimensions are not large compared to the wavelength. Hence he sought to establish a procedure analogous to that used in physical optics (1928, First lecture).

10. In an attempt to resolve the wave-particle problem, Schrödinger conceived of the possibility of a *particle* being in reality a bunch of waves, or a *wave packet*. A *wave packet* is a mixture (superposed) of different wavelengths. Heisenberg (1930, p.13) has defined the wave packet in this way, "By *wave packet* is meant a wavelike disturbance whose amplitude is appreciably different from zero only in a bounded region. This region is, in general, in motion, and also changes its size and shape, i.e., the disturbance spreads."

5. This is the date of birth of quantum mechanics according to the majority of historians of science. Some, (e.g., Jammer, 1966, p.45-46), however, maintain that, the birthday of quantum mechanics should be regarded as 19th October 1900.
6. Bohr's assumptions did a thorough job of mixing classical and non-classical physics in a rather *ad-hoc* or arbitrary manner. For example, the very hypothesis that only circular orbits are allowed is arbitrary. Moreover, that an electron moving in a circular orbit is *assumed* to obey classical mechanics while having quantized angular momentum, also seems to be *ad-hoc*. Likewise, that the electron was assumed to obey one feature of classical electromagnetic theory (Coulomb's law) and yet not to obey another feature (emission of radiation by an accelerated charged body) also smacks of ad-hocness.
7. In Bohr's theory, the interaction between matter and radiation remained mysterious. Why does not the atom emit radiation, when it is in the ground state? What really happens when an atom passes from one stationary state to another? What laws determine the probabilities of these transitions? These were some of the most relevant questions for which the theory had no explanation. For a discussion of the shortcomings of Bohr's initial theory (*cf.* L.de Broglie, 1953, pp.141-4).
8. As we shall see (section 3 below), Bohr played a major rôle in importing this positivistic tendency into the Copenhagen interpretation. His move towards an anti-realistic interpretation of quantum mechanics, was gradual and not without intellectual efforts to preserve realism at the micro level. However, it seems his approach right from the beginning has been more of a problem-solving (in a phenomenological fashion) than theoretical understanding. In fact, it can be argued that Bohr's very first papers (his trilogy), most probably unbeknown to him, paved the way for all the subsequent positivistic ingredients built into the orthodox quantum mechanics. In his first paper he had *implied* that it is *meaningless* to talk of the status of electron in the stationary state or during its probabilistic jumps. The gist of Bohr's implicit argument was that inside certain intervals, measurements cannot be carried out, therefore it would be *meaningless* to ascribe definite status to electron in theses intervals or to demand definite values for its dynamical attributes (e.g., position, momentum). This enthusiasm for solving practical problems, was, perhaps under the pressure for accounting for numerous empirical data, consolidated among all members of the Copenhagen school in later years. It is however interesting that both Bohr and Heisenberg in a number of publications have tried to reject the charge of positivism. For example, in his (1958, p.133) Heisenberg writes, "It should be noticed at this point that the Copenhagen interpretation of quantum theory is in no way positivistic. For, whereas positivism is based on the sensual perceptions of the observer as the element of reality, the Copenhagen interpretation regards things and processes which are describable in terms of classical concepts, i.e., the actual,

almost by definition, prohibits and therefore forecloses the progress towards better understanding.

Endnotes

1. For an assessment of realism vs. anti-realism dispute in biological science see Kanitscheider, 1988/ Burian, 1987.
2. Many writers have observed that the anti-realist approach is unhelpful for the advancement of science. See for example, K. Popper, 1959/68, 1963/1972. R. Trigg, 1980, p.x, has observed that "the repudiation of realism in whatever context can lead to a debilitating nihilism."
3. Boltzmann had suggested the formula $-H = k \log W$, for the statistical interpretation of any molecular system in a given state. Here W is, as Boltzmann himself put it, "the number of 'complexions' or possibilities of permuting the molecules without changing the state of the system" (Quoted in Mehra and Rechenberg, 1982, p.48). k is a natural constant now called the Boltzmann constant. In modern thermodynamics the above formula is used as a mathematical definition of disorder and W is called the *disorder parameter*.
4. In his paper, Planck employed two concepts whose interrelations is not altogether clear. The first is the idea of *monochromatic resonators* which helps him to link S the average entropy of an individual resonator (or alternatively S_N the entropy of a collection of N individual resonators, $S_N = NS$) to W the number of ways the total energy may be distributed among N resonator, via the formula; $S_N = k \log W + \text{const}$. The second idea is that energy is not treated as a continuously divisible quantity, but is composed of a well-defined number of equal parts, namely $E = P\epsilon$ where P is an integral number. Planck, in both his papers of October, and December, 1900 had ascribed the notion of energy discreteness to groups of oscillators, and had not talked of discrete energy levels for individual oscillators.
   With these not quite clear assumptions, Planck, adopting Boltzmann's method, argued that the number of ways in which P units of energy can be distributed among N oscillators is $R = (N + P - 1)!/(N - 1)!\,P!$. Planck mistakenly took the above formula to be a first approximation to *Sterling's formula*, namely, $N! = N^N$. The actual first approximation of Sterling's formula is $N! = 2\pi\, N(N/e)^N$. Even at relatively low values of N the discrepancy between Planck's and the true approximation is extreme. Thus for $N = 50$, $N! = 3.041\text{x}10^{64}$. The true first approximation gives $3.036\text{x}10^{64}$ which is off by 0.2 percent; whereas Planck's formula gives $8.88\text{x}10^{84}$ which is off by a factor of $2\text{x}10^{20}$. This extreme discrepancy however, does not introduce a significant error. On the assumptions $P >> N >> 1$ Planck's approximation produces almost the same results as the true approximation (*cf.* MacKinnon, 1982, p.136).

what exists potentially in one spatial region at an instant depends, in this way, on what exists, potentially, elsewhere - a feature of the quantum world (i.e. non-locality) not encountered within classical physics, and confirmed by the outcomes of the experiments on testing Bell's inequality. PQT's explanation for this fact is that n interacting particles do not have n distinct quantum states, but only have a joint, quantum entangled state as a whole. This whole undergoes probabilistic transitions, when the condition for such transition (collapse) is achieved. This way of describing the quantum reality prepares the ground for an experimental test which can decide between the two rival versions, namely, OQT and PQT.

For OQT, as we have already seen, all quantum mechanical phenomena (or physical systems) are to be regarded as wholes, consisting of the measuring instruments and what is being measured. What is being measured, whatever it is, always exists in a *superposition* of states, until an act of measurement, which causes a particular wave collapse, is carried out.[42] As a real example, consider a rearrangement collision between spinless particles a, b, and c, with the following two channel outcome:

(a + b) + c -----> (A) or (B), where;

(A) = (ab) + c and

(B) = a + b + c

where (ab) is the bound state. According to OQT, the outcome of the interaction is a superposition of the two channel state, (A) and (B), and only on measurement one of the two states can be detected. According to PQT however, the superposition of (A) and (B) collapse spontaneously and probabilistically (provided the condition for such a collapse is achieved) even in the absence of the act of measurement (Maxwell, 1988/ 1993b/ 1994).

To examine the validity of his claim, Maxwell has suggested a crucial test which can establish the superiority of PQT over OQT. Although this test has not been carried out yet, it is in principle possible to perform it. The proposed scheme, as a well known physicist has put it, provides an interesting research programme for advancing a realist theory of quantum world (Squires, 1989, pp.413-17).

The significance of Maxwell's interpretation and other realist approach to quantum mechanics is that contrary to the OQM they provide heuristic insights for delving further into the realm of quantum reality and thereby increase the chances of finding more effective models for comprehending deeper layers of reality. This is something that OQM, deterministic (Maxwell, 1988, p.12).

The main conceptual tool of the proposed approach is the notion of *dispositional* properties. Physical entities, macro objects or micro objects, possess properties which are dispositional in character: Their properties simply imply something about how the respected objects change, resist change, or affect change in other objects, in certain circumstances. From this point of view, the main difference between micro entities and macro entities is that while the latter have *deterministic* dispositional properties which are accounted for in classical physics,[40] the properties of quantum entities are probabilistic. These kinds of properties are called propensities[41] and the objects which posses them are called propensitons (p. 13).

Two kinds of probabilistic laws, namely, *continuous* and *discrete probalistic laws* are considered by Maxwell. Corresponding to these two laws, two kinds of propensitons, *continuous* and *discrete* propensitons are introduced. Maxwell has suggested that quantum entities (e.g. electrons, photons, ...) are varieties of the second kind of propensitons called *discrete propensitons*. As long as the physical conditions for probabilistic actualization of the propensities of these entities are not realized, they evolve in space and time *deterministically*. When these conditions are realized, they suffer an instantaneous, probabilistic change of state, determined probabilistically by the value of relevant propensities at the instant in question. In order to specify the nature of these propensitons (i.e. the nature of the propensities they possessed) three things need to be specified: i) the deterministic dynamical laws of evolution and interaction; ii) the precise propensiton condition for probabilistic event to occur; and iii) probabilistic laws governing instantaneous probabilistic transitions (p.14).

This task has been carried out by Maxwell in a number of publications. The final result is a new version of quantum theory called propensiton quantum theory, or PQT for short (Maxwell, 1988/ 1993b/ 1994). PQT, retains the dynamical equations of orthodox quantum theory (OQT) but rejects Born probabilistic interpretation of y. Instead of interpreting y as containing information about values of *observables* and about the outcome of performing *measurement* on the system (or ensemble of systems) in question, PQT interprets y as specifying the actual physical state of the individual quantum system in physical space and time, even in the absence of *preparation* and *measurement*. PQT also regards all measurements to be no more than special cases of a kind of probabilistic process occurring naturally throughout the universe. According to PQT, Bell's theorem and the results of Aspect's types experiments, in fact confirm the view advocated by sophisticated realists that adopting radically new conceptions of reality need not, and in fact does not in any way, undermine the realists' basic principle, namely the objectivity and independence of reality.

The remaining task before the realists is to show that it is possible to produce a version of quantum theory, based on the new conception of reality, which is at least as successful as OQM. This task has already been carried out by a number of writers, many of whom have put forward promising ideas along more or less similar lines.[38] The very fact that such new lines of research and interpretation have been suggested is in itself a strong piece of counter evidence (if not a refutation) of anti-realists' claim that quantum world is not amenable to realistic theories. In the remaining part of this paper I shall briefly introduce one such proposal due to N. Maxwell.

The main point of this proposal is that fulfilment of the basic aim of science, namely understanding of the fundamental structure of nature, requires the development of a micro realistic version of quantum theory. Such a version should be exclusively about micro entities and their interactions. Macro systems, and in particular *measuring instruments* should not be lurking, in however concealed a fashion, in the background as far as the basic postulates of the theory are concerned (Maxwell, 1976, p.275).[39] The key to developing such a version is the realist conviction that micro entities exist independent of the human perceivers, or in other words it is not the case that *esse est precipe*. To fulfil this requirement, any viable micro-realistic explanatory theory must have a definite, characteristic ontology of its own.

A realist guiding principle for probing the nature of unobservable entities (including quantum posits) is the general methodology of *conjectural essentialism* (Popper, 1974/ Paya, 2003). In line with this methodology two sensible assumptions, which set the basic frame work of a micro-realistic approach, need to be introduced;

1) In speaking of the *properties* of fundamental physical entities (such as mass, charge, spin) we are in effect speaking of the dynamical laws obeyed by the entities - and *vice versa*. Thus if we change our ideas about the nature of dynamical laws, we thereby, if we are consistent, *change* our ideas about the nature of properties and entities that obey the laws, and

2) The quantum world is fundamentally probabilistic in character, that is, the dynamical laws governing the evolution and interaction of the physical objects of the quantum domain are probabilistic and not

moment when the particles 1 and 2 are about to impinge upon their respective analyzers, an experimenter can make a choice between parameter values *a* and *a'*. This in turn means that he can affect the probability of the outcome $x_b = +$ for the analysis of particle 2; and if an ensemble of pairs of 1+2 is prepared in a sufficiently short interval of time, then the frequency of + outcome will be affected with certainty by the choice between *a* and *a¢*. This means that the experimenter can inform another experimenter who is observing the outcome of the second analyzer by transmitting information with the speed faster than that of light. This in turn amounts to a violation of special theory of relativity.

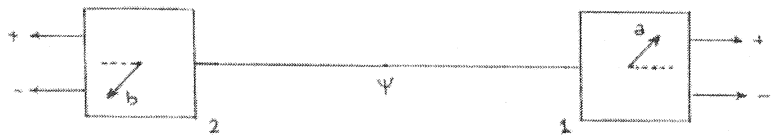
If however, *2* fails it means that the notion of locality, i.e. reality consists of localised stuff, must be abandoned. It has been shown that quantum mechanics does not violate Parameter Independence, which means that this theory is *not* a local theory. However, being a non-local theory does not amount to incompatibility with the special theory of relativity. In fact the two theories can have a peaceful coexistence (Shimony, 1988).

A caveat however, is in order. As Shimony has pointed out (p. 291) it is tempting to regard y as merely a description of the state of the scientist's *knowledge* of the two photons, or alternatively, as the description of an inhomogeneous ensemble of photon pairs, the individual members of which have definite properties that are not described by ψ (Squires, 1990). If however, we concede that y is a complete description of the polarization of the pairs of photons, then we must accept the *indefiniteness* of the polarization of each with respect to a x-y axes as an objective fact, not as a feature of the knowledge of one scientist or of all human beings collectively. We must also acknowledge the *objective chance* and *objective probability*, since the polarization analysis of each photon is a matter of probability. Such an objective probabilistic reality is dubbed differently by different writers.[37] Shimony has summarized the philosophical conclusion which can be drawn from Bell's inequality in the following way:

> The work indicated by Bell has the consequence of making virtually inescapable a philosophically radical interpretation of quantum mechanics: that there is a modality of existence of physical systems which is somehow intermediate between bare logical possibility and full actuality, namely the modality of *potentiality*.

description of the world. This new modality is defended and expanded by a number of physicists and philosophers.

To see how the realist option can be defended, it is instructive to use a representation of Bell's theorem, invoked by A.Shimony (1988, pp.287-292) and a number of physicists/ philosophers of science. (*cf.* Cushing & MacKinnon, 1989). In an EPR type experiment we define the following:



ψ is the complete specification of the properties of 1+2 when they leave the source and move towards the analyzers, whose respective adjustable parameters are shown by *a* and *b*. The channels from which the particles would emerge are labelled + and –. We define the following:

x_a = the outcome of analysis of particle 1, which can be either + or -.

x_b = the outcome of analysis of particle 2, which can be either + or -.

$P_\psi(x_a, x_b \mid a,b)$ = the probability of joint outcomes x_a, x_b.

The above definitions, would allow one to define the probability of single outcomes, and also conditional probability in terms of $P_\psi(x_a, x_b \mid a,b)$:

$P^1_\psi(x_a \mid a,b) = P_\psi(x_a, + \mid a,b) + P_\psi(x_a, - \mid a,b)$,

$P^2_\psi(x_b \mid a,b) = P_\psi(+, x_b \mid a,b) + P_\psi(-, b_x \mid a,b)$,

$P^1_\psi(x_a \mid a,b,x_b) = P_\psi(x_a, x_b \mid a,b)/P^2_\psi(x_b \mid a,b)$,

$P^2_\psi(x_b \mid a,b,x_a) = P_\psi(x_a, x_b \mid a,b)/P^1_\psi(x_a \mid a,b)$.

On the basis of the expressions, Shimony, following J.Jarrett (Jarrett, 1984, Shimony 1988, p. 205) has defined two distinct independence conditions, namely;

1. Parameter Independence: $P^1_\psi(x_a \mid a,b)$ is independent of b,

$P^2_\psi(x_b \mid a,b)$ is independent of a.

2. Outcome Independence: $P^1_\psi(x_a \mid a,b,x_b) = P^1_\psi(x_a \mid a,b)$,

$P^2_\psi(x_b \mid a,b,x_a) = P^2_\psi(x_b \mid a,b)$.

As Jarrett has shown the conjunction of *1&2* is equivalent to Bell's locality condition, namely:

$P_\psi(x_a, x_b \mid a,b) = P^1_\psi(x_a \mid a)P^2_\psi(x_b \mid b)$

The negative result of Aspect's experiment means that either *1* or *2* should be rejected. But the repercussions of the two are quite different;

If *1* fails, e.g., because $P^2_\psi(x_b \mid a,b) \neq P^2_\psi(x_b \mid a', b)$ this means that at a clear violation of Bell's inequalities. But what should we conclude from the outcome of such seemingly conclusive experiments like that of Aspect *et al*?

The opinions of physicists and philosophers widely differ on this issue. An interesting case in point is a recent anthology in honour of the sixtieth birthday of J. Bell entitled *Philosophical Consequences of Quantum Theory: reflections on Bell's Theorem*, (Cushing & MacKinnon, 1989) in which a number of writers with different philosophical persuasions have put forward a wide range of interpretations and glosses over the theorem. An anti-realist like van Fraassen has argued that the realist try to explain significant correlations by appeal to a common cause, which more often than not turns out to be unobservable. But, he goes on to say, Bell's theorem and the experimental results which violate it, have shown that there are significant correlations (i.e. spin correlations), for which no common cause can be posited. These correlations are just a brute fact (van Fraassen, 1989, pp.97-113).

Another anti-realist, Asher Peres, has concluded that any attempt to inject realism in physical theory is bound to lead to inconsistencies. Interestingly enough, a realist like Ernan McMullin, has lost any hope of rescuing realism at the quantum level, and thus has suggested that "Because of its many features, mechanics is quite unsuitable as a paradigm of science generally ... Rather than being *the* paradigm of natural science, much of physics becomes, at least in the context of this issue [i.e. realism] an anomaly". Instead he has suggested that the realist cause can be best defended by invoking the notion of *structural theories* (his term for causal explanation and/or inference to the best explanation) in fields like chemistry, geology, astrophysics, and genetic leaving aside for the time being the pursuit of realism in the quantum domain (Cushing & McMullin, 1989, pp.14-15/ McMullin 1989a).

In contrast to these rather negative attitudes, some other advocates of realism have managed to come up with a number of fairly convincing arguments and plausible interpretations in defence of realism in the micro-world. The gist of these arguments is that the moral of Bell's theorem is neither to abandon realism, nor to embrace an instrumentalistic interpretation of quantum physics but that all naïve notions of reality, and all brands of naïve realism, be it modern or classic, must be eschewed. The notion of physical reality should (and incidentally easily and naturally can be) generalized to accommodate the results of experiments inspired by Bell's theorem. The generalization consists in recognizing that *a new modality of reality* is implicit in quantum mechanical arbitrariness in the Copenhagen interpretation as to where to draw the line between the macro world and the micro system. Furthermore, since in Popper's account, the problem is being shifted from the domain of quantum physics to the realm of probability calculus, even if it can account for the issue of measurement, it has no satisfactory reply to the issue of non-locality of reality which has become apparent from the results of Aspects' experiments.

V. Bell's Inequality and its Implications

In his 1951, D.Bohm had formulated an alternative version of the EPR experiment that paved the way for experimental verification of hidden variable theories (Bohm, 1951, pp.614-15). In Bohm's experiment, a molecule is supposed to contain two atoms in a state in which the total spin is zero and that the spin of each atom is $\hbar/2$. This means that the spin of each particle points in a direction opposite to the other. If the molecule is disintegrated by some process the atoms will begin to separate and will soon cease to interact appreciably. However, the total spin angular momentum of the system will remain unchanged, because by hypothesis, no torques has acted on the system. Since the spin components are measurable, it is possible to perform experiments to verify the validity of the conclusions of EPR experiments.

In 1964, J.Bell in a theorem demonstrated that for any variant of the quantum theory that preserves *determinism* and *locality* (i.e. assumes hidden variable and separability) there are fixed limits to the extent to which the properties of pairs of quantum particles can be correlated (1964, reprinted in Bell 1987, pp.14-22). The equations relating the magnitudes of the correlations to their upper and/or lower limits are known as Bell's inequalities. Under certain circumstances, these limits can be exceeded by the prediction of quantum theory, allowing direct experimental tests to be made for a class of hidden variable theories.

Ever since the appearance of Bell's theorem, there have been a flurry of technical or otherwise presentations of the theory as well as numerous experimental attempts to test its prediction. In 1981-82 A.Aspect and his colleagues performed a series of experiments on the correlation between the polarization orientations of pairs of photons emitted in rapid succession from exited $4p^2S_0$ state of calcium atoms that had been prepared in an atomic beam by two photon laser excitation (Aspect, Dalibard & Roger, 1982, p.1804). The results of these experiments were in excellent agreement with the predictions of quantum theory and in characteristics of quantum theory but of probability theory in general" (pp. 34-35).

Applying this approach, Popper, has reasoned that Heisenberg's interpretation of the famous example of photons passing through a semi-transparent mirror which was first suggested by Einstein, is misguided. According to Heisenberg, if we find that the photon is reflected, "Then the probability of finding the photon in the other part of the packet immediately becomes zero. The experiment at the position of the reflected packet thus exerts a kind of action (reduction of the wave packet) at the distant point occupied by the transmitted packet, and one sees that this action is propagated with a velocity greater than that of light" (Heisenberg, 1930, p.39/ Quoted from Popper, 1967, p.36) However, according to Popper, this apparently reveals a conflation on the part of Heisenberg. The relative probabilities namely,

1) p (a,b) = p $(-a, b) = 1/2$, and

2) p $(a, -a) = 0$, p$(-a, -a) = 1$,

where a refers to photon passing through the mirror and $-a$ to a reflection event, and b to the experimental arrangement, are independent of each other; each belongs to a certain experimental arrangement entirely different from the other. As Popper has put it, "No *action* is exerted upon the wave packet p (a,b), neither an action at a distance nor any other action. For p(a,b) is the propensity of the state of the photon relative to the original experimental conditions. This has not changed, and it can be tested by repeating the original experiment.

Popper's approach, though not without some intuitive appeal, suffers from a number of shortcomings. Apart from lack of precision and rigour with the technicalities of probability calculus and quantum mechanics, the major difficulty with his account is that it does not provide a truly micro-realistic interpretation of quantum mechanics. This is because, in Popper's approach, propensities are attributed to the whole experimental arrangements and not to quantum entities. This in turn means that on the one hand, Popper's propensities are macro properties, and on the other hand, they cannot be regarded as a somewhat natural generalization of the notion of dispositional properties which are prevailing in all branches of science. This is because, these dispositions (e.g. fragility), are properties of the entities themselves and not the features of experimental arrangement.

Moreover, to attribute propensities to the experimental setups imports an element of arbitrariness as to what should be regarded as the proper setup in question. This arbitrariness in a way resembles the very

The reason behind the great quantum muddle in Popper's view is the appeal of quantum physicists to a subjective theory of probability. In fact, as his third thesis, Popper clearly states that, "[I]t is this mistaken belief that we have to explain the probabilistic character of quantum theory by our (allegedly necessary) *lack of knowledge*, rather than by the statistical character of our problems, which has led to *the intrusion of the observer, or the subject into quantum theory*" (p. 17).

To remedy this great misunderstanding, Popper has proposed an objective theory of probability which he has dubbed the propensity theory (1959, 68/ 1959b). Briefly stated, it is a theory for the application of the probability calculus to a certain type of "repeatable experiment" in physics and related fields such as biology (1967, p.31). In Popper's view probability statements (as against the statistical statements) should be taken as statements about "some measure of a property (a physical property, comparable to symmetry) of *the whole experimental arrangement*" (p.32). This is a measure of a *virtual frequency* (i.e. infinite sequences of well arranged experiments), while the statistical statements correspond to frequencies in *actual* (i.e. finite sequences of such) experiments.

Propensities, according to Popper, are thus some kind of abstract physical properties related to the whole experimental setups. Every experimental arrangement is liable to produce, in the course of frequent repetition, a sequence with frequencies dependent on that arrangement. These virtual frequencies or propensities are probabilities. On this approach, quantum theory is seen as a theory not about the dynamic processes in time but a probabilistic propensity theory that assigns weight to various probabilities. For example, to assert that the probability of a photon's passing through a semi-transparent mirror is one-half is to say that the entire experimental arrangements here have a propensity of letting the photon pass through the mirror in 50% of the cases.

To show that his propensity interpretation solves the problem of the relationship between particles and waves, Popper has resorted to an analogy between a pin board and a quantum system. Having explained the change in probability distribution of those balls which actually hit a certain pin due to the change in experimental arrangement (e.g. lifting one corner of the board), Popper then goes on to claim in his ninth thesis that, "In the case of the pin board, the transition from the original distribution to one which assumes a 'position measurement' (whether an actual one or a feigned one) is not merely analogous, *but identical with the famous 'reduction of the wave packet'*. Accordingly, this is not an effect potential of ordinary physical systems should be regarded as the first implicate order, while the super-quantum potential is called the second implicate order (or the super-implicate order). In principle, according to Bohm, there could be an infinite series of implicate orders with growing degrees of subtlety and generality (pp.43-4).

Bohm's implicate order, notwithstanding its possible heuristic merits, has not been developed into a full mathematical model. This is perhaps one of the main reasons that the theory has not been taken enthusiastically by the physics community.

IV.D. Propensity Interpretation: Another attempt to produce a realistic interpretation of quantum mechanics has been made by Popper (1959,68/ 1967/ 1983). In his (1967, pp. 7-44) he has produced thirteen theses which summarise his views on this issue. Popper, following Einstein, maintains that quantum theory is essentially a statistical theory which gives statistical accounts of the behaviour of ensembles of quantum systems and does not deal with the cases of individual quantum entities. However, unlike Einstein, Popper is of the view that: "the interpretation of the formalism of quantum mechanics is closely related to the interpretation of the calculus of probability". This way of looking at the issue has led Popper to both his main objection against the Copenhagen school and his own proposed solution to the apparent difficulties of the orthodox interpretation.

In Popper's view the proponents of the Copenhagen school have committed a "great quantum muddle" which consists in "taking a distribution function, i.e. a statistical measure function characterizing some *sample space* (or perhaps some 'population' of events), and treating it as *a physical property of the elements of the population* (p.19). Popper maintains that this same muddle is behind many confused talks about wave-particle duality. Many physicists according to Popper have taken the ψ-function as a physical property of the elements of the population, whereas, Popper says, "the wave shape (in configuration space) of the ψ-function is a kind of accident which poses a problem to probability theory, but which has next to nothing to do with the physical properties of the particles" (pp. 19-20). It is as if someone were called a 'Gauss-man' or a 'non-Gauss-man' in order to indicate that the distribution function of his living in a certain location has Gaussian or non-Gaussian shape. For Popper, on the contrary, the ψ-function is only a probability distribution function, whereas it is the element in question which has the properties of a particle.

response from the physics community, has been to put a successful challenge to the seemingly absolute injunction against this sort of model, imposed by von Neumann.[36] In fact, it was exactly this interpretation, which was later on re-named by Bohm as the *causal interpretation* (Bohm, 1957) that led John Bell to develop his famous theorem.

In subsequent years Bohm developed his ideas concerning the underlying reality responsible for quantum effects still further. He was particularly attracted to the rôle of language in forming our conceptions, and to the significance of the notion of "order" for shaping our scientific ideas (Bohm, 1963/ 1971). Thinking on the ways of reconciling the theory of relativity, which replaces "the concept of a permanent extended object by that of a continued structure of similar and related events, constituting a process taking place in a more or less tube-like region of space-time" (1963, p.12) and quantum theory, that "denies the notion of a continuous and exactly specifiable process-structure, because the particle movement is always being disturbed by its interaction with the environment through indivisible quantum links associated to what would classically be its continuous field" (*ibid.*) Bohm came to appreciate a new notion of order which he dubbed the *implicate order* (Bohm, 1987).

In this new metaphysical-scientific model, the notion of extentionless point particles is replaced by an undivided seamless whole whose enfoldment and unfoldment gives rise to the *explicate order*. This seamless whole has a super-quantum potential (hence the link with Bohm's former model, namely, the causal interpretation) and a wave function is assumed for the whole universe. "The general picture that emerges out of this is of a wave that spreads out and converges again and again to show a kind of average particle like behaviour, while the interference and diffraction properties are, of course, still maintained. ... The whole universe not only determines and organizes its sub-wholes, but also ... gives form to what has until now been called the elementary particles out of which everything is supposed to be constituted. What we have here is a kind of universal process of quantum potential as to give rise to a world of form and structure in which all manifest features are only relatively constant, recurrent and stable aspects of this whole" (1987, p.43).

As is apparent, in this theory, the quantum attributes are not *localized* in the quantum entity itself but reside in 'the entire experimental set up' which may have to include not only the activities in the immediate vicinity of the entity's actual detector but action arbitrarily remote in time and space from the detection site. Ultimately the whole universe may be implicated in a simple measurement. In Bohm's view, the quantum a deterministic extension of quantum mechanics could be found (p.35). To this end, Bohm reformulated quantum mechanics in a language which is closer to that of classical physics. He wrote the complex wave function in the form, $\psi = R \exp(iS/\hbar)$ and obtained two real equations, one which is essentially a classical equation of motion, the other a potential term called by Bohm "the quantum mechanical potential" (Bohm, 1952).

This second wave would act as a *pilot wave*, spreading out at superluminal velocity and coming towards where the quantum object is found, telling it how to move. The idea of a pilot wave which guides the quantum object was originally introduced by de Broglie in the Solvay conference of 1927 but rejected by the advocates of the Copenhagen school.[34] It was deemed to be a real but in principle unobservable entity which serves the function of residing in the environment and reporting its finding back to the particle which *is* detectable. The particle then acts in accordance with the information provided by its associated pilot wave.

Bohm had called his version of quantum theory a hidden variable theory. However, he later on came to regret the choice of the term. Despite the fact that Bohm's version did agree precisely with OQM in all its empirical predictions, physicists, by and large, did not look at it sympathetically. The reason, apart from the quasi-ideological dominance of the views of Copenhagen school, has been the fact the it has not accounted for at least one experiment which is not accounted for by OQM. The following quotation depicts the standard attitude of many present-day physicists towards this theory: "In the absence of experimental distinguishability between [Bohm's version and OQM], the former becomes a substructure to OQM that is scientifically gratuitous. It would be based completely on philosophical grounds rather than empirical grounds" (Rohrlich, 1983, p.1252).

Another problem with this scheme is that the *pilot wave* should travel faster than light to serve its purpose. But this is clearly contrary to the special theory of relativity. Some more positivistically inclined physicists have also objected that the fact that the pilot wave is not even in principle detectable makes its existence spurious.

Bohm's partial answer to these difficulties has been that the pilot wave is not a wave of matter, but just a wave of active information. Its effects depend only on its form, not upon its magnitude; consequently, unlike matter waves whose effects diminish with distance from the source, the pilot wave can have big effects at long distances (non-locality).[35]

Perhaps Bohm's greatest achievement, notwithstanding the cool

Bohm's attention was drawn to the notion of *indivisibility* between the quantum domain and the large-scale domain according to the Copenhagen interpretation. Time and again Bohr had emphasised that, "... [T]he fundamental difference with respect to the analysis of phenomena in classical and in quantum physics is that in the former the interaction between the objects and the measuring instruments may be neglected or compensated for, while in the latter this interaction forms an integral part of the *phenomenon*. The essential *wholeness* of a proper quantum phenomenon finds indeed logical expression in the circumstances that any attempt at its well-defined subdivision would require a change in the experimental arrangement incompatible with the appearance of the phenomenon itself"[33] (Bohr, 1958, p.72. Italics added).

Bohm, although sympathetic with this account, was uneasy about its apparent contradiction. In his inaugural lecture at Birkbeck College, University of London, he noted that, "In reality, they are only one indivisible system. Yet, our very language asserts that they are two. Hence, there is a contradiction between our common language and the facts of the case. It is this contradiction that is at the root of our inability to find a single conceptual model of the movement and behaviour of the observed system" (Bohm, 1963, p.10). In Bohm's view, Bohr and Heisenberg had resorted to a sort of conventionalism and arbitrariness as a way out of this contradiction. They had suggested "a purely imaginary 'cut', at some place where classical physics is still adequate. The precise place is not significant, as long as it is still in the classical domain. On the large-scale side of the 'cut' it is evidently adequate to go on using our ordinary classical concepts. On the other side, we apply the laws of quantum mechanics, whose sole experimental meaning is however now the prediction of probable results on the observable classical side of the 'cut'" (*ibid*).

Bohm, who was "dissatisfied with the self-contradictory attitude of accepting the independent existence of the cosmos while one was doing relativity and, at the same time, denying it while one was doing quantum theory" (1987, p.34), decided to produce an alternative micro-realistic interpretation of the formalism of quantum mechanics. His guiding thought was that, contrary to the claims of Copenhagen school, a wave function, far from presenting a complete description of reality, captures "only certain aspect of what happens in a statistical ensemble of similar measurements, each of which is in essence only a single element in a greater context of the overall process" (*ibid*)

A meeting with Einstein made Bohm interested in finding out whether according to him no wave reduction takes place, and since there is no collapse of wave function, there is no *measurement problem*. Another important feature of this scheme is that its interpretation seems to arise naturally out of the mathematical formalism, whereas the other approaches require additional assumptions associated with the distinction between the quantum system and the measurement apparatus (Rae, 1986, p.77).

In Everett's interpretation any isolated system is described by a wave function that changes only as prescribed by Schrödinger's equation. If this system is observed by an external observer then, in order to discuss what happens, it is necessary to incorporate the observer into the system, which then becomes a new isolated system. The new wave function, which now describes the previous system plus the observer, is again determined for all times by the Schrödinger equation (Squires, 1986, p.69).

However, the scheme suffers from the following rather serious conceptual inconsistency. As noted above, according to Everett, the reality is a wave function which always contain all possible outcomes and a conscious observer is capable of demanding a particular result, and thereby selecting a 'branch of world' in which he exists. But this poses a problem, because on the one hand the wave function – with all its components – corresponds to the whole reality, and on the other hand there exist a number of conscious observers over and above this whole reality which can cause the process of 'branching' (Espagnat, 1979/83, p.172).

There are other reasons for doubting the credibility of the many world model. These arise principally because it is not clear from the theory just when the alleged branching takes place. It is sometimes said that it happens whenever a 'measurement like' interaction between a quantum system and a measuring apparatus occurs, but if this is the case then the many-world model has clearly failed to solve the *measurement problem*! Alternatively, branching may occur whenever any kind of interaction takes place between two component parts of the universe. But this means, among other things, that the electron and proton in a hydrogen atom are continually interacting and creating infinities of universe! The formalism of many-world model does not provide clarifications over these difficulties (Rae, 1986, pp. 81-2).

IV.C. Hidden Variable interpretation: Among the realist physicists who took Bohr's views seriously, David Bohm is to be mentioned.

majority of physicists (Belinfante, 1975, pp. xiv-xv.). An exception is however, the American physicist, John Archibald Wheeler, who has taken Wigner's approach one step further and has declared that, "no elementary phenomenon is a real phenomenon until it is an observed phenomenon" (Wheeler, 1979-1981). For Wheeler the essence of reality is meaning and the essence of meaning is communication defined as the joint product of all the evidence available to those who communicate. In this view meaning rests on action, which means decisions, which in turn forces the choice between complementary questions and the distinguishing answers. This amounts to the basic idea of generating reality by act of measurement. Einstein, once wrote, "I cannot believe that a mouse can change the world by simply looking at it". Bohr, as we have seen before (1949, p.237), tried to distance himself from this sort of interpretation. However, his equivocal remarks, have no doubt contributed to the rise of this overtly subjective approach.

Apart from strong idealistic connotations of this approach (remember Berkeley's tree in the Quad), there are a number of internal conceptual difficulties which undermine the soundness of it. In the first place, Wheeler has restricted the act of creating reality by observation only to elementary particles, and has denied it in the case of medium size and large size objects. But such a restriction seems to be quite arbitrary, with no convincing rationale. In fact as other physicists with the same persuasion as Wheeler (e.g. Mermin, 1985, pp.38-47) have claimed all entities – cats, oranges, rainbows, even moon and stars – are not real until somebody looks at them. This is of course, a very natural conclusion, which directly derives from Wheeler's basic assumption.

The other difficulty with this scheme is that its advocates do not agree on what counts as an observation. Some of the followers of this school, including Wheeler himself, are of the view that the essence of the measurement is *the making of a record*, and this can be done even by a robot. Others believe that only *a conscious observation* counts as a measurement. Here again, due to the arbitrariness of the distinctions and lack of objective criteria, no progress has been made.

IV.B. The Many-World Interpretation: This approach due to H. Everett (1957), states that in any act of measurement, while one of the many possibilities latent in the wave function actualizes for the observer, the rest also are simultaneously actualized in the worlds parallel to, but inaccessible from, that of the observer. The important point in Everett's scheme, which by the way makes it attractive to some physicists, is that,

IV.A. Consciousness-created Reality: This interpretation was prompted by von Neumann who had concluded that if the predictions of quantum mechanics were correct, then the world could be made up of ordinary objects possessing unobservable or hidden attributes. Being an ardent advocate of the OQT, von Neumann believed that there is a definite separation between measurement devices and the quantum objects, and that the wave function collapse occurs in some vague neighbourhood between the two. He decided to calculate the size of this neighbourhood.

However, to his surprise, it turned out that the collapse, as far as ordinary experiments were concerned, could virtually occur anywhere at all. As a result of this consequence, von Neumann started thinking of the human consciousness, as a part of the long chain of measurement. However, while von Neumann himself did no more than allude to the rôle of the conscious mind in bringing about the collapse of the wave packet, this possibility was taken seriously by a number of physicists, chief among them Eugene Wigner (1961 and 1967 reprinted in Wheeler & Zurek, 1983). Wigner and others have dramatised the situation by proposing a paradox in the form of a thought experiment which draws on Schrödinger's famous cat paradox (Schrödinger, 1953).

The thought experiment involves a sealed and insulated box containing a radioactive source. The source has a 50-50 chance of triggering the Gieger counter during the course of the experiment, thereby activating a mechanism that causes a hammer to smash a flask of prussic acid, thereby killing the cat. An Observer has to open the box in order to collapse the wave function into one of the two possible states (cat = dead, cat = alive). A second observer (Wigner's friend) is then needed to collapse the wave function of the larger system comprising the first observer, the cat, and the equipment. The problem here is that now the original observer, Wigner's friend, and the equipment plus the cat, constitute a new system, which may itself require an 'Acquaintance' to collapse its wave function, and so on (Casti, 1989, p.445).

Wigner's own solution is that due to interaction between living minds and inanimate nature the state of the original system changes from an indefinite one into a definite one as soon as *any* mind would become conscious of the outcome of a measurement upon the original system. For Wigner, the conscious mind is the basic reality, and things in the world are no more than useful constructions built out of one's past experiences, somehow coded into one's consciousness.

Wigner's proposal has not been met with great enthusiasm among the epistemological aspects of his (1935) reply rather than its physical reasoning.

Experimental tests of EPR's experiment (see section V below) have established that while (contra Bohr) it is reasonable to talk of an independent quantum reality, this reality (contra Einstein) is not local. This means that the two main contenders of the philosophical aspects of quantum theory have both been partially right or partially wrong.

IV. Alternative Interpretations

The Copenhagen interpretation, despite all the conceptual difficulties referred to above (Sec. II) was, as far as predictions and calculations were concerned, a successful scheme. This aspect of the theory helped to create an environment in which the majority of physicists who were mostly interested in practical problems started using the mathematical machinery of the theory without questioning its conceptual validity (Popper, 1967, p.8). However, efforts to find alternative interpretations have continued by a number of philosophers and philosophically minded scientists ever since the Einstein – Bohr controversies. The interesting thing however is that there has been hardly any consensus among the advocates of the rival interpretations.

The situation has aptly been described by N. Herbert "Quantum theory resembles an elaborate tower whose middle stories are complete and occupied. Most of the workmen are crowded together on top, making plans and pouring forms for the next stories. Meanwhile the building's foundation consists of the same temporary scaffolding that was rigged up to get the project started ... Physicists' reality crisis consists of the fact that nobody can agree on what's holding the building up. Different people looking at the same theory come up with profoundly different models of reality ... " (1985, pp.157-197).

Although many of the proposed interpretations have covert or overt anti-realistic leanings, this fact should not bring comfort to anti-realists. This is because, on the one hand, as we shall see, these anti-realist schemes suffer from considerable conceptual deficiencies. On the other, the very existence of a number of different interpretations, realist and anti-realist alike, provides an argument against the conviction of those anti-realists who would regard the orthodox interpretation as complete and final. The following models are among the better known interpretations of quantum mechanics.

incompleteness of the quantum theory the authors warned about one possible manoeuvre for evading the above conclusion, "One could object to this conclusion on the grounds that our criterion of reality is not sufficiently restrictive"(p.130). It is exactly such an objection that forms the essence of Bohr's reply.

Bohr's reply to EPR's paradox is basically an argument from language; it rests on the claim that Einstein's criterion of physical reality is *ambiguous* and in fact does not apply properly to the realm of quantum mechanics. Bohr has summed up his reply by reiterating his main objection:

> Form our point of view we now see that the wording of the above mentioned criterion of physical reality proposed by Einstein, Podolsky, and Rosen contains an ambiguity as regards the meaning of the expression "without in any way disturbing the system". Of course there is in a case like that just considered no question of a mechanical disturbance of the system under investigation during the last critical stages of the measuring procedure. But even at this stage there is essentially the question of *an influence on the very conditions which define the possible types of predictions regarding the future behaviour of the system* . Since these conditions constitute an inherent element of description of any phenomenon to which the term 'physical reality' can be properly attached, we see that the argumentation of the mentioned authors does not justify their conclusion that quantum mechanical description is essentially incomplete. (Bohr, 1935, reprinted in Toulmin 1970, pp.138-9)

Although it is the received view among the majority of physicists that it was Bohr who came triumphant out of the controversy with Einstein, recent research by a number of philosophers of science has shown that this does not reflect the whole truth of the matter. Fine and Beller (1994) for example, have argued that Bohr's reply actually missed the main points in the EPR paper, namely, the assumptions about reality and separability.[31] In view of these two authors, Bohr's main concern in his reply was to rebut the charge of inconsistency, whereas it was the completeness of the theory which was at stake.[32] Moreover, the authors have shown that Bohr's attempt to find a physical fault with the EPR argument was not successful and that was the reason why in his subsequent discussions of this paper (e.g., his contribution to Schilpp volume), Bohr concentrated more on the philosophical and lead to a contradiction. The challenge was put in the form of dilemma: either the description of reality given by the wave function in quantum mechanics is not complete or those physical quantities described by non-commuting operators cannot have simultaneous reality.

The argument of the EPR paper hinged upon what Einstein considered to be a reasonable definition of *physical reality*: "If, without in any way disturbing a system, we can predict with certainty (i.e. with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity" (Rosen, 1935/1970, p.124).[30] There were also three main assumptions which formed the backbone of the argument, namely, *realism*: there are some properties of the world that are independent of the human observers; *completeness*: every element of the physical reality must have a counter part in the physical theory, and *separability*: a measurement made with one instrument cannot influence the result of a measurement made with a second spatially separated instrument. A more restrictive form of this assumption, known as *locality*, forbids such influences only if it is simultaneous with the original measurement. In other words, *locality* forbids that the influence would have to propagate faster than light.

Having stated their premises, the authors then suggested a thought experiment. Two quantum systems, I and II, whose initial states are supposed to be known, are allowed to interact from time $t = 0$ to $t = T$, after which it is supposed that there is no longer any interaction between the two systems. According to the calculus of quantum mechanics (i.e., Schrödinger's equation) the state of the combined system ψ_{I+II} can be calculated at any subsequent time.

We can measure the position of the first particle, say x_1. Using this datum and the data about the initial state of the two particles we can easily calculate the position of the second system, x_2. In a similar way, we could have calculated the momentum of the second one, p_2, by measuring momentum of the first system, p_1. However, since our measurements on the first system do not affect the physical properties of the second system, it follows that the second system has had the properties x_2 and p_2 all along. But position and momentum are non-commutable properties (quantities), and as such cannot be represented by a single wave function. This obviously contradicts the claim of the quantum theory to completeness. Insistence on the completeness of the theory gives rise to the other horn of the dilemma, namely, denial of simultaneous reality for non-commuting quantities. Having shown the realistic interpretations. It appears that Bohr's philosophical inclination has encouraged him to move along the dangerous path of idealism and Einstein's words to play a *risky game with reality* (Quoted in Fine, 1986, p.2). The full impact of his move towards putting the epistemological horse before the ontological cart, can be seen in the following remark,

> There is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physicist is to find out how nature is. Physics concerns what we can say about nature. (Petersen, 1963, quoted in Pais, 1991, pp.426-7)

This very attitude towards language and epistemological issues, as noted above, can be seen in Bohr's reply to the famous paradox proposed by Einstein and his colleagues to challenge the completeness of quantum theory. It is to this paradox we now turn.

Between 1927 (the fifth Solvay conference) and 1934, Einstein produced a number of thought experiments, which were mainly devised to criticise Bohr's thesis of kinematic-dynamic complementarity in its *epistemic form*. However in 1935, Einstein turned his attention to the *ontic* interpretation of the thesis (Murdoch, 1987, Ch.8). The result was a new and powerful argument, known in the literature as the EPR thought experiment[29] (Einstein/ Podolsky/ Rosen, 1935, reprinted in Toulmin, 1970). As N. Rosen, one of the co-authors of the 1935 paper has recently related:

> In view of the rôle of the probability concept in the quantum theory, Einstein regarded the theory as having a statistical character, i.e. as describing an ensemble of systems and not a single system. As such, he considered the theory to be incomplete in the sense of not providing a complete description of a single system. However, it was desirable to provide a convincing demonstration of the incompleteness, and this was the purpose of the EPR paper. The idea was to show that the description of the system by the formalism of the quantum mechanics failed to tell us everything about what the system was really like. In other words it was necessary to show that not all the elements of the physical reality associated with the system entered into its description by quantum mechanics. (1991)

The strategy of Einstein and his colleagues was to show that the acceptance of the claim that quantum theory is a complete theory would

> ... the 'real' in physics is to be taken as a type of programme, to which we are, however, not forced to cling *a priori*. No one is likely to be inclined to attempt to give up this programme within the realm of the 'macroscopic' (location of the mark on the paper strip 'real'). But the 'macroscopic' and the 'microscopic' are so inter-related that it appears impracticable to give up this programme in the 'microscopic' alone. (Einstein, 1949, p.674. See also Einstein's letter of 5 April 1948 to Born in Born 1971)

This sentiment was not shared by Bohr. In fact Bohr had shown, from the outset, with his new model of the atom, that he was ready to resort to ad-hoc measures in order to solve conceptual difficulties. A case in point, was his readiness to jettison the time-honoured principles of conservation of energy and momentum for individual processes, and to regard them as only statistically valid for ensembles of particles (Born, 1971, p.82).

Another area of difference between Einstein and Bohr was the issue of *common sense* and its rôle in the advancement of science. While for Einstein, notions like 'phenomenon', 'causality', 'being', and 'to know' were to be understood in their usual common sensical ways, and while in his view scientific concepts were nothing more than a "refinement of everyday thinking" (Einstein, 1954, pp.270-276), Bohr was of the view that at the quantum level all these notions should be radically redefined in order to become compatible with the sort of conditions which prevail there (MacKinnon 1982, Murdoch 1987, and Miller 1984/86). According to Bohr, in the quantum domain, even "words like 'to be' and 'to know' lose their unambiguous meaning" (Bohr, 1961). Bohr would regard the ambiguities resulting from uncritical use of language as partly responsible for his differences with Einstein: "Surely, in a situation like this, where it has been difficult to reach understanding not only between philosophers and physicists but even between physicists of different schools, *the difficulties have their roots not seldom in the preference for a certain use of language suggesting itself from the different lines of approach*" (Bohr, 1949, p.240). In fact, appeal to the different meaning attached to the concept of *physical reality* was Bohr's main argument against Einstein's ingenious though experiment of 1935 (briefly discussed below).

It seems Bohr's preoccupation with language and the way it helps the process of concept formation, has played a decisive rôle in encouraging him to give priority to epistemological problems over the ontological ones. This move however, opens the floodgate to all sorts of non/anti over aim, quite naturally, reflected the difference in the philosophical attitudes of the two scientists. While Einstein insisted upon a thoroughly objective approach towards micro-entities, Bohr opted for a typical anti-realistic approach, namely, transposing ontological problems to epistemological one; he was no longer interested in the question whether knowledge gained by a physical theory, in particular by quantum mechanics, pertains directly to a mind-independent reality; he was convinced that such a knowledge pertains only to the appearances of such a reality in human experience, taking in physics the form of experiment and measurement.

Einstein's notion of realism was, initially, perhaps a bit too strong and less flexible. He not only believed in the independence of reality (of all things mental), but also in its continuity, and locality:

> The concepts of physics refer to a real external world, i.e. ideas are posited of things that claim a 'real existence' independent of the perceiving subject (bodies, fields, etc.), and these ideas are, on the other hand, brought into as secure a relationship as possible with sense impressions. Moreover, it is characteristic of these physical things that they are conceived as being arranged in a space-time continuum. Further, it appears to be essential for this arrangement of things introduced in physics that, as a specific time, these things claim an existence independent of one another, in so far as these things 'lie in different parts of space'. (Born, 1971: *Born-Einstein Letters*, p.170)

Moreover, he was adamant that God has made the physical reality in a deterministic fashion and that indeterminism is not possible. In a letter to Born on 7 September 1944, Einstein wrote: "We have become Antipodean in our scientific expectations. You believe in the God who plays dice, and I believe in complete law and order in a world which objectively exists, and which I, in a widely speculative way, am trying to capture. I firmly *believe*, but I hope that someone will discover a more realistic way or rather more tangible basis than it has been my lot to find. Even the great initial success of quantum theory does not make me believe in the fundamental dice-game, ..." (Born, 1971. p. 149).

However, later on, Einstein realised that the main issue is not determinism but realism. In his later correspondence with Born, Einstein was not emphasising on determinism, but rightly insisting that realism as a framework for sound scientific research should be preserved:

doing their best to develop a thoroughly micro-realistic account of the quantum realm gradually became convinced that their interpretation is a complete one and does not need modification.[28] In this respect, the responsibility for portraying the Copenhagen interpretation as the only valid account rests mostly on Bohr's shoulders. After all, he was the philosophical mentor of the group. However, from a methodological point of view, such an inflexibility with which Bohr's prohibited even asking certain question about quantum theory, is not beneficial for the advancement of knowledge. According to realists, "setting dogmatic limitations on scientific theorizing, on the basis of obscure philosophical preconceptions, is a dangerous prejudice ... to the nature of scientific activity" (Redhead, 1987, p51).

Perhaps the answer to the question of why Bohr and his colleagues, in spite of their initial enthusiasm for preserving realism at the micro-level, radically changed tack, whereas Einstein, who had for a while entertained a positivist attitude, fought in the realist corner to the end, lies in the attitude of the two main players of this drama towards the *basic aim of science*. Einstein once had said:

> I want to know how God created this world. I am not interested in this-or-that phenomenon, in the spectrum of this-or-that element. I want to know His thoughts, the rest are details. (Salaman, 1976, p.22)

For Bohr, on the other hand, to describe an independently existing physical reality was not the main aim, but to bring greater order to our sensory and experimental observations, to coordinate our experience, and to reduce it to order:

> In our description of nature the purpose is not to disclose the real essence of the phenomena but only to track down, so far as it is possible, relations between the manifold aspects of our experience. (Bohr, 1961)

That the basic point of difference *is* over the issue of the *aim*, is something that Einstein himself quite explicitly pointed out: "What does not satisfy me in that theory (i.e. quantum theory), from the standpoint of *principle*, is its attitude towards that which appears to me to be *the programmatic aim of all physics*: the complete description of any (individual) real situation (as it supposedly exists irrespective of any act of observation or substantiation" (Einstein, 1949, p. 667). The difference to solve the wave-particle duality, which preoccupied him for a long time, is another evidence for his desire to preserve realism. However, it seems that during the year 1927 and as a result of his discussions with Heisenberg, and especially after the latter produced his uncertainty principle, Bohr came to the conclusion that realism cannot be saved at quantum level. At this stage, he introduced his principle of *complementarity*, claiming that at the micro-level both wave and particle pictures should be preserved as complementary forms of reality. From this date onward Bohr's attention was mostly shifted towards the rôle and function of language in depicting the world as it appears to us. Heisenberg in his (1958) and (1971) has given vivid accounts of the way Bohr and he himself were groping with the issue of realism.

Ironically, Einstein himself, though inadvertently, had played *a* rôle in this unhappy turn. Heisenberg in his (1971, p. 63) narrates a lively conversation with Einstein in the spring of 1926 shortly after he had introduced his matrix mechanics. After a talk in University of Berlin on the new quantum mechanics, Einstein had admonished him about the positivistic connotations of his approach:

> "But you don't seriously believe," Einstein protested, "that none but observable magnitudes must go into a physical theory?" "Isn't that precisely what you have done with relativity?" I asked in some surprise. "After all, you did stress the fact that it is impermissible to speak of absolute time, simply because absolute time cannot be observed; that only clock readings, be it in the moving reference system or the system at rest, are relevant to the determination of time." "Possibly I did use this kind of reasoning," Einstein admitted, "but it is nonsense all the same. Perhaps I could put it more diplomatically by saying that it may be heuristically useful to keep in mind what one has actually observed. But on principle, it is quite wrong to try founding a theory on observable magnitudes alone. In reality the very opposite happens" (Quoted in Holton, 1973).

What Einstein was suggesting to a rather bewildered Heisenberg was in fact an important realist methodological advice: on occasions where finding a realist interpretation for a successful theory proves to be difficult it is quite legitimate, and in fact methodologically sound, for scientists to *temporarily* make use of instrumentalistic interpretations. However, it seems that the members of the Copenhagen school instead of regarding their instrumentalistic position as a temporary stage and on he concluded that the theory is consistent but incomplete. Einstein's discontent with the theory led him to embark on a long life project of refuting OQM. His persistent efforts, as Bohr has explicitly acknowledged, contributed a great deal to pinpoint certain conceptual problems which present themselves, once one is in the quantum realm (Bohr, 1949/ Rozental, 1967).

III. Einstein vs. Bohr

Many of the conceptual (philosophical) aspects of the orthodox quantum theory have been discussed between Bohr and Einstein. The standard view regarding the stance of each side in this debate is that while Einstein has been an ardent realist, the members of Copenhagen school, have all been staunch anti-realists. For instance, a distinguished physicist like Franco Selleri has vehemently attacked the anti-realistic connotations of the views advocated by Bohr and his collaborators. He argues that Bohr's response to the three central questions about physics, namely, "1) Are the basic entities of atomic physics, such as electrons, protons, photons, and the atoms themselves actually existing independently of the human beings and the observations they are able to perform? 2) Is it possible to comprehend the structure and evolution of atomic objects and processes in terms of mental images formed in correspondence with reality? and 3) Should one formulate the physical laws in such a way that at least one cause can be given for any observed effect?" are all negative, and he concludes that Bohr is therefore undeniably an anti-realist (Selleri, 1990, ch.1).

This rather conventional view has recently been challenged by a number of writers. On the one hand, some, like A.Fine, have tried to cast doubt on Einstein's realist credentials by claiming that far from being a realist, Einstein should be regarded as a constructive empiricist like van Fraassen.[26] On the other hand, others have tried to argue that Bohr and his friends, after all have been *realists*.[27]

But how can one adjudicate between these rival views? Earlier in the paper I referred to the positivist tone of Heisenberg's original paper, a paper which gave birth to modern quantum mechanics. It should be emphasised that the choice of a positivistic approach came about only after many unsuccessful attempt to preserve a realistic approach. Bohr's unsuccessful attempt in 1924 to preserve the traditional picture of light (i.e. his joint paper with Kramers and Slater) is a good indicator of his concern for preserving the classical picture of reality. His relentless efforts theory does not want to deny the existence of quantum entities, it must refrain from ascribing any dynamical attributes to them in the absence of measurement. Thus Robert Oppenheimer has claimed that:

> If we ask, for instance, whether the position of the electron remains the same, we must say 'no'; if we ask whether the electron is at rest, we must say 'no'; if we ask whether it is in motion, we must say 'no'. (Quoted in Herbert, 1985, p.159)

This view has currently found a fresh and enthusiastic advocate in van Fraassen (van Fraassen, 1991). Van Fraassen's view, among other things, leads to an explicit agnosticism towards quantum attributes.[24]

The above unpleasant and contrary to common sense consequences are not the only undesired outcomes of the instrumentalistic outlook of the theory. This unhealthy attitude has produced a number of other significant defects in the theory:

1) OQT is an *ad-hoc* theory in that it is a mixture of classical and quantum mechanics. The purely quantum mechanical part deals with the behaviour of the quantum objects, whereas measuring instruments are subject to the laws of classical mechanics. However, in the absence of the measurement, the theory cannot say anything about the future course of behaviour of the quantum objects. As a result it can only issue in *conditional* or *counterfactual* predictions about what would be the case *if* a measurement were to be performed.

2) A further snag is that the theory cannot draw a clear cut-line between the realms of validity of each of its components. It is not clear where the realm of applicability of measuring device (which is treated by means of classical mechanics) ends, and the realm of applicability of purely quantum mechanics starts. This aspect which has rendered the theory imprecise and ambiguous, as we shall see in the next section, has given rise to a purely subjective approach due to von Neumann and E.Wigner.[25]

3) OQT cannot be generalized to include gravity (general relativity). This is because in order to quantize general relativity, space-time itself would need to be quantum states. This in turn requires to postulate preparation and measurement devices external to space-time, which is an impossible task (Maxwell, 1993b/ 1993c/ 1994).

That there is something unsatisfactory about OQT was realized by Einstein from the early stages of development of the theory. Einstein initially was of the view that the scheme is inconsistent. However, later experimental results in the field of atomic physics" (Feyerabend, 1962, p.193).

While anti-realists have naturally rejoiced over the impact of the theory, many realist writers have pointed out that OQT, notwithstanding its predictive success and the consistency of its formalism, is not a satisfactory theory, in that it suffers from a number of acute conceptual deficiencies and as such cannot be regarded as a constructive paradigm for physics.[23]

In fact, as it is shown below, all these conceptual defects are due to the instrumentalistic outlook which has been imported into OQT via the Copenhagen interpretation. This fact in itself produces a strong *reductio ad absurdum* against the anti-realism in physics: the orthodox interpretation does not fulfil the fundamental *aim* of science, that is, it does not provide us with the knowledge and understanding of the realm of quantum entities. The theory does not tell us what sort of entities are electrons or quarks or photons or their ilk. Moreover, it is unable to resolve the wave-particle dilemma in a satisfactory way. It only explains away this crucial problem by recourse to the principle of complementarity. Anti-realism leads to instrumentalism and instrumentalism forbids understanding and knowledge.

The epistemological anti-realism inherent in the theory has also led to an ontological anti-realism; being primarily a theory about the outcome of measurement, OQM lacks a characteristic physical ontology. The theory is not essentially about the ways in which definite kinds of physical objects evolve and interact in physical space and time irrespective of whether the objects are undergoing measurement. In fact, as we have seen, OQT requires us to presuppose the existence of measuring instruments in its basic axioms. Therefore, it cannot explain the macro-domain as arising solely as a result of interaction between micro entities. The state vector ψ of OQT cannot be interpreted as specifying the actual physical state of the individual quantum system in physical space and time, because there is no solution to the wave/particle dilemma; rather ψ is to be interpreted as containing probabilistic information about the results of measuring diverse quantum observables, such as position, momentum, energy, spin.

The lack of a specific ontology forces the Copenhagen interpretation to embrace the view that there is no deep reality. Hence Bohr's remark that: "There is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physicist is to find out how nature is. Physics concerns what we can say about nature" (Petersen, 1963 quoted in Pais, 1991, pp.426-7). Alternatively, if the members of the Copenhagen school towards anti-realism, seems to be their failure to fully appreciate the importance of upholding the postulate of independence and self-subsistence of reality. Apparently, the outstanding success of the theory's formalism in predicting/accounting for experimental results, combined with the (seemingly) insurmountable difficulties of the wave-particle paradox, led Bohr and Heisenberg to the conclusion that physics should concern only with *phenomena*, and *phenomena*, should only be understood as the outcome of measurement.[18]

Heisenberg, as he himself has made it clear, became convinced that he should only save the phenomena, "forgoing the space-time description and objectification".[19] This was the very reason why he developed a version of quantum mechanics which was based only on measurable quantities. Bohr's principle of complementarity too, was an effort to fudge the fundamental concern about the nature of reality by means of a philosophical doctrine.[20] This in turn, inevitably meant that, for the members of the Copenhagen school the only acceptable reality at the quantum level was the *empirical reality*, that is to say, a reality in the creation of which the experimenter himself plays a crucial role,[21] and that quantum mechanics did not ascribe underlying *causes* for the correlations between phenomena. This point was emphasised by Heisenberg, in 1927, in the following way; "One may be led to the presumption that behind the perceived statistical world there still lies a *real* hidden world in which causality holds. But such speculations seem to us, to say it explicitly, fruitless and senseless. Physics ought to describe only the correlation of observations" (Heisenberg, 1927). On this view the quantum world is at best phenomenally objective but without objects.[22]

This instrumentalistic / positivistic approach gradually hardened among the followers of Bohr and Heisenberg's views. Von Neumann's grand work on the mathematical foundations of quantum mechanics (Von Neumann, 1932) was of great significance in this respect. Using a not well-justified postulate, von Neumann, commenting on the possibility of hidden variables, claimed that, "Not only is the measurement [of these variables] impossible *but so is any reasonable theoretical definition*, i.e., any definition which, although incapable of experimental proof, would also be incapable of experimental refutation" (1955, p.326. Quoted in Feyerabend, 1962, p.193). Soon, the advocate of the orthodox interpretation of quantum theory claimed that this interpretation is the only possible interpretation of the formalism of the theory. Pascual Jordan for example, writes, "There is *only one* interpretation which is capable of conceptually ordering the ... totality of theory is basically a theory about the outcome of measurement. Quantum mechanical phenomena should be defined and described in terms of experimental arrangements, and the description of the experimental arrangement is given in the language (i.e. using the concepts) of classical physics[16] (Redhead, 1987, pp.49-51).

From 1927 onward, the formalism of the new theory was developed very rapidly and its predictive power went from strength to strength. In the same year Dirac gave a quantum mechanical description of the electromagnetic field and Pauli introduced spin into quantum mechanics. Dirac gave a relativistic theory of quantum mechanics in 1928. In 1932 von Neumann formulated quantum mechanics as an operator calculus in Hilbert space, and soon other formalisms such as the algebraic approach and the quantum logical approach, were suggested by a number of physicists (Jammer, 1974). These developments laid the foundation of a powerful predictive tool known as the *Orthodox Quantum Theory* (OQT) or *Orthodox Quantum Mechanics* (OQM). Applications of this theory, which had the Copenhagen interpretation as its backbone, to many branches of physics, met with remarkable success. These developments however, do not concern us here. We would rather concentrate on the bearing of the Copenhagen interpretation and OQT on the realism/ anti-realism dispute.

II. The Shortcomings of Orthodox Quantum Theory and the Copenhagen Interpretation

The many successes of the orthodox quantum theory (OQT) have had profound effects on the course of scientific thought in the twentieth century: due to the strong inbuilt instrumentalism / positivism of the theory, a view has taken shape among the majority of working physicists that successful physical theories should be built along the same instrumentalistic line of thinking as advocated by the members of the Copenhagen school.[17] As recently as 1986, a physicist commenting on the impact of the Copenhagen approach, pointed out that, "Most modern undergraduate courses in modern physics seem to be aimed at *conditioning* students to think in this rather positivistic way" (Rae, 1986, p.53).

Perhaps one of the reasons for encouraging Bohr to take an instrumentalistic approach has been his initial success in his introducing ad-hoc principles in order to resolve the difficulties facing the investigations at the atomic level. Another reason for the slide of schemes for dealing with atomic and sub-atomic phenomena, had caused Bohr to take the issue of wave-particle duality more seriously and to try hard to find a way to resolve the apparent paradox which had first been pointed out by Einstein. Heisenberg's work on the principle of uncertainty prompted Bohr to give further attention to the problems of interpreting the formalism of quantum mechanics and the conditions for proper use of descriptive concepts.[14] The result of this intellectual endeavour was a new principle, which Bohr called *complementarity*. This principle which occupied a significant place in Bohr's future philosophical deliberations on quantum theory was officially introduced in his lecture at the Como conference on 16 September 1927:

> On the one hand, the definition of the state of a physical system, as ordinarily understood, claims the elimination of all external disturbances. But in that case according to the quantum postulate, any observation will be impossible, and, above all, the concepts of space, and time, lose their immediate sense. On the other hand, if in order to make observation possible we permit certain interactions with suitable agencies of measurement, not belonging to the system, an unambiguous definition of the state of the system is naturally no longer possible and there can be no question of *causality* in the ordinary sense of the word. The very nature of the quantum theory thus forces us to regard the *space-time coordination* [i.e., particle behaviour] and the claim of *causality* [i.e., wave behaviour], the union of which characterizes the classical theories, as ***complementary*** but exclusive features of the description, symbolizing the idealization of observation and definition respectively. ...
>
> The problem of the nature of the constituent of matter presents us with an analogous situation. ... Just as in the case of light, we have consequently in the question of the nature of matter, so far as we adhere to classical concepts, to face an inevitable dilemma which has to be regarded as the very expression of experiment. In fact, here again we are not dealing with contradictory but with complementary pictures of phenomena, which only together offer a natural generalization of the classical mode of description. (Bohr, 1927, reprinted in Wheeler & Zurek, 1983, pp.89-91)[15]

In a sense, the principle of complementarity together with the principle of uncertainty sanctioned a totally phenomenological / instrumentalistic approach to quantum world. According to this approach, quantum to the introduction of two principles that express in qualitative terms the physical content of quantum mechanics. The first principle, the principle of uncertainty, developed by Heisenberg in February that year, stated that, it is impossible to specify precisely and simultaneously the values of both members of particular pairs of physical variables that describe the behaviour of an atomic system (Heisenberg, 1927). The members of these pairs are canonically conjugate to each other in the Hamiltonian sense: a rectangular co-ordinate x of a particle and the corresponding component of momentum p_x, the energy E of a particle and the time t at which it is measured, etc. Put more quantitatively, the uncertainty principle states that the order of magnitude of the product of the uncertainties in the *knowledge* of the two variables must be at least Planck's constant h divided by 2p;

$$\Delta x.\Delta p_x \geq h/2p = \hbar$$

$$\Delta E.\Delta t \geq h/2p = \hbar$$

The uncertainty principle, as Heisenberg first formulated it, was therefore meant to be an epistemic principle: it would lay down the limits to what we can know. On this view quantum mechanics becomes an indeterministic theory simply because the data required for deterministic predictions in the sense of classical mechanics are unobtainable. As noticed above, during this period Heisenberg was sympathetic to a positivistic theory of science, and hence he believed that the question whether quantum mechanical objects possess exact simultaneous position and momentum is *meaningless*: "When one wants to be clear about what is to be understood by the words 'position of the object', for example of the electron (relative to a given frame of reference), then one must specify definite experiments with whose help one plans to measure the 'position of electron'; *otherwise this word has no meaning*" Heisenberg (1927).[13]

The uncertainty principle could be given an ontic interpretation (or a semantic variant of the ontic interpretation): Objects possess (or can be said meaningfully to possess) only observable properties; since the exact simultaneous position and momentum of a quantum mechanical object is unobservable, no such objects possess (or can be meaningfully to be said to possess) such a property (Murdoch, 1987, p.47).

Another step towards the fully-fledged positivist interpretation of quantum theory was taken by Bohr. The experimental confirmation of the photon hypothesis, and the existence of two different mathematical generalization that included Newtonian's theory in the low velocity limit. In view of such an expectation, the question of how to interpret the wave function y was raised as the first conceptual problem for wave mechanics. The situation is well described in this quatrain by a young physicist:

Erwin with his psi can do

Calculations quite a few.
But one thing has not been seen
Just what does psi really mean. (Segrè, 1980, p.164)

Schrödinger first considered the wave function as a physical reality, i.e., the electron is actually a wave. But this soon led to a difficulty. A wave may be partially reflected and partially transmitted at a boundary, but an electron cannot be split into two parts for transmission and reflection.[11] The difficulty was removed by Max Born who proposed a statistical interpretation of the ψ-function. Contrary to Schrödinger's view, Born believed that point particles were the basic reality and that ψ wave was only a measure of where a particle was likely to found. Born argued that since what we observe ought to be real and ψ is a complex function, therefore it is $|\psi|^2 = \psi^*\psi$, where * denotes a complex conjugate, that has physical significance. Consequently Born put forward the following postulate: The wave density $|\psi(\mathbf{r},t)|^2$ does not represent an actual charge density of the electron, it rather represents the *probability density* $\mathbf{P}(\mathbf{r},t)$ for a particle to be located at point $\mathbf{r}$ at time t. Thus $|\psi(\mathbf{r},t)|^2 d\tau$ is the probability it will be in the infinitesimal volume $d\tau$ at time t.[12]

The introduction of the statistical interpretation dealt a severe blow to the classical views concerning causality and determinism. In his paper of 25 June 1925, Born noted that: "One obtains the answer to the question, *not* 'what is the state after the collision' but 'how probable is a given effect of the collision' ... Here the problem of determinism arises. From the point of view of our quantum mechanics there exists no quantity which in an individual case causally determine the effect of a collision ... I myself tend to give up determinism in the atomic world"(Quoted in Pais, 1991, p.286).

I.E. Uncertainty and Complementarity Principles

In 1927 the final stages were set for a version of quantum mechanics which is known as the Copenhagen interpretation. This was largely due

This anti-realist undertone, as we shall see shortly, was a symptom of a strong positivistic attitude which was to be built into a particular interpretation quantum mechanics that soon came to be known as the orthodox version.[8] Within a few months Heisenberg's new approach was elaborated by Born, Jordan, and Heisenberg himself, into what has become known as matrix mechanics. Their method was based on a refinement and deeper interpretation of the *correspondence principle* joined to the use of matrices for the representation of kinematic variables. The basic tenet of this method was calculating the non-commuting quantities p and q which were related via the following equation:

$$\sum_r (p_{mr} q_{rn} - q_{mr} p_{rn}) = -i\hbar \delta_{mn}$$

where d_{mn} (the Kronecker delta symbol), is equal to 1 if m=n, but otherwise is equal to zero.

In 1926 Erwin Schrödinger introduced his version of atomic physics which was dubbed wave mechanics. The theory takes its lead from a suggestion by Louis de Broglie in 1923 to the effect that atomic particles might have a wave-like aspect to their behaviour. De Broglie had linked the momentum of the particles to the wave length of those 'matter waves' by $p=h/\lambda$. Based on this assumption, Schrödinger's wave mechanics specifies the laws of wave motion which the particles of any microscopic system obey[9] This is done by specifying, for each system, the equation which controls the behaviour of the wave function, and also by specifying the connection between the behaviour of the wave function and the behaviour of the particles.[10] For a particle of mass m that moves in a potential field V the Schrödinger's wave equation is

$$-\frac{\hbar^2}{2m}\nabla^2\psi + V\psi = i\hbar\frac{\partial\psi}{\partial t}.$$

Generally, V is a function of both space and time, $V(\mathbf{r},t)$. In the above equation ∇^2 is the Laplacian operator and ψ is a wave function subject to usual classical type boundary conditions.

Soon after introducing his wave mechanics, Schrödinger showed that his own formalism and Heisenberg's matrix mechanics are mathematically equivalent despite the obvious disparities in their basic assumptions, mathematical apparatus, and general tenor.

While Heisenberg's representation was regarded as a purely mathematical tool, Schrödinger's formalism was taken to be a generalization that includes Newtonian's theory as a special case (in macroscopic limit), much as Einstein's theory of relativity was a

In 1915 he introduced a general rule of quantization which, in spite of its limitations, could account for a number of cases, including the *fine structure* of the line spectrum of hydrogen, the normal Zeeman effect and the Stark effect and thus partially solved the first problem mentioned above.

I.D. The New Quantum Theory

Despite remarkable success in accounting for a large number of unaccounted phenomena, the old quantum theory was suffering from a number of severe defects, chief among them were:

1. Lack of coherence: as noticed above, in order to solve the problems, it had to make piecemeal application of classical mechanics and electrodynamics suitably modified by quantum conditions.
2. The theory treated only *periodic systems*. Non-periodic phenomena could not be analyzed by it.
3. The theory did not provide a reliable method to calculate the *rate* at which transitions between stationary states, (different energy levels), take place.
4. After 1922 the theory faced serious problems, with regards to determining the energy states of the helium atom, and the anomalous Zeeman effect. The theory could not be used for multi-electron atoms.

In the summer of 1925 Heisenberg discovered the basis of a seemingly more coherent and certainly more comprehensive quantum theory, in which the position co-ordinates and momenta of bound electrons are treated mathematically as matrices (Heisenberg, 1958/ 1971/ Mehra & Rechenberg, 1982, vol.2). His paper had a clear anti-realist tone:

> *The present paper seeks to establish a basis for a theoretical quantum mechanics founded* ***exclusively*** *upon relationships between quantities which in principle are observable.* It is well known that the formal rules which are used in quantum theory for calculating observable quantities such as the energy of the hydrogen atom may be criticized on the grounds that they contain, as basic element, relationships between quantities that are apparently unobservable in principle, e.g., position and period of revolution of the electron. ... In this situation it seems sensible to discard all hope of observing hitherto unobservable quantities, ... Instead it seems more reasonable to try to establish a theoretical quantum mechanics, analogous to classical mechanics, but in which only relations between observable quantities occur". (Waerden, 1967, p.262. italics in original, emphasis added)

> I. That an atomic system can, and only can, exist permanently in a certain series of states corresponding to a discontinuous series of values for its energy, and that consequently any change of the energy of the system, including emission and absorption of electromagnetic radiation, must take place by a complete transition between two such states. These states will be denoted as the 'stationary states' of the system.
>
> II. That the radiation absorbed or emitted during a transition between two stationary states is 'unifrequentic' and possesses a frequency υ, given by the relation E' – E" = hυ, where h is Planck's constant and where E' and E" are the values of the energy in the two states under consideration. (van Der Waerden, 1967)

In developing his model, Bohr had made good use of analogies/metaphors and had relied on two more heuristic principles (Honner, 1987/ Murdoch, 1987/ Darrigol, 1992). One, the *adiabatic principle*, had been proposed earlier in 1913 by Paul Ehrenfest (van Der Waerden, 1967). This principle gives insight into the applicability of classical mechanics to quantum theory as far as a given stationary state is concerned. The second principle was conceived and gradually developed by Bohr himself from 1913 onwards. In 1920 he called it the *correspondence principle* (Murdoch, 1987, p.38). This principle gives the formal applicability of classical mechanics to quantum theory in the high quantum number region.

Bohr's theory, despite its *ad-hoc* appearance[6] and despite the fact that it left many important questions unanswered[7], proved to be highly successful. It managed not only to produce Balmer's formula for the line spectrum of hydrogen and Rydberg's formula for the spectrum of heavier elements, but also made several novel predictions. For example, it predicted that the Pickering series of lines belonged not to hydrogen, but to helium.

The unexpected success of the theory however, gave rise to two important questions among others. First, can Bohr's proposal be generalized? In other words, are there rules which can be applied for the quantization of any mechanical system and not solely to the hydrogen atom and the oscillators in a cavity? Secondly, can a general theory be formulated which describes physical processes in discontinuous steps and yet includes classical mechanics as a limiting case?

Arnold Sommerfeld took the next step in developing quantum theory.

verifications, including Millikan's famous experiments (Franklin, 1986/ 1990/ Broad and N. Wade, 1983), the recognition of his great conjecture, came very late, almost two decades later in 1923. In the meantime, main stream physics had produced its own interpretation of the photo-electric phenomenon: Philipp Lenard explained this effect in terms of the wave model as a resonance phenomenon and when this model could no longer account for the experimental results, many physicists, including Bohr, toyed with the idea of sacrificing the conservation of energy and momentum, in order not to accept the light quanta hypothesis (Messiah, 1962/ Bohr, Kramers, Slater, 1924 reprinted in Waerden, 1967/ Pais, 1982/ 1991).

Einstein, himself, in 1908-10 tried strenuously to resolve the problem of the dual nature of light by developing a new electrodynamics. However, all his attempts failed to produce the desired results (Pais, 1982/Mackinnon, 1982). The sad memory of these failed efforts remained with Einstein until later years of his life. In his *Autobiographical Notes* he writes:

> All my attempts, however, to adopt the theoretical foundation of physics to this [new type of] knowledge failed completely. It was as if the ground had been pulled under one, with no firm foundation to be seen anywhere, upon which one could have built. (1949/1982, p.45)

I.C. The Old Quantum Theory

Understanding the inner structure of the atom was one of the popular research topics in the early decades of the present century (Cajori, 1929/ Weinberg, 1983). Rutherford's experiments with α-particles had led him to reject Thomson's plum pudding model and introduce a new model of the atom. Although the new model was much better than the older ones, it suffered from severe deficiencies. The main difficulty with Rutherford's planetary model of atom was its theoretical instability: according to the laws of electromagnetics revolving electrons should emit energy and collapse into the nucleus almost immediately! (Tomonaga, 1962, pp. 90-93).

In 1913, in a series of three papers Bohr (1913) tackled the difficulties facing Rutherford's model. Bohr presented a bold new model of the atom which also set the foundation of modern atomic physics. Bohr's model was based on two fundamental assumptions:

> great effort. Many of my colleagues saw almost a tragedy in this, but I saw it differently because the profound clarification of my thoughts I derived from this work had great value for me. (Segrè, 1980, p.76)

I.B. The Dual Nature of Light

Einstein was the first physicist to take seriously the idea of discreteness of energy (Kuhn, 1978). He realized that the inconsistencies in Planck's equation are of fundamental significance and cannot be handled by mere mathematical adjustments (Einstein, 1949/1982, p.43). Einstein's reflections on Planck's law soon convinced him that energy quantisation is a quite general result affecting all of mechanics. In Einstein's view, classical electromagnetism, with its built-in notion of a continuous energy spectrum, could work only for phenomena which are time-averaged (e.g. reflection and diffraction) and not instantaneous values. In the latter area, e.g. cases like photo-electric effect, or photo-luminescence and photo-ionisation, one has to rely on the notion of discrete packages of energy, which Einstein had dubbed "light quanta" in his paper of 1905 (Einstein, 1905, p.65).

According to Einstein, such bundles of energy remain localized as they move away from a light source with velocity *c*. He assumed that the energy content E of each light quantum (or photon, as it came to be called later), is related to its frequency n by the equation $E = h\upsilon$. By invoking his light quantum postulate, Einstein produced a reasonable explanation for the photo-electric effect: individual light quanta are completely absorbed by individual electrons in a photocathode. (Halliday and Resnick, 1966) Having absorbed the kinetic energy of photons, electrons are ejected from the atoms of the metal and produce electric current. Einstein also predicted that the maximum kinetic energy of the ejected electrons is a linear function of the frequency of light, i.e. $K_{max} = h\upsilon - w_0$, where w_0, a characteristic energy of the metal called the *work function*, is the minimum energy needed by an electron to pass through the metal surface and escape the attractive forces that bind the electron to metal.

Einstein's light quantum hypothesis was widely rejected, even by physicists like Planck who were familiar with the problems of black-body radiation (Jammer, 1966, pp.43-44). The reason for this unsympathetic reaction was that Einstein's equation had a paradoxical nature: it was relating a discrete quantity (E energy of a photon) to a continuous quantity (υ frequency of the photon). Despite a number of experimental would prove to fit the data far better. Planck announced his formula to the Berlin Physical Society on 19th October 1900;

$$u(\nu,T) = a\frac{\nu^3}{\exp(b\frac{\nu}{T}) - 1}.$$

This formula agreed with the data in the low frequency and high temperature range and reduced to Wien's formula in the high frequency and low temperature region (Kuhn, 1978/ McKinnon, 1982).

Despite the empirical adequacy of his formula, Planck was not satisfied with what he would call a 'lucky guess' (Segrè, 1980, p.72/ Planck, 1949). To promote the status of his formula to the rank of a statement with real physical significance, he once again turned to Boltzmann, imitating one of his postulates[3], and in a slightly muddled way, and with a minor mathematical gaffe[4], he eventually arrived at the final form of the equation known as '*Planck's energy distribution law*', i.e.

$$u(\nu,T) = \frac{8\pi h\,\nu^3}{c^3}\frac{1}{\exp(\frac{h\nu}{kT}) - 1}.$$

This formula, which was announced at the meeting of the German Physical Society on 14th December 1900, heralds the coming of age of the quantum theory.[5] The crucial point in the above formula is the assumption that the fictitious oscillators which comprise the black-body (cavity) absorb and emit energy only in discrete bundles of value $e=h\upsilon$, where h is the same as constant b in Wien's formula, a constant whose value Planck had already established as 6.55×10^{-27} erg seconds. In this way the notion of energy quantisation was introduced into physics.

Planck, as he himself has mentioned in his autobiography, was dissatisfied with his approach for resolving the black-body energy distribution problem. He had tried repeatedly, albeit unsuccessfully, to accommodate the factor h into the framework of classical mechanics (1949). In a letter to his friend R.W.Wood, Planck described the introduction of the postulate of energy quanta as '*an act of desperation*', done because 'a theoretical explanation had to be supplied at any cost' (Jammer, 1966, p.22). Such a desire for *understanding* the inner mechanisms of phenomena was quite typical of Planck. At the end of his life he pointed out that:

> My vain attempts to somehow reconcile the elementary quantum with classical theory continued for many years, and cost for me

electromagnetic radiation that is enclosed within a cavity, assuming that a black-body may be treated *as if* it were a collection of linear, harmonic electromagnetic oscillators, each with characteristic frequency ν of oscillation. He also assumed that the oscillators were damped. They could only absorb or emit radiation in the neighbourhood of their natural frequency ν. Planck argued that the oscillators emit electromagnetic energy into the cavity, which is assumed to have ideally reflecting walls, and absorb electromagnetic energy from it. Thus, it should be possible to deduce the characteristics of cavity radiation from those of the oscillators with which it is in equilibrium. On May 1899, Planck presented his result at a meeting of the Prussian Academy of Science;

$$u(\nu,T)=\frac{8\pi\,\nu^2}{c^3}U(\nu,T)$$

where $U(v, T)$, is the equilibrium energy of each oscillator and the factor 8πν2/c3 gives the number of radiation modes per unit volume per unit frequency (Mackinnon, 1982/ Jammer, 1966/ Stehle, 1994).

Planck's formula had enabled the physicists to link the cavity radiation energy u to the energy of one oscillator U. The problem was now to find out the exact mathematical form of U. In June 1900, Rayleigh, applying a well known, but controversial theorem of thermodynamics, namely the equipartition theorem, to the formula obtained by Planck, suggested a definite form for U. The formula, which came to be known as *Rayleigh-Jeans radiation law* (Pais, 1982, pp.372-3/ 1991, p.84), stated the energy density, (of the black-body radiation), at frequency n and temperature T is proportional to the absolute temperature of the cavity, T:

$$u(\nu,T)=\frac{8\pi\,\nu^2}{c^3}kT.$$

This new formula agreed with all experimental data in the region of extremely low frequencies, just where Wien's law failed. However, it was clear that this formula cannot work for high frequencies. Contrary to experience, it would assign no maximum to $u(\nu,T)$ which meant that as the frequency becomes large, the theoretical prediction goes to infinity (MacKinnon, 1982). The grossly unrealistic behaviour of the prediction of classical theory at high frequencies was later on dubbed by Ehrenfest as the *ultraviolet catastrophe.* (Jammer, 1966, p.17/ Stehle, 1994, p.49).

To remedy this discrepancy, Planck, who had derived Wien's formula from his own formula by relying on his rather particular approach to *entropy,* suggested that if Wien's formula were modified in a simple way it respect to the empirical evidence, have already been developed. Moreover, the fact that currently many physicists and philosophers of science are trying (with varying degrees of success) to develop more adequate micro-realistic schemes, is yet further evidence against the claim that the quantum realm is not amenable to realist interpretation. There is of course no absolute guarantee for the success of these endeavours. However, to reject them in an *a priori* fashion, as anti-realists do, would only amount to a dogmatic attitude towards science.

To set the stage I will start by looking at the roots of quantum mechanics.

I. The Historical Background

I.A. An Act of Desperation

Historians of science customarily trace back the origin of quantum physics to research on the *black-body (cavity) radiation* carried out in the later part of the nineteenth century (Jammer, 1966/ Kuhn, 1978/ MacKinnon, 1982). Introduction of a qualitative law by G. Kirchhoff in 1860 made the search for a theoretical explanation for the black-body radiation one of the major research programmes in the latter part of nineteenth century (Kuhn, 1978/ Stehle, 1994/ Segrè, 1980).

In 1896 Wilhelm Wien formulated an equation for the energy distribution (density) of black-body radiation at temperature T and frequency ν. He showed that the energy density of thermal radiation at any one frequency, u (ν, T), does not depend on the frequency and temperature separately but on the ratio of the frequency to the temperature, namely,

$$u(\nu, T) = a\frac{\nu^3}{\exp(b\frac{\nu}{T})},$$

where a and b are constants. Wien's formula was well corroborated for radiation of relatively high frequencies and low temperatures. However for low frequencies and high temperatures the formula was not confirmed by the available data (Jammer, 1966).

Max Planck, who had a great desire to discover universal laws and absolute relations (Kangro, 1975), was also attracted to Kirchhoff's law, on which he commented, "This so-called normal energy distribution represents something absolute, and since the search for absolutes has always appeared to me to be the highest form of research, I applied myself vigorously to its solution" (Hermann, 1971). Planck examined the

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0- Introduction

Anti-realism, in its different guises, appears to be a less desirable position in comparison to scientific realism. It seems that, in classical physics as well as many other fields of empirical science, (for example, chemistry and biology), anti-realism does not fare as well as realism.[1] The reason, generally speaking, is that it furnishes scientists with a too conservative methodology to allow for the advancement of scientific knowledge.[2]

In recent years however, it appears that anti-realists have taken heart from the discussions stemming from one of the most prestigious quarters of modern science, i.e. the realm of quantum physics. Anti-realists have been quick to exploit the seemingly anti-realistic connotations of theories which deal with atomic and sub-atomic entities. Thus, for example, van Fraassen has argued that "the experimental violation of the Bell inequality is evidence against scientific realism. That is, if scientific realism does not work at the micro level, then it cannot be generally valid" (Cushing, 1989, p.13).

To see whether quantum physics actually provides anti-realists with a compelling argument against a realistic interpretation of science, we should look at the issues involved in some detail. The argument in what follows consists of three parts;

1. The orthodox version of quantum theory, developed out of the so-called Copenhagen interpretation, is neither the ultimate stage in interpreting the quantum realm, nor even a desirable one. In fact this version suffers from a number of fundamental defects which all stem from the inbuilt instrumentalistic ingredients of the theory.

2. Contrary to the conventional wisdom among anti-realists, the orthodox version of quantum mechanics, far from lending support to anti-realists conviction, provides a rather neat *reductio ad absurdum* against anti-realism and in favour of realism in the quantum realm. This *reductio* argument can be summarised in this way: If anti-realism is a valid thesis then scientists should only develop and accept anti-realistic theories. However, orthodox quantum mechanics, as a paradigm case of anti-realistic theories, suffers from fundamental defects which are all due to its basic instrumentalistic assumptions. In order to remove these defects, one has to develop a realistic quantum theory. Therefore anti-realism is not valid.

3. Micro-realistic interpretations of the formalism of quantum mechanics, which are at least as good as the standard account with

Hekmat va Falsafeh
(Wisdom and Philosophy)
Vol. 2, No. 2, August 2006, pp. 7- 66

حکمت و فلسفه
سال دوم، شماره دوم، تابستان ۱۳۸۵

Quantum Physics: A Case for Anti-Realism?

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Abstract
The aim of the present paper is to show that anti-realism in science, which has arguably become more fashionable in recent years, contrary to what its proponents assert, cannot make use of quantum mechanics and its impressive achievements as a trump card in justifying its claims. I will argue that scientific anti-realism far from providing scientific community with a progressive methodological framework is a restrictive approach which would hamper scientific progress. Focusing on the historical evidence of the ways in which quantum mechanics was developed, I will further argue that the orthodox interpretation of quantum mechanics due to Bohr and Heisenberg, among others, with its in-built anti-realistic elements provides a damning verdict against the claims of anti-realists. Following a critical assessment of a number of alternative interpretations or the calculus of quantum mechanics, I shall present realistic approaches which provide more effective and fruitful conceptual frameworks for the advancement of research in the quantum world.

Keywords: *Realism, Ant-realism, Quantum Mechanics, Scientific Knowledge, Copenhagen interpretation, Instrumentalism.*

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