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Toward a Micro Realistic Version of Quantum Mechanics. Part I

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This paper investigates the possibility of developing a fully micro realistic version of elementary quantum mechanics. I argue that it is highly desirable to develop such a version of quantum mechanics, and that the failure of all current versions and interpretations of quantum mechanics to constitute micro realistic theories is at the root of many of the interpretative problems associated with quantum mechanics, in particular the problem of measurement. I put forward a propensity micro realistic version of quantum mechanics, and suggest how it might be possible to discriminate, on experimental *grounds, between this theory and other versions of quantum mechanics.*

1. DEFINITION OF MICRO REALISM

By a micro realistic version of quantum mechanics (QM) I mean simply this: A version of QM which can be interpreted as being exclusively about micro entities and their interactions, macro systems, and in particular *measuring instruments* in no way lurking, in however concealed a fashion, in the background as far as the basic postulates of the theory are concerned. A micro realistic version of QM is, then, a version which enables us to develop a consistent model for micro system and micro phenomenon. Such a version of QM specifies exclusively the laws of interaction between micro system and micro system. In no way is such a version of QM restricted to providing laws of interaction between micro systems in the context of this or that type of measuring system.

It may be asked: If a micro realistic version of QM specifies only how micro system interacts with micro system, how can such a version of QM be

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experimentally testable? How can experimental predictions flow from such a theory? The answer can be put like this. According to such a theory, macro systems arise simply as the outcome of interactions between a vast number of micro systems. In order to extract predictions about macro systems, in particular predictions about macro systems that happen to be carefully designed experimental apparatus and instruments, from a micro realistic version of QM, one simply applies the theory to a very intricate system of micro systems which *in toto*, according to the theory, constitutes a macro system. There is thus no problem *in principle* about extracting experimental predictions (about macro experimental setups) from a theory which is in the first instance exclusively about micro systems. There may of course be practical difficulties here. Applying such a theory to the kind of incredibly intricate system of micro entities that goes to make up a macro system may in practice pose very serious mathematical difficulties. But to repeat: There is no problem of *principle*. I emphasize this point, for it was in effect denied by Bohr,[1] who argued that QM would always need to rely, in an essential way, on classical physics for a treatment of the measuring process, QM being unable to stand on its own feet independently of classical physics, as it were.

It should be noted that the above idea of a micro realistic version of QM is quite different from the rather more familiar idea of a hidden variable version of QM. A micro realistic version of QM need not be a hidden variable theory, and vice versa.

2. DESIRABILITY OF DEVELOPING A MICRO REALISTIC VERSION OF QM

It is, I claim, highly *desirable* to develop a micro realistic version of QM, in the above sense, for at least the following four reasons.

1. Our fundamental *aim* in pursuing theoretical physics should be to try to understand Nature "as it is thought, independently of its being observed."[2] Our task should be—as Einstein always maintained[3–5]—to try to discover an underlying harmony, unity, or simplicity in the universe in terms of which the apparent multiplicity of things, substances, and occurrences we come across in the world can be explained and understood. The whole history of physics is the history of an amazingly successful search for unity, or order, in nature underlying the apparent immense diversity of natural phenomena. As I have argued elsewhere,[6,7] in the end theories in physics can only be judged to be *contributions to our knowledge* to the extent that they help us toward realizing our basic aim of discovering simplicity in nature. Now a micro realistic version of QM, which enables us in principle

to explain macro phenomena as arising solely as a result of interactions between relatively few different sorts of micro entities, clearly helps us magnificently toward realizing our basic aim of discovering simplicity in nature. But a non-micro realistic version of QM, which is at best about micro systems *interacting with macro measuring instruments*, does not take us nearly so far toward realizing our basic aim of discovering inherent simplicity in nature, since such a theory needs to *presuppose* the existence of macroscopic measuring instruments in its basic postulates, and cannot therefore *explain* the multifarious macro domain as arising *solely* as a result of interactions between micro entities. Thus all non-micro realistic versions of QM must be judged to be unsatisfactory, whatever their empirical success may be.

2. Orthodox QM is unacceptable in that it is, in a highly surreptitious fashion, quite grotesquely ad hoc. This rarely noticed ad hoc character of QM can only be overcome by developing a micro realistic version of the theory.

The essential point can be put like this. Orthodox QM is a theory which only makes *conditional* predictions about what will be found *if* a measurement is performed on the quantum mechanically described systems. But this means that orthodox QM must call on some *additional* theory (e.g., classical physics) for a treatment of the measuring process itself. Any attempt to apply orthodox QM itself to the measuring process can only lead to further purely *conditional* predictions about what will be found if a *further* measurement is performed. Actual physical predictions can only be forthcoming from QM if at some point a theory such as classical physics is added to QM, which itself makes *unconditional* predictions (and is not at all tied down to making only conditional predictions about what occurs *if* measurements are made). This means that on its own, orthodox QM is completely powerless to make any actual physical predictions at all. It is only QM plus some additional (unconditional) theory which makes predictions. And this means that the theory which actually makes physical predictions—namely (conditional) QM + (unconditional) theory applied to measuring instruments—is very seriously ad hoc, in that it is made up of two inevitably inharmonious parts. The apparent amazing coherence and unity of orthodox QM is achieved only by *suppressing* vital additional postulates which it is absolutely essential to add on if the theory is to have any genuine *physical* content whatsoever.

It may be asked: But do not *all* theories, whether classical or quantum mechanical, depend on additional theories for a treatment of measurement? Would not the above argument apply just as well to Newtonian theory (NT) as to QM? In order to see the difference, let us consider the case of NT applied to predicting the temporal evolution of the solar system. In this case, NT—given the relevant initial conditions—is able to make unconditional physical predictions about future positions of planets, whether these predictions are checked up on by man or not. It is of course true that in order to determine whether these predictions are true or false, we need to make astronomical observations, using telescopes and relevant optical theory, even perhaps chemical theory if the results are recorded photographically. But these additional theories are only required by us in order to check up on the truth or falsity of the physical predictions of NT. We do not need to add optical and chemical theory to NT itself before NT has any physical content whatsoever. It is this fact which ensures that our use of additional theory in order to test NT does not thereby imply that NT is itself incomplete, and when completed, ad hoc.

Consider now the very different state of affairs that would arise if NT were capable only of issuing in *conditional* predictions about what *would* be found *if* astronomical observations were made. In this case NT (applied to the heavens) would cease to be a theory about the motion of heavenly bodies under gravitation, and instead would become a theory about the results of making *astronomical observations*. In this case only NT *plus* optical theory *plus* chemical theory (or plus other additional measurement theory) would have any physical content whatsoever—and *this* theory would inevitably be very seriously ad hoc, being a mish mash of inharmonious parts. This is precisely the situation that arises in QM. Just because QM fails to issue in *unconditional* predictions about micro systems per se, and only issues in conditional predictions about micro systems *if they are subjected to measurements*, the theory which actually has physical content must be: (conditional) QM + (unconditional) theory applied to measurement. And *this* theory must be very severely ad hoc (basically because the *interpretation* of the two parts must be so different).

How can this incompleteness of QM be cured in a non-ad hoc manner? In order to do this, what we need to do, clearly, is to produce a version of QM which itself issues in *unconditional* predictions about micro systems per se, whether they are undergoing measurement or not. But a version of QM which does this is precisely a *micro realistic* version of QM. Thus we reach the conclusion: Only a micro realistic version of QM can itself have physical content without calling on some additional theory; thus only a micro realistic version of QM can overcome the surreptitious, but very extreme, ad hoc character of orthodox QM.

3. For a long time, orthodox QM has had associated with it a highly confused debate about the so-called "problem of measurement."[8–11] As I have argued elsewhere,[12,13] in order to resolve this problem it is essential that we develop a version of QM which makes no mention of the inevitably ambiguous notion of "measurement" (or "observable") in its basic postulates

at all. But, as we have seen, in order to do this in a non-ad hoc way we need to develop a micro realistic version of QM.

4. It is well known[14] that one serious difficulty that lies in the way of any attempt to combine QM and general relativity is that whereas orthodox QM is a theory about making measurements, general relativity is nothing of the kind, being almost the ideal of a classically realistic theory. The suggestion I wish to make is that before we can hope to combine QM and general relativity we must first develop a satisfactory micro realistic version of QM to match the classical realism of general relativity. Only when this has been achieved can we, I suggest, be in a position even to *formulate* properly the problems that will need to be solved in order to "quantize" general relativity. There is, in other words, some reason to believe that a micro realistic version of QM will be required for future fundamental developments in theoretical physics.

In view of the above four considerations, I conclude that it is highly desirable to develop a micro realistic version of QM.

3. POSSIBLE REASONS FOR ABANDONING MICRO REALISM

At various times various rather general epistemological or philosophical reasons have been given for the inevitability of the abandonment of micro realism when we come to the quantum domain. Although there is not space to go into the matter here, I suggest that all such general philosophical arguments against micro realism rest on a series of mistakes, and are entirely without foundation. From the standpoint of *physics*, the only half-way cogent reason for abandoning micro realism is that one can in this way avoid the wave/particle duality problem. If QM is interpreted as being about the outcome of performing measurements on micro systems, instead of being about micro systems per se, one can in this way cunningly avoid the need to solve the awkward problem of what sort of thing a micro system, such as an electron, *really might in itself be*, in view of the fact that it appears to be both a wave *and* a particle. I suggest that the *primary* reason for the abandonment of micro realism, as far as Bohr, Heisenberg, and their followers were concerned, was that one could in this way sidestep the awkward wave/particle duality problem: The rest was rationalization.

The lesson to be drawn from this is clear: The *First* problem that any attempt to develop a micro realistic version of QM must tackle is the wave/particle duality problem.

The decisive point to recognize here is that the *wave* aspects of micro phenomena always arise as *statistical* effects. A single electron or photon always exhibits itself in a particlelike way. Wave effects—in particular interference effects, the most distinctive feature of waves—arise only when a great number of electrons or photons is involved. Such wavelike effects can only ever be detected via the detection of a great number of particlelike effects. In view of these considerations, it is quite natural to suggest that wavelike aspects of micro systems are essentially probabilistic effects or statistical effects. And corresponding to two different interpretations of probability, there are two ways in which we may seek to resolve the wave/particle duality problem which do *not* abandon micro realism.

The first approach presupposes the *frequency* interpretation of probability. According to this view, individual micro systems are *particles*, with precise positions and momenta at all times, and definite trajectories. Wavelike aspects are purely statistical effects. Such effects arise only when a large number of particles is involved. More precisely, the wavelike aspect of micro systems is a feature not of *individual* micro systems, but is a statistical feature of an *ensemble* of micro systems. Adoption of this viewpoint, it may be held, resolves the apparent wave/particle dilemma, but in no way involves Bohr's *abandonment* of micro realism.

The second approach presupposes a *propensity* interpretation of probability which will be discussed below. According to this view, the wavelike aspect of micro systems is a probability aspect: But probability statements can be interpreted as applying, in the first instance, to individual systems, and as attributing a particular kind of probabilifying property or *propensity* to individual systems. An electron, according to this viewpoint, is neither a particle nor a wave. Rather it is an entity whose *propensity* to act as a particle itself evolves in time in a wavelike manner. According to this view, an electron really does smear out in space: But what smears out is the propensity of the electron to act as a particle, should the appropriate conditions to do so arise. The electron is in short, according to this view, a new kind of entity, which combines some wave and some particle features, but is quite different from both a classical wave and a classical particle.

A number of writers have hinted at this kind of propensity view, in particular Heisenberg[15] in terms of the Aristotelian notion of *potentia* and Margenau[16] in terms of his notion of *latency*. I should add that the notion of propensity involved here is quite different from Popper's notion, as will be explained below.

Let us now look in a little more detail at the two approaches to the problem of developing a micro realistic version of QM, beginning with the statistical or frequency approach.

4. THE FREQUENCY APPROACH TO A MICRO REALISTIC VERSION OF QM

According to this approach,[(8,17–21)] individual micro systems, such as electrons, protons, etc., are essentially *particles*, with definite positions and momenta at each instant, and definite *trajectories* in space–time. "Wave" aspects of micro phenomena are essentially *statistical* effects; such phenomena only arise when a large number of micro particles is involved.

This approach takes for granted the *frequency* interpretation of probability.[2] According to this view, in asserting that the probability of such and such an event E occurring is P, one is in effect asserting that if the relevant state of affairs is duplicated a large number of times N, then E will occur n times, where $n/N = P$. In making a probability statement, then, concerning an individual system S, it is essential that this system is thought of as being a member of an ensemble E of similar systems. In particular, in applying the quantum mechanical notion of *state* to an individual system S, it is essential that S is thought of as a member of an ensemble E of similar systems—since of course the quantum mechanical notion of state contains *probabilistic* information. One and the same physical system S may be considered as belonging to two different ensembles E_1 and E_2, and may, consequently, have different quantum mechanical states attributed to it.

It is clear from the last remark that this micro realistic statistical version of QM requires that we develop two quite different notions of *state*. On the one hand there is the actual physical state of the individual micro system specified in terms of the actual instantaneous position and momentum of the system, as in classical physics. Let us call this the *classical state* of a system. On the other hand there is what we may call the *quantum mechanical state* of a system, specified in terms of the appropriate state vector ϕ (in the case of a pure state). The quantum mechanical notion of state only applies to an individual system S insofar as S is regarded as a member of some specific ensemble E. As I have already remarked, one and the same micro system S, in some quite definite, unambiguous *classical state*, may be regarded as

[2] It should be noted that Popper[(21,22)] advocates a propensity interpretation of probability, not a frequency interpretation. However, according to Popper, propensities are to be attributed to experimental setups, not to individual objects or micro systems. Popper in effect advocates the basic thesis of the frequency view, as described here, namely that a micro system can only be said to have a quantum mechanical state insofar as it is considered to be a member of an *ensemble* of micro systems. Despite his use of the term "propensity," Popper nevertheless advocates an interpretation of *QM* which is in all essentials in agreement with Ballentine's viewpoint.

being in two quite different quantum mechanical states, since we may regard S as being a member of two quite different ensembles E_1 and E_2. It is important to recognize that according to this view, the fact that an individual system has a precise classical position or momentum does not at all imply that the system is in the corresponding quantum mechanical eigenstate of position or momentum.

According to this viewpoint, QM is thus interpreted as being a micro realistic statistical theory which makes statistical predictions about the actual *classical states* of individual micro systems, given that these systems belong to some appropriate ensemble. On this view, QM is not in the first instance a theory about the results of performing measurements on micro systems: Measurements simply *detect* already possessed *classical states* of individual systems. According to this view, then, a quantum mechanical measurement involves no special, mysterious physical process, such as the reduction of the wave packet, which violates the time-dependent Schrödinger equation. All systems that fall within the domain of applicability of QM evolve in accordance with the time-dependent Schrödinger equation, including composite systems that incorporate measuring instruments.

It is important to recognize, however, that according to this micro realistic statistical view, if we wish to predict the future behavior of some micro system S, we must do so not in terms of the present *classical state* of S, but rather in terms of its present *quantum mechanical state*. It is only when the predictions of QM approach those of classical physics that the future behavior of an individual system can be predicted in terms of the present *classical state* of the system, by means of the application of the relevant part of classical physics.

What this means is that if we wish to understand how an *individual* micro system evolves in time, we can only do so by considering such a system as a member of some appropriate *ensemble* of systems—for only then does the notion of quantum mechanical state get a purchase. According to this version of QM, it is only by considering *ensembles* of systems that we can predict, and understand, anything about the temporal evolution of *individual* systems. We cannot, for example, understand the evolution of an individual micro system by considering the *classical state* of the system at some instant and then considering particular physical forces that in some way disturb or influence that specific system.

It is important to note that this inability to understand the temporal evolution of systems purely on the *individual* level is in no way whatsoever dictated to us by the mysterious behavior of nature. It is rather a direct outcome of our decision to adopt the frequency interpretation of probability. Once it is granted that nature is indeterministic, and that a fundamentally probabilistic theory is required, then our decision to adopt the frequency interpretation of probability immediately carries with it the implication that in order to understand how micro systems evolve and interact, we must consider *ensembles* of such systems.

This concludes my sketch of the statistical or frequency approach to the problem of developing a micro realistic version of QM. This approach faces a number of problems, which I shall outline in Section 8. In the meantime, let us look at the second, propensity approach to the problem of developing a micro realistic version of QM.

5. PROPENSITIES

The decision to adopt the frequency interpretation of probability inevitably carries with it—as we have seen—the implication that the evolution and interaction of micro systems cannot be understood purely on the individual level, in terms of specific *physical* features possessed by individual micro systems. It is, however, rather natural to wonder whether it might not be possible to develop a theory which *does* enable us to understand micro phenomena in terms of physical features possessed by individual micro systems—even while granting that micro phenomena are essentially probabilistic in character. In order to do this we need clearly to develop a new interpretation of probability, which enables us to make meaningful probabilistic statements about individual cases, without an implicit reference being made to some ensemble. Can such an interpretation of probability be developed?

The answer is yes. We may employ a modified version of Popper's *propensity* interpretation of probability. I shall first explicate the notion of "propensity" that I wish to employ here. Briefly, I shall indicate how it differs from Popper's original idea, and why it is an improvement over Popper's idea. I shall then discuss in some detail the micro realistic version of QM that this notion of propensity enables us to develop.

A "propensity," as understood here, is a new kind of *physical property*. It constitutes a rather natural probabilistic generalization of our ordinary notion of a physical property—namely, of a (deterministic) *dispositional* property. In attributing an ordinary physical property to an object (e.g., inflammability) we are asserting that the object is such that if it were exposed to such and such conditions C (exposed to a naked flame), then such and such an outcome O would of necessity occur (the object bursts into flames). Implicit in the very *meaning* of any term which can be used to attribute a physical property to an object there is the idea that any object which has this property will of necessity exhibit a specific kind of outcome O in circumstances C. This holds true for all such typical physical properties as elastic, magnetic, opaque, transparent, massive, electrically charged, rigid, fluid, and so on. It might be thought that all such dispositional terms could be eliminated in terms of statements about the relevant circumstances C and outcome O. But this is in fact both an impossible program to fulfill and an undesirable program to try to fulfill. Statements describing C and O will, for example, incorporate terms that are just as "dispositional" as the term we were attempting to analyze away. And in fact it is *desirable* that we have available "dispositional" terms that are "theory-laden" in the sense that the terms carry implications as to how any object, which as the corresponding physical property, will change in such and such circumstances. (See Ref. 23 for an analysis of physical properties along these lines.)

A *propensity* can be seen as a rather natural probabilistic generalization of the above notion of a deterministic dispositional property. In attributing a *propensity* to an object (e.g., "unbiasedness" to a die) we are asserting: The object is such that if it were to be exposed to such and such circumstances C (i.e., if the die were to be tossed above a horizontal surface, etc.), then such and such an outcome O would of necessity occur (the die would register 1 with probability 1/6, or would register 2 with probability 1/6,...). In attributing a propensity to some specific object we are in effect specifying a *potential* ensemble—namely the ensemble which would be created if circumstances C were repeated a great number of times. In order to *test* a statement which attributes a propensity to an object, in a direct way, we need of course to make this potential ensemble actual. A propensity can, however, be meaningfully, and truly, attributed to some specific object even though the object is not directly tested to determine whether or not it has the propensity—just as an object may meaningfully, and truly, be said to be inflammable, even though its inflammability is never put to the test.

The propensity viewpoint is clearly parasitic on the frequency interpretation of probability, in that the notion of at least a *potential* ensemble is essential to it. One might perhaps say that the notion of "propensity" sketched here is not so much a new interpretation of probability as a new idea for a kind of physical property, via which probability statements—interpreted in terms of the frequency view—may be applied to the world. A statement which attributes a propensity to an object is a straightforward factual statement: It has, however, probabilistic implications. Propensities are to be seen as straightforward physical properties—on a par with ordinary (deterministic) dispositional physical properties. Propensities—like other physical properties—can *change* with time, and can be linked to other properties in a law-like fashion.

Let me indicate briefly how the concept of propensity sketched here differs from, and is perhaps an improvement over, Popper's concept. According to Popper, a propensity is to be conceived of, not as a property of an *object*, but rather as a feature of an entire experimental setup. Thus, for Popper, a propensity is a feature of what I have called the object plus the circumstances C. One cannot attribute a propensity to a die, but only to the experimental setup of tossing a die on a horizontal surface.

There are three interrelated drawbacks to Popper's concept, when compared with the concept I have sketched here.

1. If we accept Popper's notion of propensity, we cannot see a propensity as a natural probabilistic generalization of our ordinary (deterministic) idea of a physical property. To say that a propensity is a feature of an experimental setup is like saying that inflammability should not be seen as a property of petrol; rather it should be seen as a property of the experimental setup petrol-being-exposed-to-a-naked-flame. Thus in insisting that a propensity should be seen, not as a feature of an object as such, but rather as a feature of what I have called the circumstances C, Popper violates the analogy with ordinary physical properties such as inflammability, rigidity, etc.

It is desirable to be able to interpret the idea of propensity as a natural generalization of the idea of a deterministic, dispositional, physical property, for in this case the whole idea of a fundamentally indeterministic theory, framed in terms of such a propensity idea, may perhaps be seen as a natural generalization of the classical idea of a deterministic theory. It may be possible, in other words, to see the introduction of indeterminism into physics with the advent of QM as constituting not a violent break with the metaphysical framework, the aims, of classical physics (as it was, for example, for Einstein) but rather as a natural generalization and evolution of the aims of classical physics.

2. A second drawback about Popper's notion of propensity is that it is not particularly suitable for being incorporated into fundamental physical theory. For the truth is that the fundamental physical properties, attributed to things by our fundamental theories—properties such as inertial mass, gravitational mass, electric charge, and so on—are not in the first instance features of experimental setups. We want our physical theories, in the first instance, to apply to nature (and not merely to our experimental setups). Hence if the notion of "propensity" is to be of any real use in the framing of fundamental physical theories, a propensity must not be restricted to being applicable only to experimental setups. Here again, then, Popper's notion suffers a disadvantage when compared with the notion I have sketched here.

3. Finally, Popper's notion of propensity is of no use when it comes to framing *micro realistic* theories, and in particular a micro realistic version of QM. This is of course because a propensity, in Popper's sense, is a *macro* property, being exclusively a property of experimental setups, which are, presumably, macro arrangements. Thus Popper's notion of propensity is of no use to us in developing a micro realistic version of QM. And, in view of the fact that I have produced rather general arguments for holding that

physics should aim at developing micro realistic theories, one must conclude again that in general Popper's notion is not particularly suited to be of use in physics. The notion of propensity sketched here does not, however, suffer from this disadvantage. A propensity—as explicated here—may well be a fully *micro* property, in that both the relevant circumstances C and the outcome O are specifiable in purely *micro* terms.

6. A PROPENSITY APPROACH TO A MICRO REALISTIC VERSION OF QM

Having briefly explicated the notion of propensity that is to be used here, I turn now to the problem of developing a micro realistic propensity version of QM.

The basic idea of the propensity viewpoint is that the quantum mechanical state vector ϕ can be used to attribute physical propensities to individual micro systems. In specifying the quantum mechanical *state* of a micro system, one is, then, according to this viewpoint, specifying the actual physical state of the individual micro systems, in terms of the physical propensities possessed by that system. For example, in attributing a definite position probability density to an individual system—given by $|\phi|^2$—we are providing a description of the actual physical state of the individual micro system. In asserting that the position probability density of a micro system is $|\phi|^2$, we are in effect asserting: The micro system is such that if it were to be exposed to the appropriate conditions for a localization to occur (for example, if a position measurement were to be performed on the system), then the system would be localized in volume element dV_1 with probability $|\phi|^2 dV_1$, or in volume element dV_2 with probability $|\phi|^2 dV_2$, or .... According to this view, a micro entity such as an electron is neither a wave nor a particle. Rather it is an entity whose *propensity* to act as a particle itself spreads out in space, and evolves in accordance with the time-dependent Schrödinger equation. If the normalized state vector $\phi_t(r)$, to be associated with an electron, is such that $|\phi_t(r)|^2$ has values differing from zero for small regions within a volume V, but is zero outside V, then this means—according to the propensity view—that the electron really is "spread out" throughout V. But what is spread out is the propensity of the electron to exhibit itself as a particle, to be localized in an extremely small volume element dV, should the appropriate conditions to do so arise. And where the value of the position probability density $|\phi|^2 dV$ is high, so the probability is high that the electron will be localized here, should the appropriate conditions arise. (In other words, the physical state of the individual electron is such that if this physical state were to be replicated a great number of times, then most of the electrons would be localized where the value of $| \phi |^2 \, dV$ is high, given that the appropriate conditions for localization arise in each case.) There is thus no contradiction inherent in the wave and particle aspects of the electron. According to the propensity version of QM, the individual electron can evolve in a wavelike manner, its *physical* state—as specifed by the associated state vector ϕ—evolving in accordance with the time-dependent Schrödinger equation. But *what* evolves in this way is the propensity of the electron to exhibit itself as a *particle*, should the appropriate conditions for doing so be realized. Thus contained in the very idea of the individual electron evolving in a wavelike manner there is the idea that the electron can exhibit itself as a particle.

Now it is clear that it is absolutely essential to the whole propensity viewpoint that micro systems change their physical states in two quite different ways. On the one hand the *propensity* of a micro system to act as a particle may evolve in time in a smooth, deterministic fashion in accordance with the time-dependent Schrödinger equation. But on the other hand the propensity of a micro system to act as a particle may become "actualized." In this case there will be a probabilistic "jump," and the micro system will suddenly become localized somewhere in the volume available to it. If we assume that the state of the micro system just before localization is given by ϕ, then we have that the probability that the micro system will be localized in volume element dV_1 is $| \phi |^2 \, dV_1$, and so on for volume elements dV_2, dV_3,..., that go to make up the volume available to the micro system just before localization. Thus it is essential to the whole propensity viewpoint that there should be these probabilistic physical "jumps," which of course correspond to the old idea of the "reduction of the wave packet." It is important to note that these probabilistic localizations do *not* occur in accordance with the time-dependent Schrödinger equation. According to the propensity viewpoint, the time-dependent Schrödinger equation specifies merely how propensities evolve in time *only so long as these propensities are not actualized.* The range of application of the Schrödinger equation must of course be restricted so that it does not apply when localizations occur in a system. The need to restrict the range of application of the Schrödinger equation in this way is implicit in its propensity interpretation. For once we decide to interpret the state vector ϕ as in effect specifying the propensities of the micro system in question, the Schrödinger equation, in specifying how the propensities evolve or change in time, is in effect specifying how the propensities evolve or change—but only in so far as these propensities are not "actualized."

I emphasize this point, because there is one long-standing traditional approach to the problem of measurement which takes the basic problem to be the reconciliation of the "reduction of the wave packet"—which occurs, it is supposed, when a measurement is made—with the time-dependent

Schrödinger equation. No such problem faces the propensity version of QM advocated here. It is essential to the whole idea of the propensity viewpoint that there should be two quite different kinds of physical transitions, it not being possible to subsume one kind of transition under the general heading of the other kind of transition. It is, in fact implicit in the very attribution of any propensity whatsoever to an object that that object can change physically in two kinds of ways. On the one hand the propensity itself may change—just as any other physical property, such as inflammability or rigidity, may change. And on the other hand the propensity may become "actualized"—in which case a probabilistic "jump" occurs. That there should be two kinds of transitions in QM—deterministic changes of propensities, and probabilistic "actualizations" of propensities—is then an immediate outcome of adopting the propensity viewpoint in the first place.

Here, then, is one place where the propensity viewpoint differs radically from the frequency viewpoint. The natural assumption to make if one adopts the frequency viewpoint is that no special *physical* process occurs during measurement, the "reduction of the wave packet" arising simply because one chooses to regard certain systems as belonging to two different ensembles. According to the frequency viewpoint, then, all physical transitions with which QM deals occur in accordance with Schrödinger's time-dependent equation. If, however, we adopt the propensity viewpoint we are at once committed to the view that QM postulates two quite different kinds of transitions. Probabilistic localizations—corresponding to the old idea of wave packet reduction—are real physical processes.

In Section 10 I shall suggest that this difference between the frequency version of QM and the propensity version may well lead to different experimentally detectable predictions. It may, in other words, be possible to preform a crucial experiment to decide between the frequency and the propensity versions of QM. This is important. It shows that what is involved here is not merely a difference of philosophical interpretation. Rather, the frequency and the propensity viewpoints lead to two distinct physical theories—two distinct, experimentally distinguishable versions of QM.

At this point I must stress that there is one extremely important *technical* problem that will need to be solved if we are to be able to formulate a fully adequate micro realistic propensity version of QM. Granted that any propensity version of QM is committed to the existence of probabilistic "jumps" occurring, it is clearly essential that we specify the precise, necessary and sufficient conditions for these jumps to occur in purely micro terms. That is, given any composite system $S_1 + S_2$, we need to be able to specify the necessary and sufficient conditions for a probabilistic localizing "jump" to occur within the composite system, in terms of the physical state of the system itself, in terms, that is, of the quantum mechanical state description of the system. If this can be done, then the possibility arises of explaining the quasiclassical characteristics of a near macro object—such as a large molecule, for example—as arising solely as a consequence of probabilistic localizing interactions occurring between the micro systems of which the macro object is composed.

I must confess that I do not have a solution to this technical problem of specifying precise, necessary and sufficient conditions for probabilistic "jumps" to occur in purely micro terms. The purpose of this paper is in a sense to highlight the importance of this technical problem, and to clarify the nature of the problem. For my basic task is to investigate whether it might be *possible* to develop a micro realistic version of QM, or whether insuperable *conceptual* problems stand in the say of doing this. If I can show that no such conceptual problems bar the development of a propensity micro realistic theory, and only the above technical problem needs to be solved in order to formulate a precise version of such a theory, then this will in itself constitute good reasons for taking the propensity idea quite seriously indeed.

Let us, then, for the time being leave to one side the question of what micro conditions need to be realized for a probabilistic jump to occur, and consider some of the other difficulties that need to be overcome in order to develop a micro realistic propensity version of QM.

7. LOCALIZATIONS

One obvious difficulty can be put like this. We have so far considered only the propensity of a micro system to become a particle, to become localized, to acquire a more or less precise *position*. So far it looks as if a propensity version of QM would be restricted to making predictions about *positions*. But clearly QM goes far beyond this in predictive power, in that it also makes predictions concerning other so-called "observables," such as momentum, angular momentum, energy, and so on. How is this aspect of QM to be incorporated into the propensity schema?

At first sight it might seem that the way to do this is as follows. Corresponding to each "observable" we postulate a particular kind of probabilistic physical process. Thus corresponding to position there is the probabilistic jump of "localization" we have already considered. A system with associated state vector ϕ suddenly acquires a precise position, the state vector ϕ changing discontinuously to the appropriate eigenvector of position. Likewise, corresponding to the observable momentum we postulate a momentum-probabilistic jump. The micro system acquires suddenly a definite value of momentum, and the state of the system becomes, discontinuously, the corresponding eigenvector of momentum. And so on for the other observables.

However, any attempt to develop a micro realistic propensity theory along these lines immediately runs into insuperable difficulties. In order to overcome these difficulties we need to develop a micro realistic propensity version of QM which restricts probabilistic jumps to *position* probabilistic jumps occurring at a definite *time*. Let us call such hypothetical probabilistic jumps *localizations*. A localization is then an *event* characterized by a position **r** and a time t. As a consequence of undergoing such a localization, at a time t, a system changes its quantum mechanical state in a discontinuous fashion, the new state ϕ_1 being such that $|\phi_1|^2$ is, at time t, zero except for a small region about the place of localization. On this view, QM in the first instance makes (stochastic) predictions about localizations, predictions about observables such as momentum and energy in the end being reducible to predictions about the primary "observables" position and time.

In order to give a precise articulation of the propensity version of QM that I wish to advocate, let me now introduce some terminology. On the one hand we have what I shall call *quantum variables* (position$_v$, momentum$_v$, energy$_v$, angular momentum$_v$, etc.) and on the other hand we have corresponding *quantum observables* (position$_o$, momentum$_o$, energy$_o$, angular momentum$_o$, etc.). (I use the unfortunate term "observable" here simply because of its customary use in this context; nothing about what is observable or experimentally detectable is prejudged by my use of the term in any way whatsoever.) The basic idea is now this. Quantum variables attribute physical properties—namely propensities—to individual micro systems; quantum observables attribute physical properties to appropriate localizations. More precisely, a value of a quantum variable such as momentum$_v$ let us say, can be used to attribute a specific value of a physical propensity to an individual micro system; at the same time—in line with the basic propensity idea—such a value contains *probabilistic* information about what values the corresponding quantum observable momentum$_o$ *would have if the appropriate localizations were to occur*.

In order to see how this works, let us take a specific pair, namely the quantum variable momentum$_v$ and the corresponding quantum observable momentum$_o$. In order to attribute a particular value of the quantum variable momentum$_v$ to an individual micro system we assign a specific fraction p_k to each possible value a_k of the quantum observable momentum$_o$, where (we assume for convenience) $k = 1, 2, 3, \dots, n$, and $\sum_{k=1}^{n} p_k = 1$. A specific value of momentum$_v$ is thus not a *number*; rather it is an *array* of n numbers $(p_1, p_2, \dots, p_n)$, where each p_k is assigned to just one possible value a_k of momentum$_o$. The array of numbers $(p_1, p_2, \dots, p_n)$ specifies, we are assuming, a particular value of a *physical property*—namely the propensity momentum$_v$

(or momentum probability density, as it is usually called)—which may be possessed by an individual micro system. But it is of course the essence of the whole propensity idea that the fractions p_k are to be interpreted as conditional probabilities. That is, in attributing a specific value $(p_1, ..., p_n)$ of momentum$_v$ to an individual micro system we are in effect asserting: The physical state of this individual micro system is such that if it were to be reproduced a very large number of times, and if each system were to suffer localizations to which a value of momentum$_o$ could be attributed, then, of necessity, the fraction of localizations having the value a_k of momentum$_o$ would be p_k. In this way, the array $(p_1, ..., p_n)$ specifies the physical state of the individual micro system, namely its value of momentum$_v$, and also, at the same time, determines *probabilistically* the values of momentum$_o$, should the appropriate localizations occur. The value p_k $(k = 1, ..., n)$ of momentum$_v$ is of course given by $|\langle\phi_k, \psi\rangle|^2$, where $\{\phi_i\}$ is the discrete, complete orthonormal set of eigenvectors of the Hermitian operator $\hat{p}$ corresponding to the observable momentum$_o$, and ψ is the state vector of the system in question.

Analogous remarks now apply to other pairs of quantum variables and observables, corresponding to energy, angular momentum, position, and so on, the case of position being of course particularly straightforward.

It should perhaps be pointed out that there is nothing very peculiar to *quantum mechanics* about the above schema of quantum variables and quantum observables. The schema is merely a straightforward articulation of the basic propensity idea. Indeed, according to the propensity viewpoint, the apparent "mysteriousness" of the quantum domain arises simply from the fact that in this domain propensities are *basic* physical properties, and cannot be explained away in terms of more basic deterministic physical properties. The propensities that we are used to in the macroscopic world—such as the propensity of a die—can, we believe, be explained away by assuming (a) each throw is precisely determined by the initial conditions, and (b) in a series of tosses, the initial conditions vary in such a way as to give the die the appearance of having a definite propensity. It is simply our lack of familiarity with propensities that have no such deterministic underpinning which leads us to find quantum phenomena so "strange." Once we grant that in the quantum domain propensities are basic physical properties, and furthermore are only "actualized" at discrete temporal intervals and not continuously, we are more or less bound to end up with entities whose propensities "smear out" in space and suffer discontinuous probabilistic "jumps."

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