QUANTUM SYSTEMS

Part I: THE PHYSICAL NONEXISTENCE OF PARTICLES

This essay offers a positive alternative to the traditional dialectical underpinnings commonly associated with quantum physics. The analysis revolves about the question: What is the nature of the quantum system? Part I sets the stage by seeking to clarify the philosophical status of the concept of physical system in general; the discussion then turns to quantum physics in particular. It is demonstrated that a combination of physical and epistemological principles quite distinct from the orthodox but spurious duality arguments lead to the conclusions that quantum systems are constructs sui generis, *and that particles can no longer be said to exist physically.*

1. THE PHYSICAL SYSTEM AS AN ONTOLOGICAL ENTITY. — Each branch of theoretical physics provides a description of the behavior, under diverse environmental conditions, of one or more conceptual objects called *physical systems*. Thus Newtonian mechanics has its particles; Maxwellian electrodynamics, its fields. But what of quantum physics? It is true that the classical terminology is often borrowed, so that one reads of elementary « particles » and of quantum « fields », and a « wave » nature for the « particles » and a « particle » nature for the « fields ». Indeed the common prose of textbooks in quantum physics darkly hints of some subtle metamorphosis between the « particle » and « wave » aspects. But such a characterization of the physical systems with which quantum theory is concerned is entirely negative in spirit, for it embodies a reluctance to formulate a genuinely fresh intuition when familiar concepts can no longer be applied consistently. In this paper we shall attempt to answer in a positive manner the rather broad philosophical question: What is the nature of the quantum system?

There is no universal agreement as to the philosophical status of the physical system, classical or quantal. To be explicit, one school of thought holds that physical systems are images of the real things in an ontological world which is itself beyond direct experience but is nevertheless the cause of the empirically given. On the other hand, we espouse a more modest view (cf. section 2 *et seqq.*) of the philosophical significance of physical systems, viz., that they are rather arbitrary epistemological constructs.

Perhaps the most forceful argument against interpreting physical systems as ontological entities rests on the historical observation that once cherished concepts can change radically, and not necessarily as though they were slightly unfocused images of an immutable reality being asymptotically refined by successive theories. Consider, for example, the luminiferous ether, the classical all-pervasive ocean supporting the undulations of light. Duhem [1] tells us that Lord Kelvin at one stage theorized about an ether constituted of « rigid boxes, each containing a gyrostat animated by a movement of rapid rotation around an axis fixed to the sidewalls, [and] attached to one another by strips of flexible but inelastic cloth ». Several decades later, physicists professed to have abandoned the ether altogether. Yet some day it might be reincarnated in a new form. In any case, surely it is more prudent to regard the ether, or any other physical system, as a product of scientific creativity rather than a constituent of ontological reality.

2. THE PHYSICAL SYSTEM AS AN EPISTEMOLOGICAL CONSTRUCT.

— The common jargon employed by physicists in which experimental facts are organized in terms of so-called « models » — understood to be more ephemeral than eternal — tacitly indicates that most physicists probably recognize that ontological reality is beyond the grasp of scientific methodology. This is not to suggest that physicists unfamiliar with the rudiments of philosophy would necessarily admit this impotence overtly. Nevertheless, epistemological reflection upon the actual practice of physics fosters the realization that the concept of physical system is basically a creation of the mind, expressly designed for the purpose of cataloguing certain facets of human experience [2].

This understanding that the physical system is an epistemological construct immediately resolves the historical problem alluded to in section 1, viz., that an ontological world should be immutable whereas the character of physical systems seems to evolve. Moreover, once we grant that the system resides within experience, there is no longer an inclination to seek its nature by appealing to metaphysical dogmas in the hope of apprehending some external reality. Instead, we shall, in the present investigation concerning the nature of quantum systems, focus on the conceptual framework, physical and philosophical, in which the notion of quantum system is rationally embedded and from which it obtains whatever qualities, whatever character, can be attributed to it. In undertaking such a study, one must be especially cautious to maintain flexibility in his world view, so that preconceptions traceable to ancestral bias will not distort or otherwise complicate the conclusions. To attain this perspective, scientific reasoning will be augmented in appropriate places by metascientific principles drawn from scientific epistemology.

3. UNCERTAINTY AND INDETERMINACY.

— One of the great triumphs of nineteenth century physics — the culmination of the era of mechanism in natural philosophy — was the successful application of macromechanical concepts to describe the more or less directly observable properties of gases in terms of an unseen microcosm of minuscule particles called atoms. This kinetic theory of gases could not have been inspired by the reports of any microscopist, who, having closely examined, say, a vial of oxygen, perceived through his lenses that the gas resembled myriad billiard balls engaged in rapid movement and frequent collision; for no microscope of sufficient magnification existed. Instead the atomistic conception was a theoretical extrapolation of constructs and laws that had been immensely successful both in the terrestrial physics of motion and in the study of celestial bodies. Nevertheless, because of the achievements of kinetic theory and its internal consistency as an intellectual framework for thinking about gases, few physicists could doubt that the atoms were, in some sense, real.

Suppose, however, that a shrewd dialectician with positivistic leanings, upon contemplation of the alleged physical reality of the unseen atom, had proposed an argument against the atom concept along the following lines: To measure the velocity of an atom, its positions at two instants in time must be determined. To measure the first position, the atom must be illuminated; but then, due to radiation pressure (the same momentum transfer that produces comet tails,) the second position of the atom will not be the same as it would have been if the illumination had not been imposed. Hence the measured velocity will not represent the actual velocity just prior to the onset of the measurement act. To refine the procedure so as to obtain the true velocity, clearly the radiation pressure must be reduced to zero; the second position will then be untainted by the earlier measurement act. However, now there is no earlier position determination; for without illumination, the atom goes undetected.

Imagine that our hypothetical nineteenth century dialectician has constructed numerous additional examples of the foregoing type, and now reasons as follows: Careful analysis of the usual experimental methodology of measurement commonly employed to obtain numerical values for position and velocity leads inductively to the general proposition that, strictly speaking,

(a) it is operationally impossible to measure the position and the velocity of an atom. Accordingly, it must further be concluded, in keeping with empiricist precepts, that

(b) the atom, theoretically construed as an entity possessing at all times a definite position and velocity, does not exist.

Most nineteenth century physicists surely would have rejected at least conclusion (b) and possibly even conclusion (a) of our fictitious critic. Their retort to (a) might be simply the general philosophical observation that inductive reasoning is an ill-defined procedure with dubious persuasive capabilities. Nevertheless, even if (a) were granted, i.e., even if it were in fact true that no empirical procedure whatever existed the application of which would determine both the position and velocity of an atom, still (b) would not follow. At least (b) would not follow unless one accepts a positivistic metascientific postulate to the effect that the operational possibility of measurement is the touchstone for determining existence or nonexistence. Indeed if one adheres to the epistemological theory concerning physical systems advocated in section 2, the operational possibility of measurement is less important than the theoretical consistency or inconsistency prevailing when the conception of atom is used. Inasmuch as kinetic theory with its position-and-velocity-possessing atoms was a consistent and empirically powerful philosophical mold for organizing data, it is unreasonable to declare its atoms nonexistent merely because their properties cannot be simultaneously ascertained. As a matter of fact, the very arguments like (a) which suggest the operational impossibility in question are themselves constructed *within* the theoretical framework which speaks of atoms having position and velocity; i.e., it is possible to explain without contradiction *why* comeasurement of position and velocity might be impossible by using the concept of atoms which concurrently possess position and velocity. Hence, the conclusion (b) lacks cogency.

In view of these remarks concerning the fictitious dialectician of the past, it seems incredible that many contemporary physicists accept, or at least pay lip service to, but otherwise ignore, an analogous set of arguments generally associated with the so-called Copenhagen Interpretation of quantum theory. Famous gedankenexperiments popularized decades ago by Niels Bohr[3] argue inductively, for example, that

(a') position and momentum measurements upon an electron require mutually exclusive laboratory procedures (Bohr's « Principle of Complementarity ») and that therefore

(b') the electron cannot be regarded as a particle, i.e., an entity possessing position and velocity.

Now, in the quantum case it turns out that there are strong arguments to be nade for a uniquely quantal conception of physical system which does indeed include the proposition (b'). But the orthodox (Copenhagen) route to (b') via (a') is no less spurious than the fictitious attack upon the classical atom described above. Accordingly, we shall dismiss from further consideration gedankenexperiments which purport to establish the operational noncomeasurability of position and momentum.

There are, however, other gedankenexperiments which do enable one to grasp in a manner free of mathematical encumbrance the characteristics of a quantal system, such as an electron, which do suggest that the particle concept is perhaps no longer adequate for understanding microphysical phenomena.

Consider, for example, the frequently discussed experiments involving slits and electron beams, a variation of which we shall now describe in a manner that emphasizes the distinctively quantal nature of an electron as dramatically as possible. What is described below in the form of a gedankenexperiment is of course to be understood as a set of predictions made about the results of measurements upon electrons by quantum theory. No inductive argument is intended; the electron is understood as a physical system defined constitutively by the complex of statements quantum theory makes about it. What we seek to discover is whether such an electron can be consistently *conceived* (not measured!) to be a particle, i.e., an entity possessing position and momentum. The question of the physical existence of the electron will be deferred to section 4.

Visualize now a specific experimental arrangement, consisting of three components: an electron gun, a wall impenetrable by electrons save for a narrow rectangular aperture, and a plate which registers electron impact by forming a visible dot about the impact point. After the gun has been triggered, very often a dot will appear somewhere on the plate, which is on the opposite side of the wall from the gun. If the procedure is repeated a great many times, eventually there will have formed on the plate a pattern of dots which exhibits the peculiar fact that there are certain preferred regions for electron impact separated by regions that electrons mysteriously avoid.

So far it is not difficult to comprehend the observations in terms of a classical particle model of the electron. The very appearance of dots (as opposed, say, to bands) strongly suggests a particulate character for whatever it is the gun generates and the plate detects; and even the anomalous occurrence of forbidden regions might be blamed on some irregularity at the boundary of the aperture which intercepts and alters trajectories which otherwise would have terminated in the forbidden areas.

Suppose now that the wall is punctured by a second aperture beside the first and identical to it in size and shape. Again, if the electron gun is fired many times, eventually a pattern will form on the plate; but the pattern will not be simply a superposition of two patterns of the type observed with one aperture, as a particle model of the electron would seem to require. *Instead, there are now forbidden zones where there would have been preferred zones if only one or the other of the two apertures had been open.* How is this strange fact to be interpreted?

The stock Copenhagen treatment of such physical situations invariably revolves about the so-called wave-particle duality — the notion that an electron is a particle that sometimes displays a wave nature and also vice versa. Thus, since that portion of the mathematics of quantum theory which is used to predict the patterns above formally resembles classical wave theory, it is essentially argued that each electron diffuses into a wave, then determines what trajectories are admissible by probing the impending wall in an advance search for apertures. Having thus ascertained the loci of preferred and forbidden zones, the electron reassumes its punctiform character to create a dot in the right place. In recent years a number of physicists and philosophers have questioned the Copenhagen notion of duality. In particular, Landé, in several publications including a contribution[4] to « *Scientia* », has in the opinion of the present writer utterly demolished the orthodox philosophy of dualism.

However, Landé's final conclusion, which seems to have received the concurrence of Popper[5], is one which we cannot accept, though there is no question that its intellectual palatability far exceeds the dualistic thesis. Landé argues that the electron is indeed a particle, but that the quantum laws which determine possible particle trajectories conspire to create the remarkable difference between the one-aperture and two-aperture patterns discussed above. However, it is extremely difficult to accommodate a model so mechanistic to account for the patterns, since retention of the particle concept in this way is tantamount to the invention of unknown forces with almost teleological characteristics. To see this, imagine that the electron gun is located a million light-years from the wall and plate, both of which are in a laboratory. Since admissible trajectories are determined by the number of apertures, the electron gun must « know » what experimental arrangement will be set up at least a million years in the future in order to choose a trajectory that will terminate in a preferred zone. Landé[6] rejects this view by insisting that the presence or absence of the second aperture alters the local environment of the particulate electron so as to guide it along an admissible trajectory; but this too amounts to inventing unseen forces for the sake of preserving reference to the unseen particles traveling along their unseen trajectories. Nevertheless, it must be granted that these arguments have reached an impasse; discussion of the patterns in question is scientifically inconclusive with regard to the issue as whether quantum sustems can be regarded as entities possessing position and momentum.

However, there is another related prediction in quantum theory which does have a decisive bearing on this question as to whether quantum systems can be conceived to possess position and momentum. We are referring to the famous Heisenberg Uncertainty Relation, but not to all of its mysterious interpretations. In fact only one interpretation is solidly grounded in the theoretical framework of quantum physics. That interpretation is based on the recognition that quantum theory is a statistical theory whose predictions are always expressed in the format suggested by these illustrative sentences: If a position measurement is performed upon each electron in a long sequence of electrons each emitted by a given gun, the fraction W_x of the numerical results will be in a specified position scale interval I_x; if a momentum measurement is performed upon each electron ..... the fraction W_p ..... will be in ..... I_p; etc. Now, the uncertainty principle — a theorem in quantum physics — states simply this: There does not exist a gun (more rigorously, a method for preparing electrons) such that W_x and W_p are both unity for I_x and I_p arbitrarily narrow intervals. Thus whatever the physical system envisaged by quantum theory is, the following assertion can be made about it: There is no way to prepare a quantum system such that it can be predicted in advance what the results of both a position and a momentum measurement would be. The question now arises as to whether this statistical *uncertainty* can play any role in constructing a rational argument in behalf of an intrinsic indeterminacy of position and momentum, where by the term indeterminacy we refer to a conception of the electron, for instance, as an abstract entity which does not possess the attributes of position and momentum, i.e., is not a particle. In other words, can statistical uncertainty lead to the same philosophical position — indeterminacy — spuriously extracted from the historic Copenhagen gedankenexperiments criticized earlier?

Landé, Popper, and others have made the point that uncertainty alone no more implies indeterminacy than do the gedankenexperiments; and with this point I have no quarrel. Mathematically, it is possible to construct families of joint probability distributions for position and momentum values which are at once consistent with uncertainty relations and capable of describing the properties of particles. Nevertheless, we shall argue in the following section that uncertainty, when considered in conjunction with certain epistemological insights bearing on the root scientific meaning of the notion of physical system, does support abandonment of the particle concept in favor of an abstract notion of system which features a fundamental indeterminacy of attributes.

4. REPRODUCIBILITY, PARSIMONY, AND PHYSICAL EXISTENCE. —

The inconclusiveness of purely scientific debate concerning the nature of the physical systems described by quantum theory has been exhibited in the preceding section. In order to resolve the question at hand we must therefore assume a philosophical perspective which transcends science itself but which focuses upon the nature of scientific methodology. In sections 1 and 2 the concept of physical system has already been examined from such a perspective. There it was argued that any notion of a physical system as the mirror image of a « real » object in an ontological realm beyond human experience represented an improper, and indeed pompous, extravagance for science to maintain. Instead we urged that a physical system is best interpreted more modestly as a category created by the mind for the sake of ordering human experience and endowed only with those attributes that are suggested by the theoretical matrix of constructs (with their empirical interpretations) in which the system is logically embedded.

Consider again the electron, a physical system described by quantum theory. That theory predicts probability distributions for position measurements, momentum measurements, etc. But it neither affirms nor denies that the electron possesses at all times position and momentum values; yet it does deny the existence of procedures for generating electrons certain to yield preassigned position *and* momentum values upon measurement. We shall now present an epistemological analysis which invokes two metascientific principles, in addition to the foregoing quantum theoretical points, in order to develop our contention that quantum physics denies the physical existence of particulate electrons, i.e., objects considered to possess, among other properties, position and momentum values at all times.

An important facet of the objectivity for which science is justly famed is the metascientific requirement of intersubjectivity. Thus not all human experience is considered appropriate for scientific scrutiny; only sensations of a kind familiar to the majority of rational men are susceptible to scientific treatment. With certain qualifications to be discussed below, the requirement of intersubjectivity in practice simply refers to the reproducibility of data. Thus in the scientific community much greater weight is given a particular discovery if it has been verified at independent laboratories.

There are, however, observations for which reproducibility is a practical impossibility but which nevertheless are recognized as legitimate domains of scientific inquiry. For example, the almost fortuitous measurements made in connection with cataclysmic events such as earthquakes, tornadoes, or novae are not discredited by seismologists, meteorologists, and astrophysicists merely because planned repetition is unachievable. On the other hand, reports of revelatory visions, ectoplasmic phenomena, and miraculous occurrences are generally considered to lie beyond the scope of science. What is the distinction between these two species of unreproducible events that renders one scientific, the other ascientific?

The difference is simply this: The unreproducible scientific events are unreproducible in practice but not in principle. The volcanologist may lack the means to incite the wrath of Krakatoa, but he can *conceive* in terms of the constructs of his discipline — stresses, strains, viscosity, etc. — a procedure reproducible in principle which would yield an eruption. On the contrary, no prescription exists even in principle to bring about the recurrence of a miracle.

Now in quantum physics we have seen that the uncertainty relationship denies in principle that there exist any reproducible modes of preparation for electrons which can at once guarantee preassigned results for both position and momentum measurements. Thus we insist that the particulate electron is an illegitimate scientific construct for the metascientific reason that the theoretical nexus which describes electrons does not permit the conception of an electron in a reproducible condition that can be characterized in terms of essential particulate attributes.

Beyond the criterion of reproducibility there is a second metascientific principle that has a strong bearing on the appropriateness of interpreting the electron as a particle. It is a principle of theory construction commonly called Ockham's Razor, or the Law of Parsimony, which cautions against unnecessary proliferation of concepts. Obviously, the requirement is somewhat ambiguous since no two scholars are likely to agree completely on the extent to which a given theory is parsimonious. Nevertheless, the criterion of simplicity has long been a valuable guide in the development of physical theories.

Indeed the historical evolution of the physical concept of energy illustrates that the search for parsimony can be a powerful stimulus to scientific discovery. Within the framework of analytical mechanics, where the notion of energy originated, there was but limited evidence that the concept might lead to a conservation law of universal validity. While it is true that mechanics admits of energy conservation in several interesting cases, the existence of so-called dissipative forces (under whose influence energy is not conserved) detracts from the importance of energy. Nevertheless, inspired by the elegance that a conservation principle contributes to a theory, physicists have for several centuries invented (and found empirical backing for) diverse forms of energy ranging from latent heats to the kinetic energy of massless neutrinos.

Today an experimental quest is under way to produce (and reproduce!) the theoretically proposed microsystem called the quark, a construct which may invest the taxonomic organization of contemporary elementary « particle » physics with a higher degree of parsimony. It is sometimes said that reproducibility of quarks might not be demanded if the parsimony contributed by the quark concept is truly spectacular. However, given the realistic inclinations of physicists, this seems unlikely.

At any rate, in assessing the nature of quantum systems and the applicability of the particle concept to them, we confront a situation in which both of the metascientific principles here considered — reproducibility and parsimony — are violated. Not only is an electron exhibiting particulate behavior unreproducible in principle; but the pretense that an electron is a particle anyway contributes nothing to quantum theoretical analysis but excess verbiage. For, as we have seen in section 3, treatment of the electron as a particle gives birth to related mechanistic questions concerning the nature of forces capable of guiding such particles along remarkable trajectories toward destinations consonant with quantum rules. Thus the *unreproducible* particulate electron leads to a most *unparsimonious* multiplication of concepts.

To return the language of section 3, we conclude that when the statistical uncertainty of quantum physics is supplemented by the philosophical principles of reproducibility and parsimony, there results a cogent argument in behalf of interpreting the quantum system as an abstract construct characterized by an innate indeterminacy. In short, the electron, for example, is not a particle; it should not be conceived as a punctiform body traversing Cartesian paths through space and time. A discussion of the manner in which the quantum system can be conceived, and the positive aspects of a distinctly quantal conception of it, may be found in Part II of this essay.

Finally, let us consider briefly the notion of existence. Like the term reality, the idea of existence has a multitude of connotations, so that it is not uncommon to find physicist and philosopher quibbling over the word even when they otherwise are thinking quite similar thoughts. For the present discussion, we would like to distinguish three kinds of existence that physicists regularly encounter: mathematical, ontological, and physical.

In mathematics, and hence in the algorithms of physical theories, the existential qualifier « there exists » is commonplace. When a number of conditions have been placed on a hypothetical function, for instance, the question arises as to whether any function can be found that satisfies all the conditions. If so, the hypothetical function mathematically exists; but if the conditions turn out to be mutually contradictory, the hypothetical function is declared mathematically nonexistent.

Ontological existence is a subject that philosophically naive physicists sometimes claim as the subject matter of their science — a quixotic notion we have already rejected in section 1. Whether the electron or a ghost or anything else « really », ontologically, exists is a query transcending the domain of science.

Physical existence, on the other hand, is a metascientific concept far less grandiose than ontological existence. To say, for example, that electrons *physically* exist means only this: A logically consistent theory has been devised, in accordance with established metascientific criteria, which describes in terms of various constructs equipped with experiential interpretations (e.g., operational definitions) a concept called the electron, which is itself linked to empirical experience by specifications of reproducible procedures classed as electron preparation schemes. If the theory is successful as a regularizer of data obtained from situations involving these reproducible electron-preparing schemes, if in particular it dramatically predicts with accuracy the empirical manifestations of electrons in diverse experimental arrangements, then the concept electron may be said to exist *physically*.

It should be recognized that physical existence can be conferred only provisionally, for the accumulation of data may in the course of time result in the abandonment of a theory and with it concepts of systems formerly thought to exist physically. Such was the fate of the particle in the theoretical revolution from which modern quantum physics arose.

We may summarize as follows the main conclusion of this paper in terms of this notion of physical existence:

1. Because quantum physics satisfies all of the scientific and metascientific requirements discussed above, quantum systems like the electron physically exist.

2. The quantum system is, moreover, an epistemological construct *sui generis*; it is not a particle, and it is certainly not a wave. Wave-particle duality is of historical interest, but lacks physical significance.

3. Since quantum physics has superseded classical theories as the primary means for seeking order in the deliverances of nature, quantum systems must be regarded as the fundamental entities which physically exist, and which constitute the conceptual building blocks of (present-day) physical reality.

4. It therefore follows in particular that particles (entities possessing at all times values for position, momentum, etc.) do not physically exist.

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