QUANTUM PHYSICS AND THE MACROCOSMOS

Despite the well known potency of quantum theory as a means of ordering microphysical data unfathomable by classical methods, even among quantum theorists there is a visible reluctance to disavow the Procrustean constructs of classical physics. Instead a dual epistemology is invoked which dogmatizes classical concepts as being inviolably appropriate for the reification of macroscopic experiences, but which merely tolerates quantum concepts in their appointed microcosmic place. Yet both the history of science and the untested macrophysical predictions of quantum mathematics suggest that this awkward retention of classical « common sense » cannot be rationally maintained indefinitely in scholarly disciplines, and perhaps not even in the arena of daily life.

1. - Microphysics and Macrophysics. — It is not unusual for even the most revolutionary scholar to display a certain conservatism about probing the ultimate philosophical consequences of his incipient intellectual radicalism. For the revolutionist himself, by definition, must have been educated within the very ethos from which he rebels; and as a result he may feel compelled to defend some established doctrines even as he lays the very foundation which is destined to overthrow those doctrines.

Consider Copernicus, precursor to Kepler, Galileo, and Newton, whose works culminated in the decline and fall of Aristolelian science and its attendant philosophies. Aristotelian physics featured a subdivision of phenomena into the categories of terrestial and celestial. For terrestial bodies, linearity of motion was considered natural; but for celestial bodies, circularity of motion was the dogmatic requirement. Thus in his *De Revolutionibus* [1] Copernicus, following Aristotle, asserts that

> . . . the motion of heavenly bodies is circular. Rotation is natural to a sphere and by that very act is its shape expressed.

He next proceeds to review the complexities of planetary movements, the departures from uniformity which would seem to argue against the necessity of circular perfection in the heavens. But then, having exposed the very data which inspired his bold advocacy of heliocentric astronomy, which would later motivate total abandonment of the circularity dogma by others, Copernicus made a remarkably conservative statement:

> Nevertheless, despite these irregularities, we must conclude that the motions of these bodies are ever circular or compounded of circles.

In the present century, the dismal failure of classical physics to account for atomic phenomena has resulted in what might be called the Copernican stage of a developing quantum revolution. At the microscopic level the classical approach to physical problems has essentially been renounced. Moreover, it is generally acknowledged that quantum physics is in principle applicable to all physical phenomena, large and small. Nevertheless, the prevailing intuition, or « common sense, » with, which even many modern physicists approach macroscopic phenomena is deeply embedded in the empirically discredited fabric of classical physics. It is as though there were two kinds of physics, macrophysics and microphysics, the former allegedly grounded in everyday experience, the latter necessary at the atomic level but otherwise ignorable. Indeed the term microphysics is occasionally used as a synonym for quantum theory.

This situation is somewhat reminiscent of the medieval celestial-terrestrial dichotomy. In fact, some of the pronouncements of pioneer quantum theorists exhibit a striking resemblance to the perorations of Copernicus in defense of circularity. For example, Bohr [2] seems to insist upon the necessity of the classical outlook for macroscopic experiences:

> ... however far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms.

Similarly, Heisenberg [3], in explaining the so-called Copenhagen interpretation of quantum theory, ascribes to classical physics a rather sacrosanct position in scientific methodology:

> Any experiment in physics, whether it refers to the phenomena of daily life or to atomic events, is to be described in the terms of classical physics ... the application of these [classical] concepts is limited by the relations of uncertainty. We must keep in mind this limited range of applicability of the classical concepts while using them, but we cannot and should not try to improve them.

It is my contention that the Copenhagen interpretation of quantum physics, a key point of which is indicated by the preceding quotations, is not the last word, but that it bears the same relationship to the current quantum revolution that the 16th century work of Copernicus bore to the great 17th century scientific revolution. The Copenhagen bifurcation of physical intuition into microscopic and macroscopic components is like the old celestial-terrestrial dichotomy. It attempts to conventionalize a paradoxical melange of mutually incompatible concepts in order to conserve, in part, the no longer adequate Newtonian *Weltansicht.* Thus history would seem to suggest that the orthodox insistence upon the use of classical constructs at the macroscopic level is merely a temporary birthmark of an emerging era of « quantum thinking, » in which quantum ideas might eventually come to be regarded as providing normal, « common sense » descriptions of all physical phenomena, large and small.

2. - The Preparation–Measurement Format. — The classical theories of physics are often interpreted as descriptions of a physical reality external to human observers, as pictorializations of the *ding an sich* responsible for, but beyond the grasp of, experience. There is, however, a more moderate, more candid appraisal of the scope of scientific method, an account which regards physics as an attempt to regularize certain facets of human experience without either affirming or denying the existence of a universe external to that experience. This experience-oriented viewpoint [4] epitomizes the philosophical underpinning of quantum theories.

Classical and quantum physics alike focus attention upon constructs called physical systems, which serve as the fundamental constituents of the theoretical models in terms of which experience is catalogued. Systems of varying degrees of abstraction have been hypothesized and hypostatized in physical theories. Some systems, like tables and chairs, are just conceptual representations of *Gestalten*; others, like electrons and electromagnetic fields, are very far indeed from direct experience. All physical systems, however, are to be regarded as carriers, in some sense, of observables.

A philosophical analysis which elegantly pinpoints the essential difference between the fundamental models employed in classical and quantum physics has been given by Margenau [5] in his latency theory of observables. This theory classifies the conceptual relations which link systems with their observables under two headings, possession and latency. Possessed observables are the hallmark of classical physics, where observables were regarded as labels attached to a system, i.e., as properties of the system. Within such a framework, it did not seem unreasonable to interpret the systems with their observables as visualizable models of an ontological reality behind experience.

The characteristic quantal relation of latency is subtler than that of possession. The organized data of physics consists of numbers which emerge from experiments in which the acts called measurement are performed upon physical systems. Each observable associated with a system is equipped in principle with operational definitions which give methods for the measurement of that observable. When a measurement of a given observable is performed, the numerical measurement result which emerges is recorded as the value of that observable at the instant defined by the onset of the measurement act. The difference between latency and possession lies in the theoretical interpretation of such numerical data. If possession is the assumed relation between system and observable, the measurement result is taken to be a revelation of which value of the observable the system possessed just prior to the measurement act.

If latency is the assumed relation between system and observable, the measurement result is not given this transcendent interpretation;

the system is not regarded as an object bearing definite numerical values for all its observables either before or after measurement. Instead, a report of experimental results is confined to a minimal statement of how the systems were prepared for study, which observables were measured, and what numbers these measurements yielded. Similarly, a theoretical prediction of experimental results can have only the dispositional form, « if system S is prepared in the manner Π and measurements of observable A are performed upon S, then the numerical result a will emerge with probability $W(a; \Pi)$. »

I shall call this minimal account of natural phenomena the *preparation-measurement format* for physical problems to distinguish it from the classical ideal of describing with Cartesian clarity the continuous evolution of an external world. Epistemologically, the latency viewpoint is entirely adequate for the scientific confrontation of experiential data and abstract concepts; but it stops short of identifying the numerical data of science with prepossessed properties of systems. Instead, numerical values of latent observables are considered to emerge from systems only when educed by an act of measurement.

In further elaboratoin of the important concepts of preparation and measurement, it must be especially stressed that the two are not equivalent. The term preparation signifies a reproducible physical act involving the system of interest, whereas the term measurement refers to a physical procedure upon the prepared sustem which yields a numerical datum. To gather the statistical information from which the probabilities of quantum physics may be extracted, it is necessary to reprepare in an identical manner the system of interest (or another of the same kind) many times, and to perform a measurement subsequent to each repreparation. The probability $W(a; \Pi)$ associated with the measurement result a of an observable A for a system prepared in the manner Π is operationally defined as the relative frequency with which a emerges from such *ensembles* of identically prepared systems.

Unlike the classical approach to physical phenomena, the preparation-measurement format embodies a certain finality in the measurement act. The impact of measurement on a physical system can range from negligible (macro-systems) to catastrophic (microsystems); sometimes systems are even annihilated. Accordingly, quantum physics cannot include any universal proposition concerning the post-measurement condition of physical systems.

This stricture does not, however, prohibit treatment of, say, two successive measurements within the preparation-measurement format. What would have to be done is to analyze the precise interaction with the apparatus used for the first measurement and then regard that interaction plus the original preparation as the total preparation for the second measurement. Using that information, quantum theory can be used to assign probabilities to the results of the first and second measurements; but without additional information, quantum theory is silent about the behavior of the system after the second measurement.

3. - Quantum States. — Because classical physics sought to construct essentially visualizable models of physical systems, each classical theory featured a *state* concept, a mathematical representative of the physical condition of a system. Within the classical framework, a state was characterized simply by an enumeration of the values of the system's possessed properties. An act of measurement upon a system therefore determined part or all of the state specification for that system at the instant of measurement.

In quantum physics, because of the broader preparation- measurement format for physical problems, the state concept is not so straightforwardly devised; indeed, there is not even any assurance that a state specification in the fullest classical sense can be consistently extracted from or appended to the quantum algorithm. In the preparation-measurement format, the organized data on which theory must feed is inherently statistical; the ensemble of reproducibly prepared systems is initially considered to be of more theoretical importance than the individual systems themselves. Whether or not attention can be refocused via an individual state concept upon the single systems is a question strongly dependent upon the axiomatic structure of the theory of interest.

We have investigated this largely mathematical question elsewhere [6] and drawn the following conclusions. Even if classical physics is initially set up within the preparation-measurement format, it is still possible, through analysis of the probability functions $W(a; \Pi)$, to extract unambiguously the standard classical state representations interpretable as possessed properties. On the other hand, the application of a similar analysis to quantal probability functions produces ambiguities which ultimately deny any shift of emphasis from the ensemble to the single system. Quantum theory can come no closer to individual states than the set of probability distributions $W(a; \Pi)$ which characterize the ensemble to which a system belongs.

To illustrate this seemingly strange conclusion without delving into mathematical abstractions, perhaps the following highly metaphorical example will be helpful. Consider a hypothetical physical system with which only two observables are associated, shape and color. Assume, moreover, that measurement of the shape can yield only one of the results « triangular » (T) or « round » (R), and that measurement of the color can yield only « blue » (b) or « green » (g). Imagine that the system can be prepared for measurement in many reproducible ways and, just to underscore the finality of the measurement act, imagine further that after measurement of either shape or color the system self-destructs.

If the system is governed by classical physics, it is anticipated that the following statement is a consistent one: each one of these systems, however prepared, is in actuality in one of the states *Tb*, *Tg*, *Rb*, or *Rg*; measurement merely reveals which one, or at least narrows the possibilities (in the event just one of the observables is measured). The justification for this classical assertion would consist of (1) demonstrating the existence of reproducible preparation schemes for each of these states (e.g., the existence of a procedure Π which upon repetition produces an ensemble for which $W(T; \Pi) = W(g; \Pi) = 1$ and (2) proving that for preparation schemes yielding ensembles characterized by nonzero probabilities less than unity, the assertion in question does not lead to logical inconsistencies. For classical physics, both (1) and (2) can be satisfied.

On the other hand, if the system under consideration is governed by quantum physics, in general neither conditions (1) nor (2) can be ment. For the purposes of this metaphor, suppose (perhaps contrary to fact) that the observables shape and color constitute what quantum theorists call noncommuting observables. The following situation would then prevail. No repeatable physical procedure would exist which could be used to generate an ensemble of the type contemplated in (1), wherein each observable would upon measurement always yield the same one of its two possible results. Instead, it might turn out that when any ensemble was prepared so that color measurements invariably yielded *g*, shape measurements yielded *T* and *R* with equal frequency. Similarly, when any ensemble was prepared such that *T* was the certain result of shape measurement, color measurement would yield *g* and *b* with equal frequency, etc. Thus it would be without physical meaning to regard the systems as « actually » possessing color or shape as attributes. This illustrates the general characteristic of quantum systems that lies at the heart of Heisenberg's uncertainty principle; and it is this nonexistence of ensembles dispersionless in all their observables which is the theoretical origin of the latency viewpoint.

The ensembles described in the last paragraph, though not without statistical scatter in their measurement results, were in a very important sense homogeneous; for they were generated by modes of preparation which could be refined no further. The residual probabilities they still exhibited were not further reducible. In particular, therefore, these ensembles could not even in principle be subdivided into subensembles whose measurement statistics would differ in any way from those of the original ensemble. In quantum physics such ensembles are said to be *pure*.

Because of its homogeneity, the pure ensemble would seem to be a reasonable concept on which to base a quantum state concept, and the jargon of quantum physics often misleadingly suggests that this is possible. Thus, if the « condition » of the ensemble above for which measurements would yield g with certainty, T and R each with probability ½, is symbolized by (g; ½ T, ½ R), then it is tempting to describe this pure ensemble as consisting of systems *each* of which is in the « state » (g; ½ T, ½ R). Now in the formalism of quantum me- chanics, each pure ensemble is characterized by a so-called wave function $\psi(x)$ from which it is possible, in accordance with well known rules[1], to derive the probability distributions $W(a; \Pi(\psi))$ associated with that ensemble for all observables. Thus it would appear that quantum physics might effectively regain to some extent the concept of state by this assertion: every system, however prepared, is in actuality in a quantum state represented by some wave function $\psi(x)$. (In the example just above (g; ½ T, ½ R) represents the wave function.)

It turns out, however, that this identification of a state concept in quantum theory, if taken literally, is abortive. To see why, consider again the fictitious quantum system whose observables are color and shape. Suppose a mode of preparation Π has been devised which leads to an ensemble in which measurement results occur with the following relative frequencies (probabilities):

$$W(b; \Pi) = W(g; \Pi) = W(T; \Pi) = W(R; \Pi) = \tfrac{1}{2}.$$

Such an ensemble is not pure; it can be split into two pure subensembles as follows. Consider a total ensemble formed by the union in equal parts of the pure ensembles characterized by (g; ½ T, ½ R) and (b; ½ T, ½ R). It is easily seen that the probabilities of measurement results for this total ensemble would be identical to those given above. Accordingly, the ensemble above is said to be a *mixture* of (g; ½ T, ½ R) and (b; ½ T, ½ R), each with weight ½. Applying the proposed (quantum) state concept, one could go further and declare this mixed ensemble to consist in actuality of systems of which half are *each* in the state (g; ½ T, ½ R), and half are *each* in the state (b; ½ T, ½ R).

It is not difficult to see that this interpretation leads to a contradiction, for the very same total ensemble may also be treated as a mixture of the pure ensembles (T; ½ g, ½ b) and (R; ½ g, ½ b), each with weight ½. If, therefore, the individual state assignment scheme is valid, it must now be affirmed that the original mixed ensemble is comprised in actuality of systems of which half are *each* in the state (R; ½ g, ½ b) and half are *each* in the state (T; ½ g, ½ b), a conclusion incompatible with that reached at the end of the last paragraph. This

[1] For the benefit of readers unfamiliar with the rudiments of wave mechanics, only the following properties of a wave function will be required later in this article:

(a) $|\psi(x_0)|^2$ is the probability density $w(x_0)$ for finding a system from the pure ensemble denoted by $\psi(x)$ at the point $x = x_0$.

(b) If $\Phi_k(x)$, $k = 1,2 \ldots$ represents a pure ensemble for which some observable A invariably yields the result a_k upon measurement, then the set of functions $\Phi_k(x)$ will be orthonormal. Every superposition of these functions, $\psi(x) = \Sigma_k c_k \Phi_k$ will itself represent a *pure* ensemble, and the probability in this ensemble for the emergence of a_k upon measurement of A is $|c_k|^2$.

inconsistency, born of an attempt to endow quantum theory with a state concept analogous to that in classical physics, is the essence of the famous Einstein-Podolsky-Rosen paradox.

The inconsistency disappears upon abandonment of the illegitimate literal interpretation of wave functions as states of single systems. To summarize, quantum physics is a thoroughly stochastic discipline; the quantal approach to physical problems is the preparation-measurement format in its most elemental form, in which there is no concept of intrinsic condition, or state, of a physical system.

4. - THE QUANTUM MACROCOSMOS. — Against the background afforded by the foregoing synopsis of quantal foundations, perhaps the problem of cataloguing macroscopic experiences within quantum categories can be examined from a fresh perspective. Consider first an ordinary ponderable body, the motion of which is to be observed, and then presumably described and understood by means of the concepts of a mechanical theory. The classicist would, in accordance with « common sense, » attribute to the body such *properties* as position (of the center of mass), momentum, etc., and proceed to describe that complex of experiences known as the motion of the body in terms of the temporal evolution of the values of these parameters. The quantum theorist, on the other hand, in his attempt to accommodate the same sense data within the rubrics of his discipline is prohibited by the aforementioned uncertainty principle of Heisenberg from following in the path of the analytical mechanist; for even the most homogeneous of all quantum mechanically conceivable ensembles display irreducible statistical variances in the measurement results of position, momentum, etc. This circumstance necessitates the formulation of some reasonable approximation within the quantum framework to account for the apparent « properties » with which naive realism so generously endows the macroscopic body.

Though the general problem of applying quantum mechanics to everday phenomena has never received the depth of attention that it may deserve, there is general agreement among physicists as to the manner in which the classical limit of quantum mechanics is approached. The key to the approximation lies in the recognition that, from the quantum viewpoint, any classical measurement upon a classical body is in practice far from a realization of the ideal perfect measurement act which appears as a primitive construct in quantum physics. Thus the margin of instrumental error in a typical classical measurement procedure may be as broad as the entire width of a detailed distribution of measurement results predicted by the quantum theory. Thus it is reasonable to identify the numerical value of classical properties with the mean values of distributions of quantum measurement results.

When this identification is made, as the Ehrenfest theorems long ago indicated, quantum mechanics acquires a classical limit seemingly capable of accounting for the data of the classical epoch in mechanics. Similarly, it is customary in quantum electrodynamics to exhibit, where appropriate, mean value relations of the same mathematical structure as the equations of classical Maxwellian electrodynamics.

It is important to note that the numerical identification for macroscopic systems of quantal mean values with classical possessed properties embodies (a) the tacit admission, which will occasion little surprise, that all classical measurements were intrinsically crude; and (b) the implicit detailed prediction of physical distributions for which classical observations discerned only the statistical mean values. One purpose of the present paper is to assay the propriety of various philosophical attitudes that have been maintained with regard to (b). Historically, the predicted distributions in question have largely been ignored due to the severe impracticability of detecting such quantum effects in macroscopic experience. Moreover, with but one exception very little theoretical effort has been expended in macroscopic applications of quantum physics; that exception is generally termed the quantum theory of measurement, a field which investigates and attempts to substantiate the inner consistency of the quantum algorithm together with the epistemic rules which link it to nature. Measurement theory, the central problem of which is to offer quantal descriptions of physical measurement processes, is forced by its very purpose to apply quantum ideas at the macrocosmic level; for every physical measurement act upon a microsystem involves a coupling with some kind of directly apprehensible macrosystem.

The quantal peculiarities inherent in the problem of interaction between a microsystem and a macrosystem were first popularized by Schrödinger [7] in his now famous « cat paradox, » and in later years the essential theme of that « paradox » has recurred many times in commentaries on quantum measurements; included among these is another metaphorical version, due to Rosen [8], in which a locomotive replaces the cat in the role of macrosystem.

To illustrate the fundamental problem of macroscopic quantum mechanics without becoming too immersed in abstract mathematics, it is sufficient to consider the following simple interaction between an atomic harmonic oscillator and an ordinary macroscopic body. Suppose that initially the oscillator is prepared in its first excited energy « state » and that the macroscopic body is at rest. Eventually the oscillator will decay to its ground « state ». Assume that when this occurs the emitted photon will trigger a mechanism which imparts to the macroscopic body a « classical momentum » of value b; i.e., the quantum wave packet characterizing that state of motion must predict the number b as the mean value of ideal momentum measurement results.

The (normalized) wave functions needed to describe this process are the following:

(a) Harmonic oscillator of mass m, frequency ω:

$$\alpha_1(x) = \frac{1}{\sqrt{2}}\left(\frac{m\omega}{\pi\hbar}\right)^{1/4} 2x\sqrt{\frac{m\omega}{\hbar}}\exp\left[-\frac{m\omega x^2}{2\hbar}\right] \quad \text{(first excited energy «state»)}$$

$$\alpha_2(x) = \left(\frac{m\omega}{\pi\hbar}\right)^{1/4}\exp\left[-\frac{m\omega x^2}{2\hbar}\right] \quad \text{(ground energy «state»)}$$

(b) Macroscopic body:

$$\gamma_1(y) = (2\pi b^2)^{-1/4}\exp\left[-\frac{y^2}{4b^2}\right]$$

(a minimum uncertainty wave packet for which the mean value of position measurements « y » = 0, the width of the position distribution $\Delta y = b$ and the mean value of momentum measurements « p » = 0,

$$\gamma_2(y) = (2\pi g^2)^{-1/4}\exp\left[-\frac{y^2}{4g^2} + \frac{iby}{\hbar}\right]$$

(a minimum uncertainty wave packet for which « y » = 0, $\Delta y = g$, « p » = b).

Obviously x is the independent position variable for the atomic system, and y is that for the large system. To eliminate as much as possible the dispersive effects of the uncertainty principle, minimum uncertainty wave packets (mathematical representations of ensembles whose uncertainty products $\Delta y \Delta p$ are minimal) have been used to describe the macrosystem.

Using these wave functions to describe the interaction contemplated above, we have initially a pure ensemble whose measurement statistics would be characterized by the wave function

$$\psi_0(x,y) = \alpha_1(x)\gamma_1(y).$$

If, after an interval of time equal to the half-life of the oscillator, an energy measurement were performed on each oscillator and a rough (classical) momentum measurement performed on the corresponding macrosystem, half the elements in the ensemble would yield the ground energy for the atomic oscillator, the classical momentum b for the macrobody; the other half would yield the first excited energy level for the oscillator, the classical momentum zero for the large system. Classical intuition would therefore dictate, upon translating «yields of measurement results predicted with certainty » to « values of observable *properties* of the systems, » that the ensemble in question at the instant corresponding to the half-life of the atomic oscillator could be partitioned into two subensembles of equal size, one containing excited oscillators and still bodies, the other containing decayed oscillators and moving bodies. If such a division into subensembles is to be possible, the ensemble in question must be a *mixture*, characterized mathematically by the wave functions of any set of its possible resolutions into pure subensembles together with their respective weights (fractions of the original ensemble in a given subensemble). In the present example, the mixture would consist of $\alpha_1(x)\gamma_1(y)$, weighted 1/2, and $\alpha_2(x)\gamma_2(y)$, weighted 1/2. Such is the demand of classical intuition.

There is, however, an intolerable flaw in the foregoing classically-motivated reasoning. A closed composite system (oscillator plus body) has purportedly evolved, during the half-life of the oscillator, from a pure state into a mixture, which is mathematically impossible within the framework of quantum physics. The translation of « certain measurement results » to « properties of systems » was illicit; quantum mechanics has no quarrel with the experimental results cited above, only with the transcendent interpretation of them as revelations of possessed properties. In the correct quantum version, the ensemble would still be pure at the half-life of the oscillator and might be represented by the following wave function:

$$\psi(x,y) = \frac{1}{\sqrt{2}} \alpha_1(x)\gamma_1(y) + \frac{1}{\sqrt{2}} \alpha_2(x)\gamma_2(y).$$

Since $\alpha_1(x)$, $\alpha_2(x)$ are orthonormal functions and for macroscopic bodies it can be shown that $\gamma_1(y)$,$\gamma_2(y)$ are approximately orthonormal, the physical meaning of this wave function is easily seen; the squares of the coefficients $(\frac{1}{\sqrt{2}})$ associated with each alternative for the oscillator energy- « macromomentum » measurement results stated above provide the desired equal probabilities (1/2). Thus, as far as the most interesting- or at least most readily measurable- observables are concerned, the pure ensemble predicted by quantum theory is experimentally indistinguishable from the mixed ensemble demanded by classical intuition.

Nevertheless, the fact that a macrosystem can be forced to participate in a quantum pure ensemble has given rise to considerable philosophical misapprehension among physicists and philosophers unwilling to adjust fully to what might be called pure quantum thinking. Accordingly, numerous schemes have been devised by measurement theorists for the purpose of eliminating from consideration the yet unmeasured nonclassical effects implicit in any such pure ensemble involving macrosystems. These schemes range from formal mathematical restrictions on the « observability » of those quantum observables which could serve to distinguish the pure ensemble and mixture in question to philosophical obfuscations grounded in naive realism. (For a more detailed review of these matters, cf. [9]).

It is my belief that the desire to render impotent the distinctly quantal features of the pure ensemble involving macrosystems is moored by, if not born of, the common semantic misunderstanding of the term quantum *state* alluded to in section 3. Suppose for the sake of argument the state concept could be applied literally in quantum physics; i.e., assume that the quantum world view centered on the proposition that every physical system possesses a definite wave function in the same manner that classical systems were presumed to carry their primary qualities. An immediate consequence of this view is that the mixture in the example given above would mean, in accordance with the classical ideal, that half the composite systems *each* had wave function $\alpha_1(x)\gamma_1(y)$ and that the other half *each* had wave function $\alpha_2(x)\gamma_2(y)$. On the other hand the (quantally correct) pure state $\psi(x,y)$ would have to signify a grotesque coexistence within *each* composite system of *both* states, so that each atomic ascillator-macrobody pair would somehow be smeared out in an amorphousness wholly at variance with common observation. Hence the mixture-forbidden by quantum mechanics- seems to be the only perceptually verifiable alternative, *provided* the literal interpretation of quantum states as descriptive of individual systems is espoused.

If, however, the concept of state in quantum physics is understood, as advocated earlier, as an indicator of measurement statistics conceptually attached in principle *not* to individual physical systems but to the modes of preparation by which ensembles of systems are generated, then the assignment of a superposition $\psi(x,y)$ to an ensemble involving macrosystems does not lead to any fantasy of coexisting mutually exclusive attributes. On the contrary, the ensemble interpretation of $\psi(x,y)$ is entirely positive in attitude; for the peculiarly quantal predictions inherent in $\psi(x,y)$ but absent from the classically-inspired mixture can now be regarded as scientific predictions which should not be defined away or philosophized into obscurity, but should someday be subjected to experimental tests.

5. - Thinking Quantally. — Recently the liberature of quantum measurement theory has been enlivened by a debate between the representatives of two schools of thought which seem to agree that pure ensembles involving superpositions of macroscopically distinct wave functions *ought* to be physically equivalent to mixtures but disagree heatedly as to the proper manner of achieving this goal. For

the purposes of the present discussion, these viewpoints may be dubbed formalist [10] and physicalist [11].

Formalists strive to delineate subsets of Hermitean operators (the objects representing observables in the quantum formalism) which share the property of yielding the *same* predicted mean values for both the quantally correct pure representation and the classically recommended mixed representation of microsystem-macrosystem ensembles of the type exemplified in section 4. Such subsets of all conceivable observables are then declared to be the only «observable» observables; consequently, restoration of the classical world view at the macroscopic level is achieved since the mixture may be used without physical repercussions. This kind of reasoning can persist, of course, only until some physicist discovers a consistent and workable operational definition for one of the « unobservable » observables.

More palatable in the opinion of the present writer is the physicalist approach, which seeks to establish via physical analysis of actual macroscopic measuring instruments that the only macro-observables *de facto* employed happen to be of such a character that the distinction between the pure and mixed ensembles in question is negligible. However, I am not prepared to grant this version the degree of universality its proponents often claim for it; indeed I would still insist that measurement procedures can exist for which the distinction between the pure and mixed ensembles could not be neglected.

Consider, for example, the microsystem-macrosystem interaction described in section 4. Quantum theory asserts that the ensemble (at the instant of halflife of the atomic oscillator) is pure, having the following wave functon:

$$\psi(x,y) = \frac{1}{\sqrt{2}}\, \alpha_1(x)\gamma_1(y) + \frac{1}{\sqrt{2}}\, \alpha_2(x)\gamma_2(y),$$

where α's and γ's were defined and described in section 4. If either the formalists or the physicalists are correct, the empirical distinction between a pure ensemble with the preceding wave function and a mixed ensemble which can be split into two equally weighted pure subensembles, one with wave function $\alpha_1(x)\gamma_1(y)$, the other with wave function $\alpha_2(x)\gamma_2(y)$ is either nonexistent or negligible. Thus the formalists are essentially predicting that no experiment will ever be devised which measures certain observables; and if physicalists proclaim their method to be necessary and universal, they too are denying that certain measurements can ever be performed.

Typically, arguments on both sides rage in such an abstract setting that the mathematical representatives of the key observables, the ones which might make the allegedly unwanted distinction, seem well beyond physical interpretation. This, however, is an illusion that can be dispelled by a counter example based on the atomic oscillator-macrosystem pair introduced in the last section. It is easy to calculate the joint probability distribution for the *positions* x and y in the two cases of interest, pure ensemble and mixture. While incontestable pragmatic arguments that neither x nor y are precisely measurable using contemporary technology can admittedly be advanced, nevertheless the physical concept of *position* and its associated mathematical representative are too well entrenched in the quantum mechanical framework for any declaration that x or y are unmeasurable in principle to be at all tenable. Thus if measurements of x and y could distinguish the pure ensemble from the mixture, then the formalist tack would be decidedly unconvincing. On the other hand, the success of the physicalist argument depends upon the numerical size of the difference in the distributions predicted by the pure ensemble and the mixture. Only if that difference is negligible does the physicalist viewpoint prevail. In the present example, that difference is not negligible, as will now be demostrated.

For the pure ensemble with wave function $\psi(x,y)$ defined above, the joint probability distribution for x and y is just

$$w_1(x,y) = \left| \frac{1}{\sqrt{2}} \alpha_1(x)\gamma_1(y) + \frac{1}{\sqrt{2}} \alpha_2(x)\gamma_2(y) \right|^2 .$$

Fort the mixture divisible into one pure subensemble with wave function $\alpha_1(x)\gamma_1(y)$ and a second with wave function $\alpha_2(x)\gamma_2(y)$, each subensemble having weight 1/2, the joint probability distribution for x and y is

$$w_2(x,y) = 1/2\ |\alpha_1(x)\gamma_1(y)|^2 + 1/2\ |\alpha_2(x)\gamma_2(y)|^2 \neq w_1\ (x,y).$$

To see that the difference between these two distributions is not negligible, consider the ratio of their respective values at the point $x = \sqrt{\frac{\hbar}{m\omega}}$, $y = 0$:

$$\frac{w_1}{w_2} = \frac{3/2 + \sqrt{2}}{3/2} \simeq 1{,}94$$

(For convenience, it was assumed in this calculation the $b \simeq g$.)

Clearly the difference between these distributions is not negligible; indeed the difference at this point is of the same order of magnitude as the values of the distributions themselves. It is true that this dramatic distinction will not survive the passage of time; if $\psi(x,y)$ evolves freely, very soon it will become essentially indistinguishable from the mixture so far as x and y measurements are concerned. Nevertheless, when experimental techniques are developed of adequate resolution to measure the fundamental quantum observable position with sufficient precision, the inappropriateness of universalizing the physicalist argument should become empirically manifest.

Another currently impracticable but theoretically correct illustration of the possible intrusion of quantum effects into macrophysical experience was given recently [12] in a quantal analysis of multiple collisions of billiard balls. Moreover, on the practical side there is considerable empirical evidence in low temperature physics of genuinely quantum-mechanical effects in macroscopic phenomena.

All this suggests that it might be worthwhile--if not ultimately necessary--to learn to view the world through quantum lenses, to interpret, to understand the perceptual deliverances of nature at all levels of physical experience by means of quantum concepts instead of classical ones. This intellectual task is certainly obstructed by ingrained habits of thought. Explanations of data in mechanical terms are often accepted as « common sense » by intelligent laymen; and crude descriptions even of atomic phenomena using classical constructs are frequently, and somewhat ludicrously, called « physical » explanations by physicists themselves! Obviously, it is the classical modes of thought which are regarded as somehow primary by almost everyone.

The situation is not without parallel in the history of physics. Consider the stages in the development of concepts of gravity. In the organismic universe of Aristotelian physics, ponderable bodies fell to the ground by virtue of a kind of « homing » instinct, a somewhat anthropomorphic tendency to seek out their appointed places in the Dantesque cosmos. Later, in the more scientifically precise universe of Newton, ponderable bodies fell to the ground not so much to maintain an eternal order but because they were pulled down. Today, in the even more scientifically precise universe of Einstein, ponderable bodies fall to the ground because that motion constitutes the shortest available route through curved spacetime. Yet it is probably the Newtonian version which still seems « real » to most people. Einstein's general relativity occupies an intellectual niche somewhat like that of quantum physics. Both are called upon only in emergencies stemming from excess extrapolation of the classical concepts. It is the latter which almost invariably provide points of departure for physical reasoning. However, this does not seem to be a necessity; after all, mankind did successfully cross the intellectual gulf between Aristotelian and Newtonian gravitation, so that no one now instinctively uses the latter just to make corrections to a primary organismic model.

As suggested at the outset, the contemporary era in physics would seem to be witnessing a transition in the character of physical intuition somewhat analogous to that which occurred in the 16th and 17th centuries as Aristotelian ideas gave way to Newtonian ones. Quantum mechanics as a mathematical tool for microphysical problems is well developed and widely understood; but its epistemology effectively receives only lip service. And the jargon of the experimentalist--the language of the laboratory--reflects the continuing primacy of the classical world view as the epicenter of so-called « physical » insight.

In short, man--even scientific man--has not yet begun to *think quantally*, to describe using quantum constructs in a quantum format those aspects of human experience accessible to the scientific method. Maybe quantum jargon will always seem too cumbersome and inefficient for reporting everyday physical experience. Yet it should be noted that even laymen now interpret lightning as an electrical effect rather than as the handiwork of an ethereal pyrotechnist.

Perhaps it is time to weigh this anchor of classical preconceptions, to set sail for the uncharted horizons of a pervasive *quantal* intuition. The cultural impact of such a course is difficult to presage. However, one could probably expect to encounter fewer biologists seeking to explain life against the intellectual backdrop of classical mechanism. And some philosophers might even cease denying that the human mind is an entity *sui generis*, and therefore withdraw their espousal of mechanistic resolutions of the mind-body problem. In any case, if there is to be such a « quantum renaissance », scientists and philosophers themselves will have to begin taking more seriously the epistemological implications of quantum physics.

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REFERENCES

[1] COPERNICUS N. - *De Revolutionibus Orbium Caelestium* (1543). Translated by J. F. Dobson and S. Brodetsky. *Occasional Notes of the Royal Astronomical Society 2* (1947), 9.

[2] BOHR N. - In *Albert Einstein: Philosopher-Scientist*. P. Schilpp, Ed. New York: Harper and Bros. (1959), 209.

[3] HEISENBERG W. - *Physics and Philosophy*. New York: Harper and Bros. (1958), 44.

[4] MARGENAU H. and PARK J. L. - In *Delaware Seminar in the Foundations of Physics*. M. Bunge, Ed. New York: Springer-Verlag (1967), 161.

[5] MARGENAU H. - *Physics Today* 7 (1954), 6. Cf also PARK J. L. and MARGENAU H. - « Simultaneous Measurability in Quantum Theory » (to be published in *The International Journal of Theoretical Physics*).

[6] PARK J. L. - *American Journal of Physics 36* (1968), 211.

[7] SCHRODINGER E. - *Naturwissenschaften 23* (1935), 812.

[8] ROSEN N. - *American Journal of Physics 32* (1964), 597.

[9] PARK J. L. - *Quantum Theoretical Concepts of Measurement*, Parts I and II (to be published in *Philosophy of Science*).

[10] JAUCH J. M. - *Helvetica Physica Acta* 37 (1964), 293. JAUCH J. M., WIGNER E. P. and YANASE M. M. - *Nuovo Cimento 48B* (1967), 144.

[11] DANERI A., LOINGER A. and PROSPERI G. M. - *Nuclear Physics* 33 (1962), 297; *Nuovo Cimento* 44*B* (1966), 119. ROSENFELD L. - *Supplement: Progress of Theoretical Physics*, Extra Number (1965), 222; *Nuclear Physics A*108 (1968), 241. LOINGER A. - *Nuclear Physics A108* (1968), 245.

[12] RAYMOND D. J. - *American Journal of Physics 35* (1967), 102.