QUANTUM SYSTEMS

Part II: The Primitivity of Measurement

This paper concludes a two part study of the nature of quantum systems. Part I, which appeared in the preceding issue of this journal, criticized and rejected classical conceptions of the quantum system. Part II develops in a positive manner a fresh epistemological orientation for comprehending quantum physics-based on the notion that measurement is a primitive quantal construct. Several physical consequences of this primitivity are discussed, including the possibility of simultaneous measurement of position and momentum and problems connected with the quantum theory of measurement.

5. Measurement as a Primitive Quantal Construct. — Many theoretical physicists, including the present writer, feel that a physical theory should ideally be cast in that clear logical format of which geometry is the traditional prototype. That is, there should be a list of terms, the primitives, none of which are, from a purely mathematical perspective, either defined or definable. Some or all of these mathematically primitive terms must, however, be assigned physical interpretations (epistemic links to human experience such as operational definitions) in order for the logical nexus in which they participate to be regarded as a branch of physics. The primitives should be employed to form a set of sentences which express those interrelationships among primitives that constitute the axioms of the theory. Such postulates, when considered in tandem with the aforementioned physical interpretations of the primitives, become the sweeping assumptions which in the parlance of physics are usually called laws of nature.

Only when a physical theory can be stated with such geometric clarity can the full power of mathematical deduction as a tool for making predictions about experience be realized. Via logical analysis, the laws of nature give rise to innumerable empirically testable propositions, the verification or falsification of which is the domain of normal experimental physics.

As suggested above, not all physicists, not even all theoretical physicists, regard this strictly logical structure which carefully delineates primitives, postulates, and theorems as a desirable form for expressing physical theories. Some interpret the definiteness wrought by axiomatization as a kind of rigidity which stifles creativity, whereas others perceive in such geometric precision not stultification but rather a kind of flexibility in theory construction that arises from the exact knowledge of what has been assumed and therefore of what can be modified and with what logical consequences. As a result, in actual practice physical theories are commonly set forth in a manner which represents a kind of compromise between the proponents of axiomatization and those who prefer instead an unrigorous intuitive melange of concepts.

For a philosophical analysis such as the present work attempts, it seems to me preferable to emphasize the axiomatic approach; otherwise the reasoning could easily give way to the murky obscurantism so characteristic of most discussions of Complementarity, including those of Bohr himself as well as the efforts of his apologists. It is not, however, necessary to list exhaustively every primitive and postulate of the various mathematical disciplines that serve as building blocks for quantum theory. It is essential here only to recognize that there is in principle a logical structure, including in particular as primitives the notions of system, observable, and a relation binding them.

In these formal terms, it is possible to describe the conclusions reached in Part I of this paper by stating that the primitive relationships between a system and its observables in quantum physics is radically different from the analogous relationships in classical physics. Probably the best characterization of this distinction is that proposed by Margenau [1] in his latency theory of observables (the terminology of which will be used below). However, since the latter is not widely understood, it seems appropriate to sketch its basic features in conjunction with the present analysis.

First, let us briefly reiterate the classical notion of physical system that was rejected in the arguments of Part I. The key word is *possess.* The classical system was regarded as an object *possessing* its observables as *properties*, each of which could at any given time be expressed by a number. In Part I it was established that the uncertainty principle, together with the reproducibility criterion, requires abandonment of the primitive relation possession as the conceptual link between the primitive notions of system and observable. What primitive relation replaces possession?

To answer this question, consider for a moment a similarity between classical and quantum physics that somehow supersedes the dramatic conceptual differences that have been emphasized above, viz., the identity of purpose of the measurement act. Every experiment, indeed every physical experience, can in principle be described in what I have elsewhere [2] termed the *Preparation-Measurement Format.* The essential point is that science deals with reproducible physical operations by which systems are said to be prepared for study as well as diverse physical acts, called measurements upon the prepared systems, which yield the numerical data. Observables are simply the categories by which measurement procedures and the data they produce are catalogued. This preparation—measurement format for physical experience is common to both the classical and quantal approaches to physics.

Now, when as in classical theoretical physics system and observable are connected by the primitive relation of possession, the preparation-measurement format seems an overly cumbersome expression of a simpler idea, viz., that the act of measurement is merely a careful observation of the properties borne by the system. If a system can be thought of as carrying numerical labels, one for each observable, measurement becomes nothing more than a procedure for discovering at some instant of interest the values of one or more of these labels.

In quantum physics, on the other hand, we face a situation in which experiments remain describable in the preparation-measurement format; but, due to the inevitable quantal uncertainty, no consistent labeling scheme is possible. Consequently, the primitive relation *possession* must be abandoned, and measurement can no longer be interpreted as yielding revelations of pre-existing values for observables. To return then to the original question: What, instead of possession, is the primitive relationship between a system and its observables in quantum physics? The answer toward which we have been progressing is just this: The preparation-measurement format itself is in quantum physics a primitive concept. More precisely, quantum theory employs the notion of measurement in a manner that must be regarded as logically primitive. Thus when a quantum theorist asserts that if a system is prepared in a specified manner subsequent measurement acts will yield particular numbers with stated probabilities, no deeper, hidden meaning is intended. In particular, no prediction is made about properties of the system (since it possesses none); the prediction is literally (and physically!) about measurement results subsequent to a specified preparation. Hence that which is predicted cannot even be stated without using the notion of measurement; therefore, measurement is a primitive term.

Measurement is, in fact, the primitive relation that plays the same role in quantum physics that possession did in classical physics. Wherever in classical theory the statement « system S possesses observable A with value a » would occur, the analogous place in quantum theory will feature the dispositional statement « if observable A is measured on S, the number, a, will emerge (with some specified probability) ». Margenau characterizes this feature of quantum physics that I have termed the primitivity of measurement by referring to the latency of quantal observables. Thus a quantum observable is associated with the system but no numerical label is attached to the system; however, when elicited by measurement, a numerical datum will emerge for that latent observable.

For further epistemological analysis of the concepts of latency and measurement, the interested reader is referred to other publications [3].

6. Theoretical Consequences of the Primitivity of Measurement. — One of the most controversial philosophical issues in quantum physics and one that has often been exaggerated by the suggestion that it embodies the very *raison d'etre* for the historic replacement of classical mechanics by quantum mechanics is the question as to whether pairs of observables which participate in an uncertainty relation can be simultaneously measured. As discussed in Part I the old semiclassical gedankenexperiments which seemed to « derive » the uncertainty principle featured a slightly irrational brand of positivistic reasoning. Thus it was customary to argue, for instance, that since the particular designs considered for position measurement devices required the electron (the system) to be violently scattered, the electron's momentum would change during the position determination. The irrationality intrudes when it is then concluded that no other schemes can be devised to circumvent this problem. And unchecked positivism rears its head when it is finally argued that since position and momentum measurements operationally interfere with each other, the electron cannot be regarded as possessing these attributes except in the sense of Complementarity. We have already attacked this line of reasoning in Part I.

Now, however, we have reached by a rather different route the same conclusion, viz., that a quantum system must be understood as an abstract entity possessing no numerical observable-labels. Indeed the fundamental epistemological notion that distinguishes quantum theory from the rest of physics—the primitivity of measurement, the latency of observables—has been developed independently; as a result, the problem of simultaneous measurability remains open-ended.

From the new perspective based on the primitivity of measurement, it is not difficult to dismiss the old gedankenexperiments as irrelevant to the problem of simultaneous measurement because their only relevance to modern quantum physics at all is historical but not logical. That is, their motivational value several decades past is irrefutable; but they are after all semiclassical in character and therefore philosophically incompatible with the concept of quantum system developed in Part I. The confusion of logic with history has affected presentations of quantum theory too long.

Sir Isaac Newton, it is said, was a kind of mystic; and it is perhaps not unreasonable to surmise that this unscientific aspect of his psyche contributed in some way to his ingenious formulation of mechanics in the *Principia*. But surely no one would argue that empathy with Sir Isaac's theology is prerequisite to grasping the essence of his mechanics. *Mutatis mutandis* we would argue that the old gedankenexperiments are best ignored if a contemporary understanding of quantum physics is desired.

To ascertain what strictures, if any, are placed *a priori* upon silmultaneous measurement by modern quantum theory, it is only necessary to recall the basic theoretical role of the quantal measurement construct as the primitve relation between a system and its observables. In the treatment of measurements of only one observable, the quantum model of a system precludes the assumption that even the single label was present and that measurement merely unveiled it. Instead it is insisted that no labels existed in any sense prior to the measurement; the only admissible statement is the latency-oriented one that measurement elicited a numerical datum from the system. Despite the prior non-existence of the label, however, it is never suggested that measurement of a single observable is impossible.

It would therefore be illogical to deny the possibility of simultaneous measurement of two observables just because a system cannot be regarded as possessing prior to the measurement two labels. (Recall even one label was unacceptable). Hence it is quite possible to contemplate, without generating any logical antimonies, the simultaneous measurement, for example, of position and momentum. We have explored elsewhere [4] the mathematical aspects of the simultaneous measurability question, and have given in particular explicit counter-examples to refute the apparent restrictions on simultaneous measurement suggested by the old gedankenexperiments.

To conclude this analysis of the simultaneous measurement issue it seems appropriate to juxtapose in brief form the basic assertion of the old positivistic argument for Complementarity and the philosophical position with regard to simultaneous measurement advocated here and in other publications [3, 4] of the present writer. The old arguments departed from gedankenexperiments that suggested simultaneous position and momentum measurements were operationally impossible, then concluded that the electron was not an object possessing the attributes of position and momentum. The new line of reasoning establishes first the impossibility of conceiving within the theoretical framework of quantum mechanics a reproducible preparational scheme which would endow an electron with preassigned position and momentum values certain to emerge during measurement. Measurement then replaces possession as the primitive relation between system and observable, and consequently there is no reason whatever to believe that simultaneous measurements are any less plausible than single measurements. In short, the essence of the Complementarist conclusion about the nature of systems remains, but the premises which gave rise to it are rejected and indeed reversed.

Another philosophical controversy in quantum physics for which the conception of measurement as a primitive provides fresh insight centers on the question as to what « condition » a system is in after an act of measurement has been performed. This is, of course, a part of the larger set of problems in quantum physics collectively discussed in the literature under the rubric « quantum theory of measurement ». We shall comment further on some of these problems in section 7. However, it is germane at this stage to discuss one common proposal about the post-measurement-operation « condition » of a system—the immediate remeasurement doctrine.

According to this point of view quantum physics should include as a postulate the requirement that an immediate remeasurement of any observable must reiterate the numerical result of the first measurement. There are at least two types of reasons sometimes advanced in support of this idea: (a) classical arguments, and (b) conservation law arguments. We now evaluate in turn the ideas in (a) and (b) from a vantage point which recognizes the primitivity of measurement.

(a) Advocacy of the immediate remeasurement doctrine is sometimes inspired by the simple fact that in classical physics it is obviously true. Possessed observables vary continously in time, and for a sufficiently short time interval the values of any observable at the end points of the interval will be arbitrarily close. And superficially this may seem like the kind of broad statement whose validity could encompass and help unite all of physics, classical and quantal. Examples of such universal scientific principles includes, for example, relationships such as that between rotational invariance and the conservation of angular momentum as well as the preparation-measurement format of scientific investigation discussed earlier in this paper. There is, however, an empirical reason to disavow the suggested universality of the immediate remeasurement doctrine: not every procedure that would normally be considered a measurement is capable of immediate repetition. Moreover there is also a philosophical objection to be raised.

The desire for an immediate confirmation of a measurement result presupposes tacitly that the first measurement was intended to discover what value of a given observable is possessed by the system. But if measurement, not possession, is the primitive, it is no longer permissible to imagine that the first measurement revealed any property at all; hence, the notion of confirmation becomes meaningless.

Just as the primitivity of measurement ruled out the assignment of labels to a system before measurement, it rules out such assignment after measurement. The relation between system and observable is *at all times* expressible only in the conditional form « if observable A is measured on system S, the numerical result, a, will emerge (with some predicted probability) ». Thus just as recognition of the primitivity of measurement opened up the possibility of simultaneous measurement, it also erases old strictures on the post-measurement condition of a system.

(b) Occasionally one reads that the immediate remeasurement doctrine is essential because without it conservation laws would lose empirical meaning. To see that this argument is untenable, it is necessary to understand the sense in which quantum mechanics speaks of « conservation laws » at all. The only dynamical statement about an observable that quantum theory can make concerns not the temporal evolution of the possessed values of the observable but the time development of the *probability* in a time sequence of conditional statements of the type « if observable A is measured at time t on system S, the number, a, will emerge with probability W (a; t) ». If, for some particular A, W (a; t) is independent of t, then in quantum mechanics A is said to be conserved. However, when a measurement is performed, the system S can no longer be said to have been prepared (for subsequent measurements) in the same manner which led to the earlier family of conditional statements. Hence there is no reason to believe that the W (a; t) would still be applicable. Moreover, even if they did continue to be valid subsequent to the first measurement, still it would be logically improper to conclude that a second measurement would confirm the first. No matter how often a coin is tossed, the probability that it will yield a « head » remains ½; obviously, this does not insure that if a head appears on the first toss, it will necessarily reappear on the second toss. The analogy is not perfect, but it expresses the essential point. If measurement is a primitive, it is improper to speak literally of any observable as being conserved in the classical sense.

7. Remarks on Quantal Measurement Theories. — The classical concept of possession as the primitive relation between system and observable is ingrained from childhood in the minds of contemporary men; it is in fact a part of that diffuse body of ideas confidently termed common sense. No need to challenge the supposed obviousness and universality of the possession concept arises in ordinary macroscopic experience, but it is well known to quantum physicists that microphysical phenomena cannot be ordered under the old world view to which possession is central. Yet interestingly enough even quantum theorists are at present reluctant to develop a consistent quantal mode of thought capable of embracing both microscopic and macroscopic experience. In short, in the present epoch, few quantum physicists seriously try to think quantally. A previous publication [2] in the present journal explored this state of affairs in depth.

There we noted that even the most modern attempts to develop a quantum theory of measurement—a theoretical description of measurement procedures—rely openly on a classical world view of the macroscopic laboratory apparatus. Thus, instead of accepting the positive aspects of a quantal treatment, viz., its predictions of unexpected phenomena, measurement theorists labor to extract from the preparation-measurement format of quantum theory features contradictory to that format which seem to restore to the apparatus what is often called objectivity. However, « objectivity » in this context refers to the possession concept, which is in turn a vital aspect of « common sense ». Hence the search for a so-called « objective » description of apparatus is symptomatic of the reluctance even of quantum theorists to regard measurement as a primitive construct appropriate for physical thinking at all levels of experience from cosmic to subnuclear.

Beyond calling attention to this reluctance to « think quantally », the purpose of the present section is to signalize the important distinction between the philosophical position advocated here—that a primitive measurement construct replaces possession in quantum mechanics—and an opposing viewpoint which retains a modified form of possession and which regularly appears in proposed measurement theories.

Since quantum mechanics is cast in the preparation-measurement format, the mathematical theory, strictly speaking, deals only with probability distributions of measurement results for the various conceivable modes of preparation and choices of observable to be measured; hence, the empirical referent of the formalism is the *ensemble* of identically prepared systems that is required to give physical meaning to any probability distribution. There are several well known mathematical devices commonly used in quantum theory to summarize the predicted distributions—the density matrix, the state vector, the wave function (and other representations of the state vector). But the physical meaning of each one involves probability, a property not of a single physical system but only of an ensemble of such systems.

Unfortunately, the structure of quantum mechanics together with the jargon used by all physicists to discuss quantum phenomena permits a careless mimicry of the classical possession concept. Specifically, consider that representation of probability distributions for potential measurement results called the state vector ψ. (For the benefit of nonphysicist readers, perhaps I should note that ψ resides in an infinite-dimensional space and that each of its components is simply related to the probability for obtaining a certain number when a measurement of some specified observable is performed upon a system prepared in the manner represented symbolically by the vector). Quantum dynamics governs the causal evolution of the state vector much as Newtonian mechanics describes the changing values of possessed observables for particles. Consequently, it is commonplace to read in the literature of quantum physics that a system is « in state ψ » or that it has a given probability of being « in state ψ » or of « having state ψ ». In short, the jargon suggests that the symbol ψ has the same theoretical role in quantum mechanics that possessed observables had in classical mechanics. Thus when this language is employed it is easy to overlook the point emphasized above that ψ summarizes probabilities which in turn refer empirically not to single systems but to ensembles. We have discussed in a different context the impropriety of assigning ψ possessively to a single system in a past issue of this journal [2], to which the reader is referred for a more thorough analysis.

The philosophical impact of referring to ψ as though it were an attribute of a single system is especially evident in theories of measurement of the kind alluded to earlier which seek to establish « objectivity ». The primitivity of measurement is typically ignored; instead of « thinking quantally », i.e., attempting to adjust intellectually to the preparation-measurement format description of the apparatus, measurement theorists seize from the jargon a notion of possession—not of observable-labels, but of abstract vectors—and then try to circumvent the latency feature of quantum physics by making demands involving *possessed* state vectors in the name of « objectivity ». Thus, for example, the common denominator of most quantum theories of measurement has been an « objectivity » demand which may be described as follows.

A laboratory measurement procedure involves an interaction between two physical systems, the one being measured (called simply the « system ») and the one that the scientist in some sense directly experiences (the « apparatus »). Quantum theoretically, the interaction is deemed suitable to effect a measurement procedure if it leads to a prediction of a type, which I shall now describe rigorously although rather ankwardly, in the strict language of the preparation-measurement format. After the interaction has occurred, a successful measurement is said to have been accomplished if the following pair of theoretical probabilities are equal:

(i) The probability that a primitive measurement of the system's observable of interest at the onset of the interaction would have yielded any specified result; and

(ii) the probability that a post-interaction primitive measurement of an observable associated with the apparatus will yield any specified number from a set that can be placed in correspondence with the set of potential results in (i).

Equality of these probabilities is the mathematical expression of a measurement correlation since primitive measurement of the apparatus after the interaction yields data that can be theoretically linked to unperformed primitive measurements on the system itself. If one accepts the primitivity of measurement universally, i.e., as being equally appropriate for describing apparatus as well as system, the foregoing description of the correlation is physically complete.

Measurement theorists seeking the elusive « objectivity » are unsatisfied, however, and demand in addition to the above correlation between primitive measurements that the following statements be valid after the interaction:

(i) The apparatus shall possess a state vector which predicts that an immediate second measurement on the apparatus will confirm the result of the first *and*

(ii) the system shall possess a state vector which predicts that an immediate (primitive) remeasurement would yield the same result as that just inferred from the measurement procedure.

Requirement (i) is an attempt to come to terms with the common observation that macroscopic objects can be « watched continuously » and do not deliver to the observer a chaotic sequence of different observable-values. But (i) goes too far when it attributes a *state* vector possessively to a system. The result is not a quantal explanation of the apparent possessed observable-labels of macrosystems, but merely a verbal attempt to force quantum physics into an incompatible classical mold. The experimental root of (i) remains a great unsolved problem in quantum mechanics partly because the problem is generally poorly formulated, the essential primitivity of measurement being ignored.

Requirement (ii), often called « wave-packet reduction », is just another form of the immediate remeasurement doctrine, whose philosophical roots have already been criticized in section 6.

8. An Alternative to both the Copenhagen and Russian Interpretations of Quantum Physics. — For historical reasons, an ill-defined body of ideas commonly termed the Copenhagen Interpreation of Quantum Theory is effectively the orthodoxy of modern physics. It is arguable that there is really no such thing as *the* Copenhagen Interpretation, since the term is only vaguely understood by most physicists as referring in some way to Bohr's Complementarity notions. As a practical matter, the majority of physicists are just not engaged in research so fundamental as that which originally motivated the Copenhagen philosophizing, and they are therefore not greatly interested in it. Nevertheless, when confronted with a basic theoretical dilemma, such as might arise in connection with a quantum theory of measurement, most quantum theorists repeat at least some of the pronouncements traceable to Copenhagen, if only because of the suggestive phrases of workaday jargon. We have already criticized in section 7 what is perhaps the most egregious « Copenhagenism »—the literal interpretation in terms of the spurious notion that a system possesses a state vector of such expressions as « an electron in state ψ », « the probability of finding an electron in state φ », or « the probability of a transition from state ψ to state φ ». Although such terminology has a practical, heuristic value, its picturesque connotations describe a semiclassical microcosm alien to the spirit of quantum theory.

Nevertheless, it is quite natural in view of the authoritarian respect accorded the Copenhagen Interpretation by many physicists that most papers on the theory of measurement introduce the problem at least implicity in the Copenhagen language. Hence, from our point of view, they are philosophically crippled at the outset and stand little chance of illuminating the measurement concept. Elsewhere [3] we have offered a detailed critique of Heinsenberg's measurement theory; that discussion serves generally to expose the inadequacies of many theories of measurement.

In what appears at first to be sharp contrast with Copenhagen thinking, Russian theorists typically emphasize the primacy of the ensemble over the single system in quantum physics. Moreover, since much of the Copenhagen literature stresses an alleged « subjective » quality for microphysical states, Russian commentators, in order to maintain allegiance to the Russian commitment to materialism, regularly disavow much of the Copenhagen Interpretation.

Blochintsev [5], for example, proposes an interpretation of Complementarity in terms of mutually exclusive ensemble preparations which seems at the outset identical to our epistemological concept of the primitivity of measurement. Yet when he devises a quantum theory of measurement, the measurement process is required to effect precisely the same state changes we criticized in section 7. Thus in the end there is little practical difference between Blochintsev's philosophy and that of the Copenhagen proponents. There is, however, apparently a distinction concerning the meaning of materialism. In an extraordinary rebuttal for someone who himself dismantled the classical world view, Heisenberg [6] has described Blochintsev's emphasis on the ensemble (the part of the Russian view with which I concur) as « taking us far—perhaps too far—from materialistic ontology ». Each side is accusing the other of being antimaterialistic!

Landau and Lifshitz [7] have likewise rejected the Copenhagen view in word but not in deed. Insisting that an apparatus must be « classical », they characterize its classical nature by demanding that « at any given instant, we can say with certainty that it [has one of a known set of state vectors] », again essentially the same stricture criticized in section 7. Yet earlier in the same book, these authors assert [8] that « it must be decidedly emphasized that we are not here discussing a process of measurement in which the physicist-observer takes part ». Like Blochintsev, Landau and Lifshitz reject the subjective tendencies of the Copenhagen orthodoxy; yet their theory of measurement entails wave packet reduction!

We therefore conclude that neither the Copenhagen nor the Russian interpretations of quantum theory embody a consistent determination to « think quantally » at all levels of human experience. Hence the concept of primitivity of measurement advocated here is the basis for a genuine alternative which, we suggest, represents most faithfully the meanings of quantal concepts as exhibited in the practice of physics.

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