QUANTUM THEORY AND THE MECHANISTIC PARADIGM

J. B. CRANSTON

The quantum of action is, perhaps, the most fundamental concept in contemporary physics. But it is also the source of serious philosophical problems, problems which have troubled philosophers of science and philosophically minded physicists for more than half a century now. These problems emerge from attempts to give a consistent physical interpretation to the mathematical formalisms of quantum mechanics. In terms of what we often take as our "natural" conceptualization of the physical universe as composed of interacting bodies located in space-time and possessing well-defined motions and of waves propogating through a medium (or through empty space), in terms of this kind of physical world, the formalisms of quantum mechanics seem to suggest only paradoxical pictures of nature. And these paradoxes have important consequences for such well-worn philosophical issues as determinism, causality and the nature of physical reality.

The problem can be illustrated in a non-technical way by considering the well known two slit experiment.[1] A monoenergetic beam of electrons is directed at a screen which can detect and record their impacts. A diaphram capable of stopping the flow of electrons, but pierced by two narrow slits, is placed between the electron source and the recording screen. In order to strike the screen the electrons must pass through one or the other of the slits in the diaphram. The experiment is conducted first with both slits open and then with only one slit open. What is observed on the screen when both slits are open is a series of light and dark areas or bands characteristic of a wave interference pattern. When only one slit is open the interference pattern disappears. The most obvious explanation of these results is in terms of wave trains emanating from the slits. When both slits are open there are two interfering wave trains, one emanating from each slit. With one slit open there is only one wave train and, hence, no interference.[2] In other words, the electron beam exhibits wave-like characteristics. Monochromatic light produces analogous results.

Now suppose that the intensity of the electron beam is reduced to the point where the impacts of individual electrons can be separately recorded. The experiment is repeated and the position of each electron strike on the screen is recorded. There no longer is any question of a wave phenomenon as we ordinarily conceive of waves. Yet the results of the experiment will be the same as before. With both slits open the electron hits will gradually accumulate until they form the same pattern as before. That is, the electron strikes will be distributed on the screen in an interference-like

pattern. And similarly for the one slit situation, no interference pattern will appear.

The results of this experiment are entirely consistent with the mathematical formalisms of quantum theory. Yet, how are we to account for these results in terms of a physical reality? It is almost as though an individual electron "knew" whether the other slit was open when it passed through the diaphram and then governed its subsequent path accordingly. Furthermore, the electrons exhibit both wave-like characteristics (interference pattern) and particle-like characteristics (discrete impacts on the screen). But this involves a further paradox. A wave is spread out in space. It has no precisely defined position. Neither does it have a mass. A particle, on the other hand, is precisely locatable in space and has a well defined mass. Surely an electron cannot be both, especially not both at the same time.[3]

A number of solutions or interpretations have been proposed for this and similar problems arising from quantum theory. A discussion of them is outside of the scope of this paper. However, it seems to me that they generally can be reduced to some variation or combination of the following two theses. The first amounts to something like this: There actually isn't any paradox. Nature has shown us that it behaves in such a way that a complete explanation of micro-events requires two different but "complementary" descriptions. In other words, we must learn to live with the paradoxes because this is the way nature is.[4] The second thesis maintains that the paradoxes are the result of our present incomplete knowledge of the finer structure of nature. When our knowledge has advanced sufficiently, we may discover that the apparent paradoxes are causally explainable in terms of a deeper level of nature.[5]

Both of these theses presuppose a mechanistic kind of physical reality. The second thesis is often quite openly mechanistic, at least insofar as it proposes solutions which are broadly mechanistic in context. But the first thesis also implicitly assumes a mechanistic world model, and this in spite of much talk about the "new nature" of the physical world revealed by quantum physics. The kind of mechanism presupposed by these theses may vary in some respects from that presupposed by classical mechanics, but it nevertheless constitutes a conceptualization of the world in broadly mechanical kinds of terms.[6] That this is the case and that the difficulties in giving a really satisfying physical interpretation to quantum theory necessarily follow from this will constitute the thesis of the remainder of this paper.

The mechanistic ideal underlying quantum theory is suggested by the very name, quantum mechanics, given to the mathematical formalisms which describe the phenomena of the quantum realm. Quantum theory arose in the first place out of attempts to reduce all of physics to classical mechanics—the ideal that, ultimately, all physical phenomena must be describable and explainable in mechanistic terms. More accurately, the concept of the quantum of action arose out of such reductionist attempts. Quantum theory itself originated in the extension of the quantum of action to a general principle concerning micro-nature: micro-nature is quantized. Thus, it might be helpful to take a look at the quantum of action and the sources from whence it sprang.

The quantum of action was introduced into physics in 1900 by the German theoretician Max Planck in connection with the blackbody radiation problem. Planck was able to solve this heretofore unsolvable problem in heat theory by postulating that radiant energy is emitted only in discrete elements equal to integral multiples of the frequency of radiation times a constant.[7] He assigned the title "quantum of action" to his constant because its dimensions are the same as those of the classical concept of action as developed by Maupertuis and others in the principle of least action. That is, the dimensional units of Planck's constant are those of momentum multiplied by distance or, equivalently, energy multiplied by time.[8] Now, the principle of least action applies to classical mechanics. It states, in effect, that a particle moving between two points will take the path which uses the least total action. In other words, between any two points there is a most economical path in terms of action, a perferred path, and a particle moving between these points will "naturally" take this preferred path. Later, Hamilton modified this idea and substituted the concept of "stationary action" for that of "least action." A preferred path became one for which the difference in action between it and closely adjacent paths is minimum. The concept of least action was itself an outgrowth of an earlier concept in geometric optics known as Fermat's principle of least time. Fermat's principle asserts that in traveling between two points a ray of light will follow the path which takes the least time.

Now, both the principle of least action and the principle of least time seem to be heavily loaded with metaphysical preconceptions about the nature of physical reality. Some of these preconceptions go back to the origins of science in Greek antiquity. Others seem to have their sources in post-scientific revolution (modern) science or, what may be the same thing, have made the transition from the Aristotelean to the modern scientific world view. It is the latter group of presuppositions with which I am concerned here. For, the characteristic world view of modern science has been that of mechanism, and that more than a vestige of this world view is retained by contemporary quantum physics is what I wish to show.

Whatever its roots in pre-mechanistic science, action itself seems to be a mechanistic concept. It is conceived in terms of those standard mechanistic entities: point masses, motion and space (or energy and time). But why should bodies tend to take certain paths and not others? Why *least* action or *stationary* action? Doesn't the principle of least action transcend any possible mechanistic explanation? Maupertuis himself saw in his principle evidence of divine guidance in the world. However, a closer inspection reveals an intimate relationship between the principle of least (or stationary) action and the conservation laws. It has even been suggested that the relationship is one of equivalence.[9] If various physical entities such as energy and momentum are to be conserved, then the notion that certain paths (or physical states) are permitted while others are not makes a great deal of sense. Certain paths or states will be consistent with the conservation of momentum and energy and others will not. If momentum is to be conserved, for example, then there must be restrictions on the expenditure of momentum. Vectorially, the sum of all momentum increments must add to zero. But this is equivalent to a restriction on the paths which material bodies may follow. The principle of least action simply expresses the claim that if bodies always follow the paths for which the total action is least, then the conservation of momentum (and energy) will be assured. On this view, the principle of least action is simply an alternative statement of the principles of the conservation of momentum and of energy.

Now, one of the most fundamental characteristics of a mechanistic system is that it is conservative. In a "machine," one must be able to account for all of the various forces, motions, energies, etc. The balance sheet must tally up. If the system is closed, then the various physical entities are constantly recycled or transformed into one another. Nothing is ever lost. The conservation laws express this aspect of the mechanistic paradigm. That is, the conservation laws are formulations of the so-called laws of nature in terms of the conservative aspect of the mechanistic paradigm. Newton's second law, for example, can be viewed as an expression of the conservation of energy.[10] Thus, the concept of conservation grew out of the mechanistic world view and is entailed by it. Furthermore, the concept of conservation would seem to presuppose some sort of causal-like interrelating or interacting of physical events and entities, and this, in turn, would seem to presuppose a regularity in nature. And a causal kind of regularity in nature is the very situation which the mechanistic paradigm is designed to picture. I would stop short of asserting that the concept of conservation entails mechanism, but I think that it comes very close to this in practice. In any case, the conservation laws and thus the principle of least action, as they are developed in classical physics, are thoroughly mechanistic concepts.

But what about the quantum of action? Is it also mechanistic? Does it carry the mechanistic paradigm over into the realm of the quantum? When Planck introduced his universal constant he was engaged in a project typical of classical physics. He was trying to reduce thermodynamics to mechanics, trying to demonstrate that heat phenomena can be described adequately in terms of the variables and laws of classical mechanics. In other words, he was trying to account for the observed phenomena, in this case thermal radiation, within the general mechanistic model of nature. In this, Planck was completing the work of other physicists, most immediately that of Clausius and Boltzmann. Of all the branches of physics, only thermodynamics remained to be fitted into the mechanistic paradigm; it alone still resisted reduction to Newtonian mechanics. Even electromagnetic theory could be viewed as an extension of this model of nature. In a sense, electromagnetism seemed to complete the model.[11] But thermodynamics posed a special problem. The second law of thermodynamics and the concept of entropy entail that some natural processes are irreversable. The equations of mechanics, on the other hand, describe only reversable processes. It was to solve a paradox which arose from this, i.e., the blackbody radiation problem, that Planck postulated the quantum of action. With this postulate, thermodynamics seemed to fit the mechanistic paradigm—mathematically at least.

Although Planck himself realized the revolutionary implications of his postulate, he did not believe that it constituted a real break with the underlying mechanistic nature of things. "The quantum postulate will not be regarded as implying that there is no causality for emission; but processes which cause emission must be assumed to be of such a concealed nature that for the present their laws cannot be obtained by any but statistical means."[12] But over the following decades, as the quantum of action was extended to the whole sub-atomic realm, it became clear that the traditional version of the mechanistic paradigm was in serious trouble. Sub-atomic entities no longer could be pictured unambiguously in space and time. Men such as Niels Bohr began to talk of a new nature, a nature in which simultaneous space-time and momentum-energy coordinates of an object cannot be known with precision. It was asserted that a sub-atomic particle does not possess an exact location and an exact motion at the same time. Or, position is simply the result of a position measurement, motion the result of a measurement of motion—these properties of a micro-object have no meaning apart from the corresponding measurement operations. At the very least, precise position and precise motion are mutually exclusive on the epistemological level and, perhaps, on the ontological level as well. This is the message of the Heisenberg uncertainty principle and, apparently, an inescapable

consequence of the quantum hypothes.

But does this kind of talk really presuppose a "new" paradigm or model for physical reality? Or is it more of a last ditch stand to save the mechanistic world view? I think that it is the latter. In his book, *Physics and Philosophy*, Heisenberg points out that natural language and the language of classical physics apply only to phenomena for which Planck's constant can be considered infinitely small (and for which the speed of light can be considered infinitely large). In other words, he claims that the mechanistic paradigm fails at the sub-atomic level. Yet it seems that we must hang on to it, for there is no other language or paradigm available. The founder of the Copenhagen interpretation of quantum theory, of which Heisenberg is a leading adherent, explicitly asserts this to be the case. Niels Bohr says, "...however far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms."[13] But at the same time, these men are insistent that the quantum has revealed a new kind of nature, a new realm in which mechanism does not apply. How are we to explain this new realm if we do not, perhaps cannot, possess concepts or language adequate to the task? How can we even be sure that we are asking the right questions?

Heisenberg, of course, is correct in asserting that the language of classical physics, i.e., mechanism, fails us at the quantum level.[14] But this means that the mechanistic paradigm itself has failed us. And the reason that this failure is crucial in quantum physics is that this paradigm is involved in the very structure of quantum theory. The quantum of action brings with it into quantum physics both the new idea of a quantized or discontinuous nature and the old idea of preferred states which insure the validity of the conservation laws. The old idea is an essential part of the mechanistic paradigm, a paradigm now modified and extended, distorted, to try to account for the new idea of discontinuous behavior in micro-nature. One might say that the paradigm which is presupposed by the new physics is mechanistic, but with exceptions or gaps in its mechanism. This is the kind of metaphor which is brought to mind by many recent attempts to give physical interpretations to quantum mechanics. The "machine" of the paradigm seems to be quite worn out and to be grinding slowly and haltingly to a stop. Perhaps it has run out of fuel—or choked on too much entropy.

In any case, against the background of the mechanistic paradigm there seems no way in which to give a non-paradoxical physical meaning to quantum mechanics. In a mechanistic world we are permitted only two ways in which to describe the transportation of energy: in terms of waves or in terms of particles. But these two descriptions are mutually exclusive. An energy transport phenomenon can fit one or the other but not both at the same time. That is, it cannot fit both at the same time and still presuppose a purely mechanistic paradigm. And yet, this is precisely what is attempted in the standard physical interpretations of quantum theory. The paradox is inevitable. So long as we presuppose a world in which the transport of energy (or energy-matter) can occur in only two ways and these two ways are taken to be mutually exclusive, then phenomena which do not conform to this dichotomy will not be fully explainable. We have been able to create mathematical formalisms which in some sense describe the phenomena, but the physical meaning of what is describe remains quite obscure.

The quantum of action itself is what allows us to convert from the particle description to the wave description and back.[15] It is the unifying concept in the quantum view of nature. In effect, the quantum of action asserts that particles and waves are two permissible explanations of natural phenomena at the sub-atomic level and that these two kinds of explanation are in some sense equivalent. The quantum of action unites the two conceptions of energy transport. But in so doing, it blurs the distinction between matter and energy, a distinction crucial to the mechanistic paradigm. It tries to save the mechanistic model in spite of the apparently non-mechanistic behavior of the phenomena. The result is a paradoxical picture of physical reality.

* * *

Is there a way out of this difficulty? I am not certain at present what direction a solution might take. But it occurs to me that there is some similarity between the situation in contemporary physics and that in Medieval astronomy just before the Copernican revolution. Hellenistic and Medieval astronomers had worked out a basic conception of what the universe is like. Their problem was to account for the observed astronomical phenomena within the framework of a universe composed of concentric spheres and involving only circular motions. The crowning glory of their efforts was the Ptolemaic system. By the proper combination of such mathematical devices as the eccentric, the equant and the epicycle, any conceivable celestial observation could be fitted to the system so as to "save the appearances."

Modern classical physicists have held a basic metaphysical conception of what nature is like. Their problem has been to account for observed phenomena within the mechanistic paradigm. Some of their successes and failures we have mentioned. The introduction of the quantum of action was originally an attempt to make heat theory fit this paradigm. And with the quantum postulate, heat theory appeared to fit–mathematically at least. Planck's move in postulating the quantum seems somewhat

analogous to the Medieval astronomer adding another epicycle to the Ptolemaic system. Both moves were made to "save the appearances," to make the observations fit the general paradigm or model. Only what are really being saved in both cases are the paradigms themselves, the metaphysical assumptions behind the theories–not the appearances or phenomena.

On this analogy, quantum theory may amount to a body of mathematical assumptions which have been introduced into physics in order to "save the appearances" without having to let go of our basic metaphysical view of nature. We are presently amassing data (observing phenomena) from the sub-atomic and sub-nuclear realms at an accelerating rate. But our theories, our explanations, of what it is that we are observing are adequate, if at all, only on the mathematical level of language and conceptualization. The theories seem to work as descriptions of nature only in some very abstract sense and only at the cost of excluding a satisfying physical interpretation. The situation seems much like that in Ptolemaic astronomy: the adding of more epicycles could not fail to describe the phenomena, but the system itself eventually failed as an explanation.

In astronomy it took a revolution in metaphysical viewpoint to yield a more satisfactory interpretation of the phenomena and, thus, a new physical theory and a new paradigm. Perhaps contemporary physics needs a Copernican revolution, or needs at least to complete the revolution started in 1900. The language available at present seems to be inadequate for the task of yielding a non-paradoxical interpretation of the quantum formalisms and of the phenomena they describe. But the language available is that of classical physics and of mechanism. Our concepts are mechanistic, our view of nature is mechanistic and, thus, what we say about nature is mechanistic. But the mechanistic world view is no more the *natural* or *true* view of the physical world than was the Aristotelean view and language which dominated science for some 2000 years.

NOTES

[1] There are a great number of published discussions of the two slit experiment. Almost any college physics text includes some exposition of the experiment. Among the clearest general explanations is that of David Bohm in his *Quantum Theory* (New York, 1951), Chap. VI.

[2] Diffraction is ignored here in order to simplify the example.

[3] More accurately, the electrons seem to be governed simultaneously by the laws describing particle behavior and by those describing wave behavior. But the paradox remains.

[4] This thesis, of course, is meant to include the Copenhagen view and its principle of complementarity: "At the quantum level, the most general physical properties of any system must be expressed in terms of complementary pairs of variables, each of

which can be better defined only at the expense of a corresponding loss in the degree of definition of the other." *Quantum Theory*, p. 160.

[5] Most of the "hidden variable" theories fall under this thesis.

[6] By mechanistic paradigm or mechanistic world model I mean the general logical structure which characterizes the theories of classical physics. As a minimum, I take this to involve the nature of physical objects or systems and of physical events or states in space and time, the events occurring in such a way that their development can be described causally by law-like rules. That is, given the physical state of an object at any time, its future and past states can be determined with any desired degree of precision by means of mathematical equations which function as descriptive laws of nature. The mathematical equations are reversible and are invariant in form with respect to time. The objects or systems are usually taken to be sharply distinguishable from the observer and from the instruments used to make the observation. Although not essential to the paradigm, the logical structure is usually taken to be in some sort of correspondence with (i.e., to represent) a physical reality which is independent of the observer.

[7] The blackbody radiation problem arose from attempts to explain the radiant energy emitted by a heated body by an analogy with a volume of heated gas. Boltzmann's statistical mechanics which described the behavior of a heated gas assumes that the total energy is equally divided between a large but finite number of molecules. But in the case of radiation there are an infinite number of possible wavelengths or frequencies among which to divide the total energy. The paradoxical consequences of this situation are that each frequency will be alloted an infinitely small amount of energy and that, in a closed box or Jeans cube, energy injected at one frequency will quickly transform itself into energy of ever increasing frequencies. The latter consequence was pointed out by Rayleigh and Jeans and is called the "ultraviolet catastrophe." Since neither consequence occurs in nature, existing theories were clearly inadequate. Planck solved the problem by postulating that radiant energy is emitted only in discrete units of size $nh\nu$, where $n = 1, 2, 3, \ldots$, h = Planck's constant and ν = the frequency of radiation.

[8] The value of Planck's constant is approximately 6.63×10^{-27} erg. sec in c.g.s. units.

[9] Henry Margenau in *The Nature of Physical Reality* (New York, 1950), pp. 184-86, argues that both Newton's second law, $m\, d^2x/dt^2 = Fx$, and Hamilton's principle of stationary action, $\int_{t_1}^{t_2} L\, dt$ = constant (or a minimum), are equivalent to the principle of conservation of energy, $E_k - E_p$ = constant.

[10] $(m\, d^2x/dt^2 = Fx) \Leftrightarrow (\frac{1}{2} mv^2 - \int_0^x Fx\, dx = \text{constant}) \Leftrightarrow (E_k - E_p = \text{constant})$. Margenau argues thusly in *The Nature of Physical Reality*, pp. 182-83.

[11] One might argue whether the introduction of the concept of the field was a move towards mechanism or away from it. A mechanism extended to include this concept is no longer a simple "machine" analogy. Yet, I would argue that it still retains certain essential features of a mechanistic system. (See note 6.)

[12] Max Planck, *The Theory of Heat Radiation*, trans. Morton Masius (New York, 1959), p. 153.

[13] Niels Bohr, "Discussion With Einstein," *Albert Einstein: Philosopher-Scientist*, ed. Paul Schilpp, 3rd ed., *The Library of Living Philosophers*, VII (La Salle, Ill., 1970), 209.

[14] In fairness to Heisenberg, it should be pointed out that he seems to be convinced of the possibility of creating or discovering new concepts more adequate for the quantum realm. See especially Chapters IX and X of his *Physics and Philosophy* (New York, 1958).

University of New Mexico