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The British Society for the Philosophy of Science

Quantum Propensiton Theory: A Testable Resolution of the Wave/Particle Dilemma
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Source: *The British Journal for the Philosophy of Science*, Vol. 39, No. 1 (Mar., 1988), pp. 1-50
Published by: Oxford University Press on behalf of The British Society for the Philosophy of Science
Stable URL: http://www.jstor.org/stable/687112
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Brit. J. Phil. Sci. 39 (1988), 1–50 *Printed in Great Britain*

Quantum Propensiton Theory: A Testable Resolution of the Wave/Particle Dilemma*

NICHOLAS MAXWELL

I PROBLEMS OF ORTHODOX QUANTUM THEORY

What sort of physical objects are electrons, protons, photons, atoms, molecules—the entities of the quantum world—in view of the contradictory wave and particle properties that these objects appear to possess? This deserves to be regarded as *the* fundamental problem concerning the nature of the quantum world. It is above all this problem that we must solve if we are to have an adequate understanding of the quantum domain.

Orthodox quantum theory (OQT) *evades* and does not *solve* this key problem. The creators of OQT—Heisenberg, Bohr, Born, Dirac and others—decided, in effect, that no consistent, fully micro realistic theory of quantum objects evolving and interacting in space and time could be developed which did justice to both wave and particle aspects of quantum phenomena. As a result, they developed OQT as a theory which is solely about the results of performing

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* I am especially grateful to the following for helpful criticisms of earlier drafts of this paper: Robert Seymour, Ian Thompson, Basil Hiley, Euan Squires, Gordon Fleming, Chris Isham, Richard Healey and Frank Arntzenius. Final revisions were made at the Center for Philosophy of Science at Pittsburgh University: I am grateful to the Center for providing me with the time to do the work.

measurements on (prepared ensembles of) quantum systems. The state vector ψ of OQT cannot be interpreted as specifying the actual physical state of the individual quantum system in physical space and time, because there is no solution to the wave/particle dilemma; rather ψ is to be interpreted as containing probabilistic information about the results of measuring diverse quantum observables, such as position, momentum, energy, spin. It is not possible to specify the instantaneous physical state of the individual quantum system in terms of the values of its quantum observables at that instant, because quantum systems do not in general, according to OQT, possess precise values of observables in the absence of measurement.

OQT has met with extraordinary experimental success. This has led many physicists to believe that it does not matter in the least, as far as physics itself is concerned, that OQT does not solve the wave/particle problem. In this they are wrong. OQT suffers from the following seven severe defects *as a physical theory* just because it fails to solve the wave/particle problem.

(i) *OQT cannot be given a micro realistic interpretation: the theory has no definite, characteristic physical ontology.* Fundamental dynamical theories of classical physics—such as Newton's theory of gravitation (NT) and Maxwell's theory of electromagnetism (MT)—can be interpreted micro realistically, as specifying the manner in which definite kinds of physical objects evolve and interact in physical space and time irrespective of whether the objects are undergoing measurement. Thus NT can be interpreted to be about point-particles, possessing inertial mass and gravitational charge, and therefore, as a result, being surrounded by a spherically symmetrical, rigid, infinite gravitational force-field which falls off in proportion to the inverse of the square of the distance. Likewise, MT can be interpreted to be about the electromagnetic field, specifying the precise way in which this evolves in space and time.

QT is above all a theory which is about micro objects or systems, and which seeks to predict and explain macro phenomena in terms of micro phenomena. If QT is to achieve this, it is clearly important to develop QT as a theory which can be interpreted micro realistically, like classical theories, as being about micro systems evolving and interacting in space and time—a theory with its own definite, characteristic physical ontology. But OQT cannot be given such a micro realistic interpretation, just because OQT provides no solution to the wave/particle problem.

Granted that we hold, with Galileo, Faraday, Maxwell, Boltzmann, Planck, Einstein and many others that it is a basic task of physics to improve our (conjectural) knowledge and understanding of the universe as it is in reality, independent of observation and measurement, then the failure of OQT to solve the key mystery of the nature of quantum objects as they are in reality, independent of measurement must be judged to be a serious defect indeed. However, many physicists, and some philosophers (e.g. van Fraassen 1980) reject this realist task for physics, and hold instead that physics has the more modest aim of developing theories which merely predict more and more phenomena more and more accurately (without necessarily describing unobserved reality). Granted this more modest instrumentalist aim, OQT cannot be held to be defective solely because it fails to tell us what kind of objects electrons and protons really are.

What follows can be regarded as providing a powerful case for rejecting instrumentalism (including van Fraassen's 'constructive empiricism') and adopting realism as the basic aim for physics instead. For I shall argue that *even if realism is rejected*, and OQT is assessed from a purely instrumentalist standpoint, nevertheless OQT must be judged to suffer from the following six severe defects, (ii) to (vii), it only being possible to overcome these six defects by developing a fully micro realistic version of QT, satisfying the demands of realism. In other words, even if instrumentalists are not interested in realism at all, nevertheless they are forced to adopt realism to the extent that non-realistic versions of QT, like OQT, suffer from severe defects, from the instrumentalist standpoint, which only a realist version of QT can overcome. And the point is quite general: some of the defects which OQT suffers from through not being realistically interpreted are the kind of defects which must plague any fundamental physical theory not realistically interpreted.

Here then are six defects of OQT which all physicists must take seriously, whatever their philosophy of physics, whether instrumentalist or realist—six defects which arise however as a consequence of defect (i), as a consequence of the non-realism of OQT *due to the lack of a solution to the wave/particle problem.*

(ii) *OQT is a very severely ad hoc theory, in a surreptitious and rarely noticed way, as a result of failing to solve the wave/particle problem.* The purely quantum mechanical part of OQT is not *ad hoc*; but this part of OQT is devoid of physical content in that it can issue in no physical predictions at all, because it lacks its own consistent quantum ontology. No combination of initial conditions and dynamical equations, formulated in purely quantum mechanical terms, can predict any actual physical state of affairs. On its own, OQT can, at most, only issue in *conditional* or *counterfactual* predictions about what would be the outcome *if* a measurement were to be performed. In order to issue in unconditional predictions, OQT must call upon some additional theory, with its own consistent physical ontology, for a specification of the physical states of preparation and measurement devices. As Bohr always emphasized, only OQT *plus some part of classical physics for a description of measurement* has genuine physical predictive content (Bohr 1949; see also Landau and Lifschitz 1958, p. 3). Attempts to dispense with classical physics by describing measuring instruments quantum mechanically must fail because such a purely quantum mechanical description can in turn only issue in predictions about what *would* occur *if* a measurement *were* to be made by some additional measuring instrument which must itself be described in terms of classical physics. (Such attempts must fail for other reasons as well: the dynamical equations of OQT assert that quantum states evolve deterministically, pure states never being converted into mixed states; measurement, however, is in general a probabilistic interaction, and one which *does* convert pure states into mixed states. For further details see Wigner 1967, ch. 12, Fine 1970, Maxwell 1972b.)

It is thus only the purely quantum mechanical part of OQT plus (some part of) classical physics (OQT + CP) which has any physical content, and thus constitutes a physical theory. But this hybrid theory, OQT + CP, is appallingly, grotesquely *ad hoc*, due to the fact that it is made up of two conceptually incoherent parts.

In recent years attempts have been made to develop a version of quantum theory (QT) applicable to macro phenomena in a quasi classical manner, and thus capable of weaning OQT of its conceptual dependence on classical physics (see Hepp 1972; Machida and Namiki 1984). If some such macro quantum theory (MQT) proves to be technically feasible, it would become possible to regard the physical theory of QT as being OQT + MQT rather than OQT + CP. But this does not help much: OQT + MQT must be almost exactly as *ad hoc* as OQT + CP. Freeing OQT of its dependence on CP in this way can do little to reduce the *ad hoc* character of the physical theory.

It is of course true that in order to check up on the predictions of a classical theory such as Newtonian theory (NT), we often need to employ additional physical theories, as when optical theory is used to check up on predictions of NT applied to the solar system. This does not mean, however, that NT is *ad hoc* in the same way in which OQT is. The difference is simply this. Because we can interpret NT as having its own consistent physical ontology (of massive, gravitationally charged particles), NT (plus specification of initial conditions) does issue in quite definite physical predictions about actual physical states of affairs—the positions and velocities of planets at definite times, for example—in the absence of optical or other physical theories, for measurement. NT is a physical theory with physical content in its own right; OQT is not.

(iii) *Despite its immense empirical success, OQT is seriously defective from the standpoint of enabling us to explain and understand quantum phenomena.* There are at least three reasons for holding this to be the case. (a) A basic task of QT is to predict and explain complex macro phenomena in terms of elementary micro phenomena—so that macro phenomena can be explained and understood as the outcome of interactions between vast numbers of micro systems. But this OQT cannot do, because the theory lacks a consistent model for micro systems, a consistent micro ontology (point (i) above). OQT can only specify and describe states of micro systems relative to prior classical descriptions of macro systems—preparation and measurement devices. Description of micro states presupposes, as a matter of conceptual necessity, description of macro states. That which is to be explained must be presupposed! Hence OQT cannot conceivably, even in principle, explain macro phenomena as arising solely as a result of interactions between large numbers of micro systems. (Instrumentalists may, with some justice, hold that this argument simply presupposes realism: this is not true however of the following two arguments (b) and (c).) (b) QT has the task of explaining the (approximate) empirical success of classical physics from purely quantum mechanical postulates. But this, again, OQT cannot do. In any physical application, OQT must presuppose (some part of) classical physics for an account of preparation and measurement devices. Once again, just that which is to be explained must be presupposed. (c) In order to be explanatory, a theory must not be *ad hoc*. But we have seen that the theory which has physical content, OQT+CP (or OQT+MQT), is very seriously *ad hoc*. Therefore, OQT is very seriously non-explanatory.

(iv) *OQT, regarded as a physical theory, is unacceptably imprecise.* On the face of it, QT is a fundamentally probabilistic theory. According to OQT, probabilistic events occur if and only if measurements are made—or at least if and only if measuring-type interactions occur. If OQT is to be a precise theory, it must specify precise physical conditions for probabilistic events to occur. But this cannot be done in terms of the imprecise notion of measurement. Physical processes cannot be precisely subdivided into those that do, and those that do not, constitute measuring-type processes. Furthermore, specifying measurement in terms of conscious observation, the occurrence of a macro process, a classical process, or an irreversible process, does not help as these notions are all irredeemably imprecise as well (Maxwell 1972b). Employing some MQT of macro quantum phenomena, as envisaged by Hepp or Machida and Namiki, cannot help much either, as any such MQT will be applicable to a great number of quantum systems, and will thus be highly imprecise from an elementary standpoint. OQT+CP (or OQT+MQT) is thus severely imprecise, in an irredeemable way, and to an unacceptable extent.

(v) *OQT is a seriously ambiguous theory, in that it is ambiguous as to whether probabilistic events occur at all.* Granted that a quantum mechanically described system S (or ensemble of such systems) is measured by a classically described measuring instrument M, OQT makes in general a probabilistic prediction about the outcome. One might suppose from this that OQT asserts unambiguously that probabilistic events occur when measuring-type interactions take place. But this is not correct. In principle the *deterministic* dynamical equations of OQT could be applied to the joint system S + M, in which case OQT predicts that S+M evolves deterministically until a further measurement is performed by an additional measuring instrument M*. This has led some to conclude that OQT is fundamentally a *deterministic* theory, probabilistic predictions emerging only because measuring instruments are in different quantum mechanical states when different particles are measured. Something like this must be assumed by all those who try to solve the so-called quantum 'problem of measurement' by trying to show that all measurement interactions evolve in accordance with the deterministic dynamical equations of OQT. A solution to this problem, conceived of in this way, would demonstrate the fundamentally *deterministic* character of OQT. In brief, OQT is only a fundamentally probabilistic theory in a highly *ambiguous* fashion.

(vi) *OQT is seriously restricted in scope.* It is standard practice these days to apply QT to states of the cosmos soon after the big bang, in physical conditions which preclude the very possibility of the existence of anything remotely corresponding to preparation and measurement devices. OQT cannot be applied in this way. Only a version of QT which has its own micro ontology could be thus applied.

Current theorizing about early states of the universe makes it desirable to be able to apply QT to the cosmos as a whole (thus creating the new discipline of quantum cosmology). Once again, OQT cannot be employed in this way, it being conceptually impossible that the cosmos as a whole should be subject to preparation and measurement!

(vii) *OQT cannot be generalized to include gravity.* Within the framework of OQT, a physical system only has a quantum state insofar as it is subject to preparation and measurement devices which are external, or additional, to the system in question. In order to quantize general relativity, space-time itself would need to be given quantum states. In order to do this within the framework of OQT, it would be necessary to postulate preparation and measurement devices external to space-time. No such devices can exist. Hence general relativity cannot be quantized within the framework of OQT.

In the light of the above seven defects, OQT must be declared to be a seriously unsatisfactory theory. (See also Maxwell 1972b, 1973, 1976a, 1982.) Even instrumentalists must reach this conclusion, since only defect (i) presupposes realism, whereas defects (ii) to (vii) do not. In fact, as I have already remarked, the above arguments do not just tell against an instrumentalist defence of OQT; they also tell against instrumentalism itself. For the six defects (ii) to (vii) all arise from defect (i)—from the failure of OQT to be open to a realist interpretation in the sense that the theory has its own consistent (possible) quantum ontology entirely independent of the ontology of classical physics. Furthermore, *any* fundamental physical theory which is not interpreted realistically as having its own (possible) ontology must inevitably suffer from defects (ii) and (iii)—and probably defects (vi) and (vii) as well: there is here, then, a general argument against instrumentalism, against 'constructive empiricism' (van Fraassen 1980), and *for* realism.

There is also the following additional argument which powerfully reinforces the arguments (i) to (vii) designed to show that OQT is a seriously defective physical theory, despite its immense empirical success. Elsewhere, I have shown that the widely held thesis that scientific theories are, in the end, to be judged solely with respect to empirical success and failure is untenable. Two kinds of criteria must always be employed in judging scientific theories: (1) *empirical* criteria, and (2) *non-empirical* criteria that have to do with the extent to which the theory is explanatory, non-*ad hoc*, unified, conceptually coherent, capable of fitting coherently into the best overall scientific understanding of the universe. Science requires both kinds of criteria equally. Without the non-empirical critera (2), the whole scientific enterprise breaks down: science would become overwhelmed by infinitely many empirically highly successful but grotesquely *ad hoc* theories, and all scientific knowledge, at the level of theory, becomes impossible. (For a detailed presentation and development of this argument see Maxwell, 1972a, 1974, 1976b, 1977, 1979, 1980, and especially 1984, Ch. 9.)

The attitude that we must adopt, then, in science if we are to be honest, is the following. In order to be scientifically acceptable, a theory must satisfy *both* criteria, (1) *and* (2) equally. A theory which satisfies beautifully non-empirical criteria (2) but fails dismally to satisfy empirical criteria (1), cannot be held to be a part of scientific knowledge, and must be rejected. But equally, *a theory which satisfies beautifully empirical criteria (1), but fails dismally to satisfy non-empirical criteria (2), cannot be held to be a part of scientific knowledge either, and must be rejected.*

This latter is the situation as far as OQT is concerned. The above seven points show, dramatically and decisively, that OQT is very seriously defective from the standpoint of non-empirical criteria (2)—from the standpoint, that is, of the search for explanation and understanding. (This is true even of point (vi), which concerns the inadequacy of OQT from the standpoint of attempting to understand early states of the cosmos, and the cosmos as a whole.)

The conclusion we ought to draw, then, is this. Despite its immense empirical success, QT given its orthodox interpretation cannot be held to be a part of scientific knowledge, and deserves to be rejected. We urgently need a better version of QT.

It is of decisive importance to appreciate that the above seven defects of OQT (including the so-called measurement problem) all arise because OQT *evades* and does not *solve* the wave/particle problem. For it is this *evasion* which makes it necessary to build the notions of observable and measurement into the orthodox concept of quantum state—thus creating the problems discussed above. *Solve* the wave/particle problem, and all this becomes unnecessary. It becomes possible to formulate QT as a (testable) theory about quantum objects *per se* evolving in space and time, the theory thus making no reference to observables, measurement or classical physics whatsoever. Measurement becomes a conceptually unproblematic physical process just like any other physical process, namely: quantum objects evolving in space and time in accordance with the laws of QT. The above seven defects vanish at a stroke. In short, in order to develop an acceptable version of QT, free of the above defects, free of the so-called measurement problem, the key problem that must be solved is the wave/particle problem—the problem of specifying a consistent ontology for the quantum domain. Einstein was absolutely correct when he remarked '. . . one simply cannot get around the assumption of reality—if only one is honest. Most . . . [physicists] simply do not see what sort of risky game they are playing with reality—reality as something independent of what is experimentally established.' (Einstein, 1950.) The orthodox *evasion* of the wave/particle dilemma does indeed have grave repercussions, sensed by Einstein but not by Bohr, Heisenberg and other authors of the orthodox viewpoint.

2 INADEQUACY OF EARLIER ATTEMPTS TO SOLVE THE PROBLEM

Over the years a number of attempts have been made to solve the wave/particle problem: but these are all, in one way or another, inadequate. There is Schrödinger's idea that quantum objects are quasi-classical wave-like entities, evolving deterministically in accordance his own famous quantum wave equation:

$$\frac{i\hbar\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + V\psi.$$

But this wave interpretation of QT (WQT) suffers from the fatal flaw that it cannot do justice to the probabilistic and particle-like character of the quantum domain. There is the idea of Einstein, Popper, Landé, Ballentine and others, according to which quantum objects can be held to be quasi-classical particles obeying non-classical, statistical laws of QT. But this particle-like, statistical interpretation of QT (SQT) suffers from at least three serious defects. First, the wave-like, interference effects of QT become utterly enigmatic. There can be no explanation for wave-like effects in terms of the physical states of individual physical systems—but only in terms of statistical laws that apply to ensembles of such systems. Attempts made by Landé (1965, ch. 1) and more recently by Audi (1973, pp. 107–119) to explain the interference effects of the two-slit experiment in terms of Duane's quantum rule for objects periodic in space, seem to be untenable (Maxwell, 1975). Second, SQT is just as dependent upon classically described preparation and measurement devices as OQT is, since the statistical laws of SQT are formulated in terms of the ψ-function defined, as for OQT, in terms of preparation and measurement, and not in terms of the instantaneous physical state of quantum particles. Thus SQT is just as *ad hoc*, imprecise, restricted in scope and non-explanatory as OQT is, and for just the same reasons. Third, there is the grave objection that the positions of quantum particles of SQT just before measurement cannot be held in general to be the positions actually detected by measurement (Gardner 1972). This renders unobserved positions of quantum particles wholly metaphysical. There is the idea of de Broglie and Bohm—the idea of the 'double solution' or 'quantum potential'—according to which QT is to be interpreted as a theory about quasi-classical particles guided by a non-classical pilot wave or quantum potential, the state of which can be derived from the ψ-function of OQT. But this 'double solution' interpretation of QT (DQT) suffers from the second defect of SQT, just indicated. The state of the quantum potential in any given experimental set up is not determined by the trajectory of the individual particle in physical space, but rather by the entire experimental arrangement, the classically described preparation and measurement devices. This means DQT is just as dependent on classical physics as OQT is—and hence that it is just as *ad hoc*, imprecise, restricted in scope and non explanatory as OQT is. (For references to the interpretations of QT just discussed see Jammer 1974, Bohm and Hiley 1987.) Finally, there is Cramer's transactional interpretation of QT (TQT), according to which the quantum object, such as the photon or electron, is the outcome of the exchange of advanced and retarded waves between emitter and absorber (Cramer 1986). But insofar as quantum systems can, according to TQT, only be understood as the outcome of transactions between emitters and absorbers, TQT suffers from the same difficulty facing the other interpretations of QT just considered, namely that quantum systems can only be given quantum states with respect to other systems which are not described in terms of QT. In the case of OQT, these other systems are preparation and measurement devices; in the case of TQT they are emitters and absorbers. Perhaps much more seriously, TQT suffers from the difficulty that it requires there to be causal influences from the future to the past, as well as from the past to the future.

It is sometimes held that quantum field theory, for example quantum electrodynamics (QED) succeeds (where non-relativistic OQT fails) in solving the wave/particle problem. But this is not the case. QED, just like non-relativistic OQT, evades and does not solve the problem, in that it is a theory about the results of performing measurements, and cannot be interpreted to be a theory about the evolution of physical states of quantum fields entirely independent of preparation and measurement. All the defects which plague non-relativistic OQT, indicated above, also plague QED and other quantum field theories interpreted in the orthodox manner.

The wave/particle dilemma has been with us now for over eighty years (ever since Einstein put forward his conjecture concerning light quanta: Einstein, 1905). Some of the greatest scientific minds ever have, in one way or another, been defeated by the problem—most notably Einstein, Schrödinger, Bohr, Heisenberg, Pauli, Dirac. When an old man, Einstein remarked: 'All these fifty years of conscious brooding have brought me no nearer to the answer to the question "What are light quanta?". Nowadays every rogue thinks he knows it, but he is mistaken.' (Einstein, 1951.) In the circumstances, it is not perhaps surprising that even those concerned with interpretative problems of QT should have grown tired of the wave/particle problem—judging it no doubt to be inherently insoluble. (It is, however, let me repeat, *the* key problem we need to solve to improve our understanding of the quantum domain: the arguments of section 1 above show clearly that no version of QT can be satisfactory which fails to solve the wave/particle problem.)

Bearing all this in mind, it may seem somewhat presumptuous to claim to have *solved* the problem. This nevertheless is my claim. In this paper I not only solve the problem: I put forward a version of QT, based on this solution, which has its own consistent, distinctive quantum ontology; this version of QT is free of the defects of OQT, and in addition, leads to predictions that differ from those of OQT, as yet untested. (For earlier sketches of this version of QT see Maxwell, 1972b, 1976a, 1982, 1984, Ch. 9.) This said, I must also immediately acknowledge that many unsolved theoretical and experimental problems arise in connection with the version of QT I advocate in this paper. Far from wishing to deny their existence, quite to the contrary, the chief purpose of this paper is to highlight the existence and importance of these long neglected problems. For too long the general acceptance of a bad philosophy of science (a combination of Copenhagenism and instrumentalism) has blinded physicists to the existence of major theoretical and experimental problems of physics, having to do with the nature of quantum objects. The change of viewpoint, or of paradigm, advocated in this paper, brings these long neglected problems into sharp focus. In this sense I am advocating a new research programme rather than a new version of QT. But this, as I have argued elsewhere (Maxwell 1974, 1976b, 1984), is what the philosophy of science ought constantly to be trying to achieve: to propose new aims for research, new fruitful possibilities, neglected because of prejudice, or bad philosophy of science.

3 PROPENSITON SOLUTION TO THE WAVE/PARTICLE PROBLEM

The solution to the quantum wave/particle problem to be advocated here rests on the following two assumptions.

Assumption (I): In speaking of the *properties* of fundamental physical entities (such as mass, charge, spin) we are in effect speaking of the dynamical laws obeyed by the entities—and *vice versa.* Thus, if we *change* our ideas about the nature of dynamical laws we thereby, if we are consistent, change our ideas about the nature of the properties and entities that obey the laws.

Assumption (II): The quantum world is fundamentally probabilistic in character. That is, the dynamical laws governing the evolution and interaction of the physical objects of the quantum domain are probabilistic and not deterministic.

These two assumptions—or conjectures—are very different in character: (I) is a somewhat philosophical thesis about how we ought to conceive of the relationship between physical entities and dynamical laws quite generally, whatever the nature of the physical universe may be, while (II) is a substantial physical, or metaphysical, thesis about the nature of the quantum world.

Granted *conjectural essentialism*—a doctrine expounded and defended in the appendix below—assumption (I) follows as a triviality. (I) ought however to be accepted independently of conjectural essentialism. Almost everyone will want to concede that all physical properties are *dispositional* in character, in that they determine how things change (or resist change) in certain circumstances. (For a good, brief discussion of this point see Popper, 1959a, pp. 424–5.) Whether we have in mind rather crude common sense properties such as rigidity or inflammability, or precise, highly theoretical properties such as mass or electric charge, the result is the same: in attributing such a property to an object we thereby imply something about how the object changes, resists change, or affects change in something else, in certain circumstances. We imply something, vague or precise, about the lawful behaviour of the object. Thus in specifying the physical properties of an object we specify, vaguely or precisely, the laws that the object obeys, and *vice versa*. There is thus a one to one correspondence between the nature of (hypothetical) physical objects on the one hand, and the nature of dynamical laws on the other hand: if we change our ideas about the one we *ipso facto* change our ideas about the other—the crucial tenet of assumption (I).

As to assumption (II), this is, it may be argued, an entirely reasonable conjecture to adopt given the probabilistic character, and immense empirical success, of OQT, and given the difficulties that beset attempts to interpret OQT deterministically.

Granted (I) and (II), we are now in a position to solve the first part of the quantum wave/particle dilemma. In moving from the classical to the quantum domain there is a dramatic change in the nature of the dynamical laws taken to prevail, from *deterministic* to *probabilistic* laws (assumption (II)). This in itself demands that as we move from the classical to the quantum domain there will be a corresponding dramatic change in the kind of physical objects and properties we encounter (assumption (I)). Quantum objects and properties must differ dramatically from classical objects and properties—just because of the fundamentally probabilistic character of the quantum domain. It is thus absurd to try to understand such quantum objects as the electron and photon in terms of such inherently deterministic objects as the classical particle, the classical wave, the classical field. There is nothing inexplicable whatsoever about the fact that quantum objects such as the electron and photon differ dramatically from all deterministic classical objects (particle, wave, field). Indeed, the thing is all the other way round: granted the fundamentally probabilistic character of the quantum world, *it would be utterly inexplicable if probabilistic quantum objects did closely resemble classical objects.* Far from requiring, for comprehensibility, that quantum objects must be understandable in terms of classical notions of particle, wave or field, we must require the opposite: if the quantum world is to be comprehensible, then its objects must be understandable in terms of new probabilistic objects and properties that differ radically from classical, deterministic objects and properties.

It may be objected that classical statistical mechanics constitutes a counter example to this argument. Classical statistical mechanics is a *probabilistic* theory, and yet is about entirely classical objects—classical particles (atoms or molecules). In fact this is not a counter example. Classical statistical mechanics is not a *fundamentally* probabilistic theory: it presupposes that the basic dynamical laws are *deterministic.* Probabilism enters into classical statistical mechanics via probabilistic distributions of initial and boundary conditions in relevant ensembles of physical systems.

Einstein, Bohr, Heisenberg, Schrödinger and the other authors of QT, despite their differences, in effect agreed on one key point: if quantum objects cannot be understood in terms of the deterministic notions of the classical particle, wave or field, then this creates a severe problem for the task of developing a fully micro realistic version of QT. Bohr and Heisenberg concluded that this severe problem cannot be solved, and as a result developed a version of QT which *evades* the problem—orthodox QT. Einstein and Schrödinger were aware of the damaging consequences of this evasion, and hoped it would be possible to understand quantum objects in classical terms. What Einstein, Bohr, Heisenberg, Schrödinger et al. failed to appreciate—and what almost everyone since has failed to appreciate as well—is that the problem they all desired to solve (but which most thought insoluble) is entirely the *wrong* problem to try to solve in the first place. Failure to represent probabilistic quantum objects in terms of deterministic classical objects does *not* in itself create any kind of problem for quantum micro realism at all. Quite the contrary, a severe problem for quantum micro realism would be created if it did prove possible to represent probabilistic quantum objects in terms of deterministic classical objects. Everyone has tried to do what ought never to have been attempted in the first place. Success would have been a disaster: longstanding failure ought to be regarded as a promising sign that the quantum world may well make perfect micro realistic sense after all!

Once we appreciate what Einstein, Bohr, Heisenberg, Schrödinger et al. failed to appreciate—namely that the wave/particle problem as traditionally understood is the *wrong* problem—we can move on to formulate and solve the *right* problem. There are in effect *two* problems we need to solve in order to develop an acceptable, fully micro realistic theory of probabilistic quantum objects. First, we must specify, in general terms, the nature of entirely *unproblematic* probabilistic objects, wholly irrespective of any considerations taken from QT. Second, we must show that no difficulties lie in the way of holding that quantum objects are just such entirely unproblematic probabilistic objects (no doubt of a distinctively quantum type). We have, in short:

Problem 1: What sort of entities are unproblematic, fundamentally probabilistic objects quite generally (entirely independent of quantum mechanical considerations)?

Problem 2: Can quantum objects be construed to be varieties of a special quantum kind of such unproblematic fundamentally probabilistic objects?

Physical properties which determine how physical objects interact with one another *probabilistically* will be called here, following Popper (1957), *propensities*. Any propensity P has associated with it a number of possible outcomes $O_1 \ldots O_n$; in specifying the value of the propensity P at any instant we specify the probability p_r that outcome O_r will occur should the propensity be actualized through the occurrence of a probabilistic event at the instant in question, with $r = 1, \ldots n$, and $\sum_{r=1}^{n} p_r = 1$. (For an account of the notion of propensity that is being appealed to here, and its close analogy with deterministic, classical physical properties, see the appendix; for an account of the way this notion differs crucially from Popper's anti-essentialistic, relational notion, see Maxwell, 1976a, pp. 283–6; 1985, pp. 41–42.) Physical objects with propensities as properties will be called *propensitons*. In accordance with assumption (I), fundamentally probabilistic dynamical laws can be interpreted as specifying how values of propensities evolve, how propensitons evolve and interact.

Two kinds of fundamentally probabilistic laws need to be considered: *continuous probabilistic laws* which assert that systems evolve probabilistically continuously in time, and *discrete probabilistic laws*, which assert that systems only evolve probabilistically intermittently in time, when relevant physical conditions arise, the values of propensities (or the states of propensitons) otherwise evolving deterministically. Corresponding to these two kinds of probabilistic laws there are two kinds of propensitons, *continuous* and *discrete* propensitons.

There are, then, three kinds of dynamical theories which deserve to be regarded as equally viable from an *a priori* standpoint (other things being equal): deterministic, continuously probabilistic and discretely probabilistic theories. There is nothing intrinsically *ad hoc* or inexplicable about the instantaneous probabilistic transitions of discretely probabilistic theories: such transitions are an inherent feature of this kind of theory. Corresponding to these three kinds of equally viable theories, there are three kinds of equally viable physical entities: deterministic entities such as the classical point-particle and the classical electromagnetic field; continuous propensitons; and discrete propensitons.

The basic thesis of this paper is that electrons, photons and other quantum objects are varieties of *unproblematic discrete propensitons* (or *smearons* as they were called in an earlier paper: see Maxwell, 1982). I therefore indicate, in a little more detail, the general character of the (unproblematic) discrete propensiton.

As I have just indicated, the physical state of the discrete propensiton (and the values of the propensities it possesses) evolve *deterministically*, as long as the physical conditions for probabilistic actualization are not realized. When these latter conditions are realized, the propensiton suffers an instantaneous, probabilistic change of state, determined probabilistically by the values of relevant propensities at the instant in question. Likewise, values of propensities change instantaneously. In order to specify the nature of any (discrete) propensiton—the nature of the propensities possessed by the propensiton—three things need to be specified: (i) the deterministic dynamical laws of evolution and interaction; (ii) the precise propensiton conditions for probabilistic events to occur; (iii) probabilistic laws governing instantaneous probabilistic transitions.

One might try to visualize the evolution and interaction of the discrete propensiton in terms of the flight of a magnetized die tossed into a varying magnetic field. As the die falls the value of its propensity varies continuously and deterministically; when the die hits the table top and comes to rest, the propensity is actualized in a discontinuous, probabilistic way. This is, however, only a very inadequate model for the evolution of the discrete propensiton. The evolution of a real life, individual die can be conceived of entirely in terms of changing values of *deterministic* properties; the propensity of the die is the outcome of the statistical distribution of different initial conditions of different tosses. In the case of an evolving (discrete) propensiton, however, there is no evolution of values of *deterministic* properties—only a deterministic evolution of values of *probabilistic properties* or propensities (which is quite different). There is no *deterministic* state; only a *propensity* state. This ensures that all (discrete) propensitons are utterly unlike familiar objects, such as dice and coins, to which propensities can be attributed but which can be conceived of, more fundamentally, in terms of classical, deterministic properties.

The evolution of a genuinely (discrete) *propensiton* die would have to be conceived of in something like the following terms. The propensiton die is tossed. As the die flies through the air it is gradually transformed into six potential, virtual, ghostly dice, each with a different face uppermost, each with a different (probability) density (all equal in the case of unbiasedness), which may very well vary with time. When the six potential dice hit the table top, five vanish and one solid die remains. If the die is tossed repeatedly, the statistical outcomes are determined by the probability densities of the six virtual dice just before contact with the table top.

This, then, is the general character of the discrete propensiton. Its state evolves (i) deterministically into a smeared out range of *virtual* or *potential* states; then, when (ii) appropriate propensiton conditions arise (iii) instantaneously and probabilistically, the *virtual* states become *vacuous* except for one which becomes *actual*. Once *discrete probabilism* is conceded, this general character of the (unproblematic) propensiton is inevitable. As a special case, it is possible to envisage a kind of discrete propensiton which is such that the values of its propensities remain fixed during deterministic evolution. In this case, values of propensities will not spread out during deterministic evolution. In general, however, the propensity state of discrete propensitons will spread out during deterministic evolution—whether spatially, or in some other way. It is, in other words, not absolutely essential that discrete propensitons exhibit quantum-mechanical-type spatial smearing out, or non-locality; it is, however, entirely natural that discrete propensitons should exhibit such typically quantum mechanical features.

As a second example of a possible (unproblematic) kind of discrete propensiton, consider the following. The propensiton is in the form of a sphere, which expands at a fixed rate. The stuff of the sphere is position probability density, uniformly distributed within the sphere. The condition for probabilistic actualization to occur is for two spheres to touch. The outcome is that the two spheres collapse instantaneously into two small spheres of some minimal size, each localized probabilistically by the position probability density of each sphere. It is vital to appreciate that there is nothing inherently problematic, *ad hoc* or inexplicable about the instantaneous probabilistic collapse of the propensiton spheres (to re-emphasize a point already made). To demand that any such instantaneous, probabilistic collapse of virtual states must be *explained* in terms of some continuous evolution of state amounts to holding that only deterministic or continuously probabilistic theories are acceptable, discretely probabilistic theories being unacceptable on *a priori grounds.* Once it is conceded that these three kinds of dynamical theories are equally acceptable *a priori* (other things being equal), it is thereby conceded that the instantaneous, probabilistic collapses of propensiton states postulated by discrete probabilism are not intrinsically problematic or inexplicable—not especially in need of further explanation in terms of some continuous process.

Propensitons of this rather simple-minded type can easily be made a little more sophisticated by postulating that the position probability density is variable in space—even in a wave-like way. If the conditions for probabilistic events to occur are modified, it would even be possible to create a possible kind of propensiton which is such that an ensemble of such propensitons, passed through a two-slitted screen, creates an interference pattern of the kind created by electrons or photons.

There is nothing *ad hoc* or arbitrary about the discrete propensiton as it has just been characterized. As I show in the appendix below, as we generalize deterministic dynamical laws to become probabilistic dynamical laws, so *deterministic objects* generalize to become either *continuous* or *discrete propensitons.* The propensiton (continuous or discrete) is *the* natural generalization of the deterministic object.

So much for my solution to problem 1. My solution to problem 2 is that quantum objects can indeed be conceived of as unproblematic discrete propensitons, very roughly of the type just indicated. The two-slit experiment, for example, which so strikingly reveals both the wave-like and the particle-like aspects of electrons (or photons) can be understood in the following way. Each individual electron is in the form of a wave packet, a spatially smeared out discrete propensiton. The wave-like character of the electron propensiton is such that the absolute phase is without physical significance; only phase differences which persist through a constant change of phase of the entire wave packet are of physical significance. As a result of this, in many circumstances the wave-like character of the electron propensiton is implicit, rather than being explicit in a wave-like variation of position probability density. The propensiton states of individual electrons evolve deterministically, in accordance with the dynamical equations of QT: what evolves, however, is the propensity to interact in a probabilistic and quasi particle-like way, should the appropriate physical conditions to do so arise. The deterministic equations of QT do not of course apply to such probabilistic actualizations of propensities. When the electron wave packet encounters the two-slitted screen *either* the electron is absorbed by the screen and there is an instantaneous, probabilistic collapse of the wave packet, *or* the electron wave packet passes through both slits. Granted the latter then, on the other side of the screen, the implicit wave-like character of the propensiton state of the electron leads to interference (as a result of phase differences which cannot be eliminated by any constant global change of phase): the wave-like character of the propensity state of the electron becomes explicit in an interference-like variation of position probability density. The wave packet then encounters the photographic plate and interacts with all available silver bromide molecules. The physical condition for a propensiton or wave packet probabilistic collapse are then realized: abruptly, the electron continues to interact in a highly localized way with just one silver bromide molecule (or crystal) in such a way as to create a developable dot of silver on the photographic plate. The position of the dot is probabilistically determined by the interference pattern of position probability density of the electron propensiton just before the wave packet collapse. As a result, in the case of an ensemble of similarly prepared electrons with the same momenta, and therefore the same wavelengths, the developable dots on the photographic plate fall into the characteristic observed interference pattern—mirroring the interference pattern in position probability density of each individual electron propensiton just before probabilistic localization occurs.

It deserves to be noted that the electron, conceived of as a distinctively quantum mechanical kind of discrete propensiton, exhibits particle-like features in two ways. First, a particle-like aspect is exhibited whenever, as a result of a probabilistic propensiton collapse, the electron is detected in a localized way as a dot on a photographic plate, or as a trail of ionized molecules or water droplets in a Wilson cloud chamber. Second, a particle-like aspect is exhibited in the dynamical character and behaviour of the electron propensiton. The field of force created by the electron propensiton corresponds, not to a classical charged point-particle, but rather to a *superposition* of charged point-particle states. Consider Schrödinger's time-dependent equation for two particles:

$$i\hbar\frac{\partial}{\partial t}\psi(r_1r_2t) = -\frac{\hbar^2}{2m_1}\nabla_1{}^2\psi(r_1r_2t) - \frac{\hbar^2}{2m_2}\nabla_2{}^2\psi(r_1r_2t) + V(r_1r_2)\psi\ (r_1r_2t).$$

In the case of two non-relativistic electrons interacting by means of their electrostatic force alone, the potential function $V(r_1r_2)$ becomes e^2/r_{12}, and the last term of Schrödinger's equation, $e^2/r_{12}\psi(r_1r_2)$, can be regarded as specifying a *superposition* of electrostatic forces between all pairs of coordinates r_1, r_2, for which $|\psi(r_1r_2t)|^2dr_1dr_2 > 0$.

There are now a number of tasks I need to accomplish to transform this solution to the wave/particle dilemma into a fully fledged propensiton version of QT (PQT). First, I need to specify how OQT is to be modified so that it becomes PQT—a version of QT which is exclusively about quantum propensitons evolving and interacting in space and time, in the first instance entirely independently of preparation, measurement and classical physics (PQT thus being free of the seven defects which plague OQT). Second, and most important of all, I must specify the precise, necessary and sufficient, quantum mechanical conditions for probabilistic events to occur—for quantum propensitons to suffer instantaneous collapse. Third, I need to specify precise probabilistic laws governing quantum propensiton collapse. Fourth, I must show that PQT recaptures all the empirical success of OQT, even though PQT eschews all reference to observables, measurement and classical physics. Fifth, I need to indicate crucial experiments capable of deciding between OQT and PQT. These five points are taken up in turn in the remaining sections of the paper.

4 FROM ORTHODOX TO PROPENSITON QUANTUM THEORY

OQT consists of two parts. On the one hand there are the dynamical equations, such as Schrödinger's time-dependent and time-independent equations, the Klein-Gordan and Dirac equations, and the equations of quantum field theory. On the other hand there are the interpretative postulates of OQT, which interpret the ψ-function in terms of measurement. These generalize Born's 1926 postulate (Born, 1926, 1927), and may be taken to assert:

(1) If a measurement of observable A is performed on a system (or ensemble of systems) in a state ψ, then the probability of obtaining a value between a_r and $a_{r+dr} = |(\alpha_r, \psi)|^2 dr$, where (a_r) and (α_r) are eigenvalues and eigenvectors of the Hermitian operator $\hat{A}$ corresponding to the observable A.

PQT retains the dynamical equations of OQT but rejects the interpretative postulate (1). Instead of interpreting ψ as containing information about values of *observables*, about the outcome of performing *measurements* on the system (or ensemble of systems) in question, PQT rather interprets ψ as specifying the actual physical state of the individual quantum system in physical space and time, even in the absence of preparation and measurement. All quantum systems are conceived to be discrete propensitons (as indicated in the last section). ψ is interpreted to contain information about the values of various quantum propensities of quantum propensitons, such as position, momentum and energy probability density, and angular momentum or spin states. In specifying how ψ evolves in time, the dynamical equations of QT specify how values of these propensities evolve deterministically, just as long as no probabilistic events occur. From the outset, and necessarily, the *scope* of the dynamical equations of QT is restricted to the deterministic evolution of quantum propensitons. Whenever quantum propensities, such as position, momentum or energy density, are probabilistically actualized then, at that instant, deterministic dynamical equations do not apply. (It is this restriction of the scope of the dynamical equations of QT, basic to the whole propensiton idea, which ensures that any precisely formulated version of PQT must differ experimentally from OQT, at least in principle.) Instead of the generalized Born postulate (1) of OQT we have, within PQT, postulates which specify the precise quantum propensiton conditions for probabilistic events to occur, and the precise instantaneous and probabilistic changes of propensiton state that result. All quantum measurements will turn out to be no more than special cases of a kind of probabilistic process occurring naturally, throughout the universe. PQT enables us to derive Born's postulate from purely quantum mechanical postulates, without any assumption being made concerning observables, measurement or classical physics. Stable macro objects and macro phenomena, obeying approximately classical laws, emerge naturally, according to PQT, as the outcome of vast numbers of quantum propensitons interacting with one another in a probabilistic manner. (Earlier sketches of PQT are to be found in Maxwell 1972b, 1976a, 1982, 1984 Ch. 9, 1985.)

It might seem that the *complex* character of ψ constitutes a serious obstacle to interpreting it as specifying *real* values of propensities of real propensitons. But this is not the case. We may take $|\psi|^2dV$ to specify the real value of the propensity, position probability density, within each dV. Analogous remarks hold for momentum and energy probability density, and spin. In this way ψ, a complex function of space and time, is interpreted to attribute real values of quantum propensities to quantum objects in physical space and time. (This does not reintroduce the notion of measurement. Quantum propensities presuppose probabilistic *localizations*, but not *measurements*: see Maxwell, 1976a, pp. 661–3.) It would seem that ψ is complex in order to do justice to the often implicit wave-like character of quantum systems, alluded to above, in the last but one paragraph of section 2. Thus a quantum system in an eigenstate of momentum has a definite wavelength associated with it, even though position probability density is constant in space. If ψ is complex, this state of affairs is easy to depict. The wave character of the quantum state may be represented by: $e^{i\alpha} = \cos\alpha + i\sin\alpha$; since $|e^{i\alpha}|^2 = 1$, the square of the amplitude can be constant and the wave character of the state still exist. The time-dependent Schrödinger equation specifies how such an implicit wave-like feature of a quantum state can, in certain circumstances, become explicit as an interference-like variation of position probability density in space—as a result of diffraction, for example.

It might seem that the fact that, for 2 (or n) interacting systems we need to resort to a ψ-function in six (or 3n) dimensional configuration space delivers a fatal blow to the propensiton interpretation of QT. How can such a ψ-function be interpreted as specifying the real physical states of 2 (or n) objects in 3 dimensional physical space? In order to carry through such an interpretation, we must first appreciate that n interacting quantum objects do not have independently specifiable propensity states: only the composite object as a whole has a definite propensity state. The propensities of this composite propensiton, in 3 dimensional physical space, need to be understood as follows. Consider position probability density. For an n particle system in a state ψ, this is represented by $|\psi|^2 dr_1 \ldots dr_n$, and is to be understood as determining: the probability of particle 1 being available for a probabilistic interaction in dr_1, particle 2 in $dr_2 \ldots$ and particle n in dr_n (for all possible values of $dr_1 \ldots dr_n$). Instead of interpreting $|\psi|^2 dr_1 \ldots dr_n$ as assigning a probability to a small region in 3n dimensional configuration space, we interpret it as assigning a probability to n small regions $dr_1, \ldots dr_n$ in 3 dimensional physical space. The *value* of this propensity cannot be uniquely specified for particle 1 in region dr_1 independently of the other particles: as $dr_2, \ldots dr_n$ are moved through space, the overall probability of particle 1 being available for interaction in the *fixed* region dr_1 (and the other particles being available in $dr_2, \ldots dr_n$) will *vary* as well. What exists potentially in one small spatial region at an instant depends, in this way, on what exists, potentially, elsewhere—a feature of the quantum world not encountered within classical physics. To say this, however, is just to say that the n interacting particles do not have distinct quantum states, but only have a joint, quantum-entangled state as a whole. In order to specify how the value of the n-fold position probability density of the n-particle system, and the values of other such propensities, evolve in physical space and time, it is convenient to resort the mathematical fiction of a ψ-function with a unique value at each point in 3n dimensional configuration space. This is to be interpreted physically, however, as assigning a unique value to any n points in 3 dimensional physical space.

This physical interpretation of the propensities of interacting and composite quantum objects may well be of special significance when it comes to the question of how the conditions for probabilistic events to occur are to be specified—as we shall see below.

5 VIRTUAL, POTENTIAL AND ACTUAL PARTICLES

According to the version of PQT to be considered here, probabilistic events occur (with the actualization of quantum propensities) when and only when, as a result of inelastic collisions or decay processes, new *actual* (as opposed to merely virtual) particles are created—all quantum measurements that detect systems being merely special cases of particle creation.

One reason why this postulate seems worthy of serious consideration can be put like this. As long as quantum objects interact with macroscopic objects in an *elastic* fashion as when electrons are diffracted through a crystal or two-slitted screen, no probabilistic localization seems to occur. It is when quantum objects interact *inelastically* in a highly *localized* fashion, to create new particles or ionized molecules, that probabilistic wave packet collapse seems to occur. All quantum measurements that actually *detect* quantum systems (and do not merely *prepare* quantum states) must involve some such *inelastic*, particle-creating process—usually millions of such processes—simply to produce a permanent record (necessary for measurement to have taken place). Granted that *detection* is (in general) a sufficient condition for a probabilistic event to occur, and granted we seek some elemental quantum condition for the occurrence of probabilistic events, it seems not unreasonable to conjecture that creation and annihilation of particles—whether elementary or composite—is the proper necessary and sufficient quantum condition for the occurrence of probabilistic events (quantum measurements thus exemplifying physical processes that occur in Nature all the time).

One immediate objection which may be made to the above proposal is that it requires something which does not exist—an absolute distinction between virtual and actual particles. But to this we can reply that the distinction can be drawn quite straightforwardly as follows. Virtual particles are particles whose persistence is constrained by a combination of uncertainty relations and conservation principles, whereas actual particles are subject to no such constraint.

Strictly speaking, within the framework of orthodox quantum field theory, it is possible to distinguish *three* kinds of status for particles: *virtual*, *potential* and *actual* (an important point that does not seem to have been made explicitly hitherto in the literature). Whereas virtual particles are such that their persistence is restricted by conservation principles, both potential and actual particles are, according to OQT, subject to no such restriction. *Potential* particles arise whenever, as a result of inelastic collisions, two or more interaction channels result, different kinds or numbers of elementary particles being associated with each channel. The channels are *alternative possibilities* rather than *actualities* (in that measurement can detect only *one* channel). *Actual* particles, on the other hand, are particles which are not a part of any such superposition of alternative possible particle states.

These distinctions can be clarified by means of the following example. Consider a photon sufficiently energetic to create an electron/positron pair. In the vacuum such a photon may be regarded as creating virtual electron/positron pairs: conservation of momentum and energy ensures, however, that such pairs do not persist. Here, the electron/positron pairs are irredeemably *virtual*, whereas the photon is *actual*. If however the photon encounters a nucleus, a persisting electron/positron pair becomes possible, since the nucleus can carry off energy and momentum in such a way that both energy and momentum are conserved. Suppose there is a probability $= 1/2$ that the photon will subsequently be detected, probability $= 1/2$ that the electron/positron pair will be detected. OQT predicts that the system persists as a superposition of these two alternative possible channel states until a measurement is made. Here, the electron/positron pair on the one hand, and the photon on the other hand, are *potential* rather than *actual* particles. A measurement which establishes the non-existence of the photon converts the electron/positron pair from *potential* to *actual* status. Likewise a measurement which detects the electron converts the status of the positron from *potential* to *actual*.

It is of vital importance to appreciate, here, that a system which consists of an *actual* photon and an *actual* electron/positron pair is quite different from a system consisting of a *potential* photon and *potential* electron/positron pair. In the former case appropriate measurement detects *both* photon *and* electron/positron pair: in the latter case measurement can only detect *either* the photon *or* the electron/positron pair. In the former case there is sufficient energy and momentum for *both* photon *and* electron/positron pair to exist: in the latter case there is only sufficient energy and momentum for *either* the photon *or* the electron/positron pair to exist.

According to OQT, superpositions of different *potential* particle states can persist without limit. Thus, in the above example, the superposition of the potential photon and potential electron/positron pair persists indefinitely, as long as no measurement is performed. According to OQT, indeed, the *only* way *potential* particles can become *actual* is as a result of measurement. Even more paradoxically, according to OQT, the number of potential particles increases without limit, in the absence of measurement. The number increases every time there is an inelastic collision with more than one interaction channel outcome. This is the case even if we allow that particles can be annihilated as a result of interactions or decay—since such processes do not decrease the number of alternative potential particles. Strictly speaking, of course, particles cannot be annihilated in this way, since there must always be a non-zero amplitude for the particles not to be annihilated—which only makes the situation worse.

We have here a new difficulty facing OQT, a new 'potential particle' paradox, somewhat analogous to Schrödinger's cat paradox, but with this difference: whereas Schrödinger's paradox arises when OQT is applied to the macro domain (e.g. to a cat), the potential particle paradox arises entirely within the quantum micro domain itself.

PQT solves this new potential particle paradox at a stroke: PQT demands that potential particles persist only for as long, roughly, as corresponding virtual particles do, and then either cease to exist or become actual, entirely independent of measurement.

6 PARTICLE CREATION AND ANNIHILATION AS THE QUANTUM CONDITION FOR PROBABILISTIC EVENTS TO OCCUR

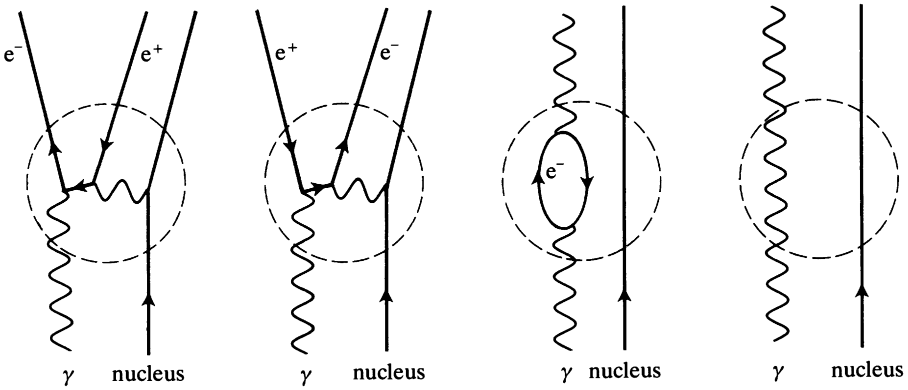
Suppose that, as a result of an inelastic interaction between wave packets, alternative possible interaction channels are created, each channel having its own distinctive clutch of potential particles. In the case of the $\gamma \rightarrow e^+ + e^-$ interaction discussed above, there are *two* channels, the first consisting of photon and nucleus, the second consisting of e^+/e^- pair and nucleus. Whereas OQT asserts that such channels persist indefinitely until measurement detects one or other channel outcome, PQT asserts:

Postulate (2): A *sufficient* condition for the superposition of channel states to have decayed probabilistically into one or other channel state, with its distinctive clutch of potential particles becoming actual, is that the interaction responsible for creating the potential particles of the different channels ceases, due to the spatial separation of interacting wave packets.

Thus, according to (2), for the $\gamma \rightarrow e^+ + e^-$ case, the superposition of potential photon state and potential $e^+ + e^-$ state is *either* the actual photon state (with probability $= \frac{1}{2}$) *or* the actual $e^+ + e^-$ state (with probability $= \frac{1}{2}$) once the initial photon has separated spatially sufficiently from the nucleus.

The basic idea of (2), and of all more precise postulates to be formulated below, is that interactions proceed entirely in accordance with the dynamical equations of OQT with this one exception: whereas OQT asserts that different channel outcomes of inelastic interactions persist as superpositions, PQT asserts that such superpositions decay spontaneously and probabilistically into one or other channel state. We have here, then, a possible propensiton alternative to orthodox quantum field theory (OQFT), namely propensiton quantum field theory (PQFT)—or relativistic quantum propensiton theory, as it ought perhaps to be called. The difference between OQFT and PQFT can be illustrated by means of (a perhaps somewhat illegitimate use of) Feyman diagrams of the $\gamma \rightarrow e^+ + e^-$ process already discussed (see diagram 1).

In the space-time region indicated by the dotted circles (the region of the interaction $\gamma \rightarrow e^+ + e^-$), OQFT and PQFT agree: what exists is a superposition of the four processes indicated, and processes represented by all higher order diagrams (here neglected). In space-time regions outside, and after, the region



(a) (b) (c) (d)

Diagram 1

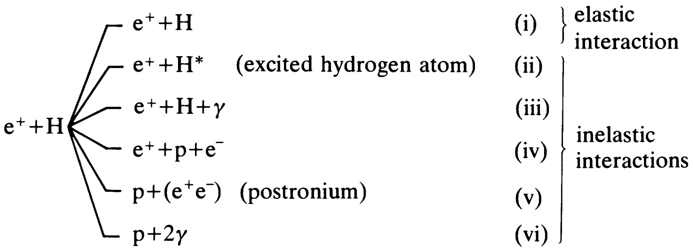

$e^+ + H$
$e^+ + H$
$e^+ + H^*$ (excited hydrogen atom)
$e^+ + H + \gamma$
$e^+ + p + e^-$
$p + (e^+e^-)$ (postronium)
$p + 2\gamma$
(i)
(ii)
(iii)
(iv)
(v)
(vi)
elastic interaction
inelastic interactions

Diagram 2

indicated by the dotted circles, OQFT and PQFT disagree. According to OQFT, the superposition of (a), (b), (c) and (d) persists; according to PQFT, the individual system is *either* in the state that is the outcome of (a) and (b), *or* in the state that is the outcome of (c) and (d). If we neglect this difference, then OQFT and PQFT agree. In particular, the two theories agree concerning the evolution of systems composed of persistently interacting virtual or potential particles.

Postulate (2) has its limitations. It does not specify precisely when, where and how the decay of channel states occurs. It is restricted to spatially finite wave packets, and does not seem to be applicable to decay processes. It is put forward as a first approximation to a more satisfactory postulate, to get the discussion of possibilities underway. In the next section, a number of rival postulates will be considered, each specifying more precisely, and in a more generally applicable way, how, when and where probabilistic collapse of channel superpositions occurs. The rest of this section is devoted to a discussion of the crucial question: How are interaction channels to be distinguished?

The point is this. The basic idea behind (2) is open to two interpretations, namely:

(2A): Probabilistic events occur when and only when *elementary* particles are created or annihilated.

(2B): Probabilistic events occur when and only when new particles are created *whether elementary or composite*, as long as the total rest mass of particles in different potential outcomes is different.

(2A) and (2B) are different versions of postulate (2), in that they interpret the key notion of 'interaction channel' differently, as this notion figures in (2). Thus, according to (2A), there are *two different* interaction channels (emerging from the same interaction) if and only if there are different potential elementary particles in each channel (including different numbers of the same kind of elementary particle). According to (2B), on the other hand, there are *two different* channels if and only if there are different potential particles in each channel, whether *elementary or composite*, the total rest mass of particles in different channels being different.

The difference between (2A) and (2B) can be clarified by considering the interaction in diagram 2.

There are here, according to (2A), just *three* alternative channel outcomes (only one of which survives probabilistic collapse) namely [(i), (ii), (iv), (v)], [iii)], and [(vi)]. According to (2B), on the other hand, (i), (ii), (iv) and (v) are *different* channel outcomes, since each consists of different composite particles with different total rest masses. (The mass of the hydrogen atom H is slightly less than the sum of the masses of its constituents p and e^-.) Whereas (2A) predicts that the superposition of states (i), (ii), (iv), and (v) persists indefinitely, (2B) predicts that this superposition decays spontaneously and probabilistically into one or other state. However, (i) and (iii), which are distinct potential particle states for (2A), are the same for (2B), since they do not differ in total rest mass.

Postulates (2A) and (2B) give rise to different problems, and will be discussed in turn.

Postulate (2A), on the face of it by far the more attractive possibility, is confronted by at least four problems. First, in order to be acceptable, (2A) must predict that probabilistic events occur for all types of quantum measurements that actually detect particles. It would seem, however, that measurements can be performed without the creation of new elementary particles—as when electrons are detected by means of the ionization of molecules in a cloud or bubble chamber, or by means of chemical processes associated with photography. Second, there are straightforward coherent quantum states of the electromagnetic field to which no definite photon number can be assigned: (2A) however seems to require that photon number is not ambiguous in this way. Third, there is a problem concerning the identity of photons. When a photon interacts with an electron, as in Compton scattering, or with an atom, so that it is absorbed and emitted by the atom, under what circumstances does such a process constitute (a) an elastic interaction of one photon (there thus being no probabilistic event) or (b) an inelastic interaction involving the annihilation of one photon and the creation of a second photon (there being in this case a probabilistic event)? Fourth, what is the status of elementary particles in hadrons, nuclei and other persisting composite quantum objects? In such cases it is difficult to see what alternative we have to holding that the composite object is, internally, a superposition of virtual or potential particle states, the *composite* object, nucleon, nucleus or whatever, being the *actual* particle.

The first problem is not too serious. According to (2A), whenever a measurement of the kind indicated is performed, an atom or molecule (at the very least) goes into a superposition of two states (as when a molecule is in a superposition of the non-ionized and ionized state, or silver and bromide atoms are in superpositions of the atomic and molecular states). These states interact with photons in quite different ways, creating and annihilating photons quite differently. According to (2A), it is the creation and annihilation of such secondary photons which leads the superpositions of atomic and molecular states to collapse probabilistically into one or other state—thus creating the definite observed outcomes of measurement. The second objection is much more serious, and may indeed suffice to demolish (2A). In order to rescue (2A) from this objection it would seem to be necessary to restrict (2A) to contexts in which photon number is unambiguously defined (unless a way can be found to reformulate (2A) so that precise conditions for probabilistic events to occur are specified even when the number of photons being created or annihilated is, within certain limits, ambiguous). The third objection can be overcome by insisting that, for a probabilistic event to occur, photon annihilation must be *actual* and not just *virtual* or *potential*. Granted that the energy of the photon is dE, actual annihilation only occurs if the photon is annihilated for a period $dt >> \hbar/dE$. The fourth objection can be met with the reply that even if quarks in hadrons and nuclei have a virtual or potential status, the composite particle alone being *actual*, nevertheless it can still be the case that probabilistic events occur when created potential elementary particles emerge from interaction cells (or tubes) in the way indicated above.

I turn now to a consideration of postulate (2B). This postulate avoids entirely the four problems that beset (2A), but at the price of creating two new difficulties. How can the *bound* state of N elementary particles be distinguished from *excited* bound states, or indeed from unbound states, in a sufficiently precise, general, non-arbitrary way to provide an adequate basis for specifying precise conditions for probabilistic events to occur, as required by (2B)? What rationale can there be for holding that the creation or annihilation of a bound state leads to a probabilistic event when all that is involved is a rearrangement of elementary particles?

In order for N particles to constitute *one* composite particle throughout some space-time region, in the sense required by (2B), the following must be satisfied. First, it must be possible to factorize the state ψ_N of the particles at any instant into two parts: on the one hand there is the 'internal' state ψ_{int}, formulated in terms of the relative positions of the N particles, and corresponding to some *definite energy level*; and on the other hand there is the 'external' state ψ_{ext}, a wave function of the centre of mass of the system in three dimensional space, and varying with time. Second, this state must persist for long enough for the fixed internal energy level to be distinguishable from other possible energy levels. The bound particle then has a mass equal to the mass of the N particles minus the mass corresponding to the binding energy associated with the energy level in question. This state is distinct from bound states that are superpositions of energy levels, and distinct from interacting, unbound states. (2B) asserts that a superposition of (a) any such composite particle state (with a definite internal energy level) and (b) other states decays probabilistically into *either* (a) *or* (b).

A preliminary rationale for adopting (2B) rather than (2A) quite independent of the problems which confront (2A) can be given as follows. In appropriate circumstances, the laws of QT appear to be just as simply and straightforwardly applicable to complex phenomena as to elementary phenomena (in striking contrast to dynamical theories, whose applications usually become rapidly much more complicated as phenomena cease to be elementary). This feature of the laws of QT is illustrated by the elementary quantum mechanical behaviour of complex, composite particles, in appropriate physical circumstances. It is illustrated by the phenomenon of phonons—elementary quanta with a highly complex molecular composition. And it is illustrated by such macroscopic quantum phenomena as superfluidity. QT appears to be a general mechanics concerned with the way energy, momentum, frequency and wavelength are inter-related (at levels comparable to Planck's constant) however elementary or complex the objects may be which are undergoing motion and vibration. Once we adopt this standpoint, it becomes clear that (2B) is more appropriate than (2A)—as long as (2B) can be formulated with absolute precision and generality.

The intended basic idea behind both (2A) and (2B) is the entirely natural and plausible postulate that:

(3): Probabilistic events occur when and only when quantum objects of some characteristic kind are created or annihilated.

Postulate (2A) clearly captures the basic idea of (3): but does (2B)? How can the creation of new bound states of the *same* elementary particles be held to constitute the creation of new kinds of quantum objects?

That (2B) does capture the basic idea of (3) can be argued for as follows. Consider a system of N elementary particles. This system in the form of a bound state, with a stationary internal state, is indeed a different kind of physical object in physical space and time from the object made up of the same elementary particles interacting in a non-stationary way, or not interacting at all. In the case of the stationary bound state, the N elementary particles have an external quantum state in physical space *as a whole*. On the one hand there is the external state of the composite particle; this can be conceived of as a propensiton state of a physical object in physical space, analogously to the way in which the propensiton quantum state of an elementary particle can be conceived: on the other hand there is the stationary internal state of the composite particle. The bound state behaves as if it were an elementary particle, without internal structure, with overall spin and charge properties that may be quite different from those of its constituents, as long as it interacts with its environment sufficiently non-energetically for its internal structure to remain unaffected. The case of the N elementary particles interacting in a non-stationary way is different. Here the quantum state of the entire system can, it is true, be represented as the product of a state vector ψ_{ext} that is a function of the coordinates of the centre of mass of the system in physical space, and a state vector ψ_{int}, that is a function of the relative coordinates of the N elementary particles. But in the first place this depends on Galilean invariance: such a factorization is not in general possible within relativistic QT. Secondly, ψ_{ext}, which may in a sense be regarded as representing the external quantum state of the system as a whole in physical space, does not represent the propensity state of an actual physical object: it represents only the centre of mass of the N elementary objects. This can in general only be detected *via* the detection of the

N distinct particles. The composite particle, on the other hand, can be detected as a single particle; it may interact with other systems as a whole physical object in its own right, as long as its internal structure remains unaffected. The composite particle with a stationary internal state is, in short, a different kind of object from the system of N interacting elementary particles without a stationary internal state. (That these two cases represent fundamentally different kinds of objects in physical space is strikingly apparent within the framework of PQT, according to which all quantum state vectors must be interpreted as specifying propensity states of objects in three dimensional physical space. When this restriction is relaxed, as it is within the framework of OQT, and the state vector of N particles can be interpreted in terms of a wave function in 3N configuration space, the fundamental character of the above distinction may well be overlooked.)

There is, it must be emphasized, nothing unorthodox about the thesis that composite particles have quantum states *as a whole*. The fact that the two-slit experiment or the Stern-Gerlach experiment can be performed with *atoms* demonstrates convincingly that composite quantum objects can have wave packets in physical space *as a whole*, as if the composite object were elemental, without internal structure. In the case of the proton and neutron, indeed, it was not realized for some decades that these objects have a complex inner structure. As Gottfried and Weisskopf (1986, p. 14) remark: 'A system in its ground state can be considered to be endowed with fixed, unchanging properties as long as the energy exchanges with its environment are much less than the difference ΔE between the first excited state and the ground state. It then acts like an 'elementary' particle with fixed properties. Among those properties we mention its spatial extension and symmetry, its angular momentum, and its magnetic and/or electric multipole moments. The system changes these properties only if it is excited to higher states; whenever it returns to the ground state the system regains the properties typical of that state.'

Where PQT (incorporating (2B)) differs from OQT is not in its assertion that composite objects have external quantum states *as a whole*, but rather in its assertion that non-interacting superpositions of such states and non-bound, non-stationary states of the same elementary particles *decay spontaneously into one or other state.*

I give now an argument in support of (2B). Two closely related principles of QT are:

(4): A system in a superposition of energy eigenstates differing by ΔE oscillates with frequency $= \Delta E/\hbar$.

(4*): A system in a superposition of different potential particle states with internal energies differing by ΔE oscillates with frequency $= \Delta E/\hbar$.

Oscillations of the nitrogen atom of the amonia molecule illustrate (4): oscillations of the K_S and K_L (potential) particle states associated with neutral kaon decay illustrates (4*). In the physics literature, these two kinds of cases are treated as if they exemplify one and the same quantum mechanical principle: see Feynman et al. (1965, Chs. 8–11); Frauenfelder and Henley (1974, pp. 214–221). In fact, even though closely related, (4) and (4*) are not quite the same. Whereas (4) requires that the system be in a superposition of distinct eigenstates of energy, (4*) does not. (4*) asserts that a superposition of different potential particle states, with rest masses or internal energies differing by ΔE, oscillates between these particle states even if the overall system is (nearly) in an eigenstate of energy.

Granted that (4*) is an universally valid principle, corroborated by neutral kaon decay and other phenomena, we now have the following remarkable result. Whenever inelastic collisions create two or more different potential particle states then, according to OQT, oscillations must persist, in accordance with (4*). On the other hand, as wave packets associated with these different particle states separate spatially, oscillations become physically impossible in that probability density cannot oscillate between the states. *The superposition of alternative potential particle states has become an impossible state.* OQT, implying both (4*) and the persistence of superpositions of potential particle states, leads to a contradiction. Granted that (4*) is upheld, the orthodox thesis that superpositions of different potential particle states persist must be rejected. (4*), in brief, implies (2B). This constitutes a strong argument in support of (2B). In what follows, (2B) rather than (2A) is presupposed.

7 POSSIBLE LAWS GOVERNING PROBABILISTIC EVENTS

In order to give precision to PQT (and to the nature of quantum propensitons) two laws governing probabilistic events need to be formulated. The first kind of law, like the one formulated in the last section (whether as postulate (2A) or (2B)) specifies precise necessary and sufficient quantum conditions for an instantaneous probabilistic event to occur, in terms of the state ψ of the system. The second kind of law specifies how, given that a probabilistic event occurs, the state of the system ψ determines n possible outcomes ψ_r ($r = 1\ldots n$) and assigns probabilities p_r to each ψ_r (with $\sum_{r=1}^{n} p_r = 1$).

It is assumed here that the first kind of law is of the following general form: whenever a certain kind of superposition of states $\psi = \sum_{r=1}^{n} C_r\psi_r$ comes into existence, then this superposition decays probabilistically into one or other ψ_r. Granted this, then the dynamical laws of QT, together with this first kind of law, determine the second kind of law. The form of the second law will be:

(5) Probability $[\psi(t) \rightarrow \psi_r(t)] = |C_r|^2$, where $\psi(t) = \sum_{r=1}^{n} C_r\psi_{r(t)}$, $r = 1...n$, and

$\sum_{r=1}^{n} |C_r|^2 = 1$.

It suffices, then, to consider only candidates for the first kind of law. I now consider six possibilities.

Suppose that, as a result of inelastic wave packet collision, or decay, new potential particles are created in a region of what may be called the configuration space-time of the total system—the outcome being a number of different interaction channels. This creation interaction region of configuration space-time—the region within which and throughout which creation of potential particles can occur—can be interpreted as specifying a creation region in physical space-time. The creation region in configuration space-time can be subdivided into N creation cells, each of which specifies a creation cell in physical space-time, $dr^3 \cdot dt$. For simplicity, we suppose that there are just two possible channel outcomes—for example the photon, and the e^+/e^- pair, in the $\gamma \rightarrow e^+ + e^-$ interaction discussed above. To a first approximation, the dimensions of the creation cells are given by $dt = \hbar/dE$, $dr = cdt$, where $dE = dMc^2$, and dM is the difference in total rest mass of the potential particle states. (In the case of the $\gamma \rightarrow e^+ + e^-$ interaction, dM = rest mass of the e^+/e^- pair.) We then have:

(6A): Within each cell there exists a superposition of the elastic channel state and the inelastic channel state created within the cell (e.g. a superposition of the potential photon and potential e^+/e^- pair states). Outside the cell, this superposition decays spontaneously and probabilistically into *either* the elastic channel state (the photon) *or* the inelastic channel state (the e^+/e^- pair). This is the *only* way in which the evolution of quantum states differs from that which is specified by OQT (or by OQFT). If all *inelastic* channel outcomes, created in all cells, fail to become actual, no probabilistic localization takes place, and the elastic channel outcome is a superposition of outcomes of interactions of all possible interaction cells—whether *creation* cells or not (with possible contributions from *virtual* inelastic channel states). If however one inelastic channel outcome, created within one cell, becomes actual, then there is at that instant a probabilistic change of state: all other channel outcomes, associated with all other interaction cells, are instantaneously annihilated, and the entire system emerges in a highly localized way from the one cell as the inelastic channel outcome. Thus, in terms of the $\gamma \rightarrow e^+ + e^-$ interaction, if one potential e^+/e^- pair, created within one cell, becomes actual, then there is at that instant a probabilistic change of state: the photon, and all other potential e^+/e^- pairs are instantaneously annihilated, and the actual e^+/e^- pair, and the nucleus, emerge in a highly localized way from the specific cell in question.

If the e^+/e^- pair is equally likely to be created in any one of N cells, the probability it is created in any specific cell $= 1/(2N)$, given probability $\gamma \rightarrow e^+ + e^-$ as a whole $= 1/2$.

It may be that for certain interactions, such as neutral kaon decay for example, creation interaction cells have more the form of time-like tubes rather than cells, the position probability density of the persistently interacting potential particles within each tube becoming progressively attenuated as, roughly speaking, potential particles pass through the surface of the tube with the passage of time. In this case, as created potential particles pass through the surface of the interaction tube, *either* they are annihilated, *or* they become actual, instantaneously and probabilistically, in a localized fashion. In short, the case of the interaction tube does not introduce anything essentially new that is not already found in the case of the interaction cell.

In the case of interactions that lead to more than two different channel outcomes (as in the $e^+ + H$ interaction discussed above), the spatial part of each creation cell needs to be conceived of as a sort of interaction onion, different channel outcomes becoming progressively annihilated as each spherical shell of the onion is reached, the energy difference between channels becoming progressively less and less.

Whether quantum wave packet collision theory can be modified so as to incorporate postulate (6A) is, for me at least, an open question. One elementary consideration which suggests that it may not be possible to modify quantum wave packet collision theory so as to incorporate (6A)—and so as to be compatible with experimental results—is the following.

As a result of insisting that actual particle creation takes place, to a first approximation, in some specific small region of space of size $dr = c\hbar/dE$, (6A) places a severe restriction on the form of subsequent quantum states of the created particles. It is possible that inelastic channel states, initiated in this spatially highly restricted way, cannot yield the actual results of scattering experiments successfully predicted by OQT. It must be remembered that OQT rejects (6A). Given two spatially extended wave packets colliding in such a way as to create new particles then, according to OQT, in the absence of measurement, the new particles are *not* created in some specific small region of space (but rather in a superposition of such small regions). This difference between OQT, and PQT based on (6A), may ensure that scattering experiments already performed confirm OQT but *refute* this version of PQT.

If so, (6A) can, it seems, be modified to avoid such a refutation. Let us suppose that for any given type of interaction there is a 'minimal interaction region' dR, which is the smallest spatial region to which wave packets of created actual particles can be restricted, in order that PQT yields the predictions of OQT for experiments performed on any one channel. We then have:

(6B): Wave packet collisions, or decays, which create new particles, occur as

(6A) asserts except that the outcomes of neighbouring cells persist and interfere with one another throughout minimal interaction regions, dR: for any particular dR, *either* inelastic channel outcomes emerging from dR spontaneously vanish *or* one inelastic channel becomes *actual* and all other states of the system vanish.

If dR = dr, (6B) becomes (6A). If dR = R, the entire region of interaction of the wave packets, then (6B) becomes:

(6C): The necessary and sufficient condition for superpositions of channel states to decay into one or other channel state is that the interaction responsible for creating the different channels ceases, due to spatial separation of interacting wave packets.

(6C) is simply postulate (2) of the last section reformulated as a *necessary* condition—in addition to a sufficient condition—for probabilistic actualization to occur.

Some defects of (6C) or (2), already indicated, can be overcome by reformulating the postulate as follows. Given that two long wave packets interact in a potentially inelastic way, at any given instant, the state ψ of the total system occupies three spatial regions. There is R_1, the region which contains that part of ψ which has not yet interacted (sufficiently strongly to create the inelastic outcomes); there is R_2, the region of interaction; and there is R_3, the region which contains that part of ψ that has ceased to interact. (6D) asserts that as the interaction proceeds, at some instant the total state ψ decays probabilistically into one or other of the outcome states occupying R_3. The probability P_t that this has occurred at some instant up to time t is given by $\int_{R_3} |\psi(t)|^2 dV$. We have:

(6D): $P_t = \int_{R_3} |\psi(t)|^2 dV$.

The fifth possibility to be considered is:

(6E): The necessary and sufficient condition for the superposition of different channel outcomes of an interaction confined to some region R_1 to collapse probabilistically into one or other channel state is that the interaction products begin to interact inelastically with some new system in some region R_2, there being no spatial overlap between R_1 and R_2.

There is one more postulate that must be formulated because of the key role it plays in quantum mechanical measurement—according to PQT.

(7): If a system S_0, in the form of a spatially spread out wave packet, interacts inelastically and simultaneously with N highly localized systems $S_1 \ldots S_N$ ($N \geqslant 2$), in such a way that for each interaction the conditions for a probabilistic event to occur are satisfied (depending on which of (6A) to (6E) turns out to be correct) then *either* S_0 interacts with just *one* of $S_1 \ldots S_N$ in a highly *localized* way (and there is a probabilistic collapse of the wave packet of

S_0) *or* S_0 interacts elastically with *all* $S_1 \ldots S_N$, interference may result, and there is no reduction of the wave packet. If the state of S_0 just before the interaction is ψ_{S_0}, then the probability that S_0 interacts in a localizing way with S_r so as to be localized within dV_r, is given by $|\psi_{S_0}|^2 dV_r$, assuming here that the probability of an elastic interaction with $S_1 + S_2 + \ldots S_N$ equals zero. Having been localized by the system S_r in this way, S_0 may of course go on to interact with further systems—as when electrons leave trails in cloud or bubble chambers, or in photographic plates.

It deserves to be noted that the phenomenon of coherent inelastic diffraction—of neutrons by a crystal, for example—does not refute (7). For interference to occur, it is necessary that the quantum of energy taken up by the crystal is *not* localized more or less permanently at one or other molecule of the crystal, but is in the form of an unlocalized phonon. This means that, for interference to occur, neutrons must *not* interact with one or other molecule of the crystal in a way which satisfies any of (6A) to (6E)—the conditions for a localizing probabilistic event to occur.

As we shall see, (7) enables PQT to recover the predictions of OQT concerning measurement of position—and of other observables as well. Two views may be taken concerning (7). On the one hand it may be regarded as a consequence of any of (6A) to (6E). On the other hand, (7) may be regarded as a rival to (6A) to (6E), (6F) let us say, essentially a modified form of (6E). (6F) just asserts that if S_0 interacts inelastically with $S_1 \ldots S_N$ so that each interaction is in a superposition of different channel outcomes, and there is no oscillation of these states between $S_1 \ldots S_N$, then *either* S_0 interacts inelastically in a highly localized way, with one or other of $S_1 \ldots S_N$, *or* it interacts *elastically* (or inelastically with oscillations in the energy states of $S_1 \ldots S_N$) with the entire system $S_1 + \ldots + S_N$.

Since I first argued in 1972 and 1973 that QT needs to be modified so that it contains precise, elementary quantum theoretic conditions for probabilistic events to occur, all reference to measurement, observables and classical physics being eliminated from the theory (see Maxwell 1972b, 1976a, Jammer 1974, pp. 520–1), a few people have, independently, sought to modify QT in this way by means of postulates different from those considered above. There is the postulate of Bedford and Wang (1975, 1977) which asserts that if two systems A and B interact briefly to form the superposition: $c_1|A_1\rangle|B_1\rangle + c_2|A_2\rangle|B_2\rangle$ with $\Delta E = |E_{A_1} - E_{A_2}| = |E_{B_1} - E_{B_2}|$, where E_{A_1}, etc. are the energies of the systems, then the superposition collapses spontaneously into *either* $|A_1\rangle|B_1\rangle$ or $|A_2\rangle|B_2\rangle$ with probabilities $|c_1|^2$ and $|c_2|^2$ respectively. Following up the idea of Bedford and Wang, there is Bussey's proposal (1984, 1986) that elastic collision leads *either* to collision *or* to non-interaction—an idea subsequently extended to include decay (Bussey 1987). There is the proposal of Ghirardi et al. (1986) according to which wave packets spontaneously localize in such a way that this occurs infrequently for the isolated particle but frequently for many particle systems. Finally, there is Penrose's suggestion (1985) that it is *gravity* which induces superpositions to decay into one or other state: see also Károlyházy (1966).

I have now four comments to make about the six possible postulates I have put forward above, each a slightly different version of the basic idea that it is particle creation which leads to probabilistic wave packet collapse.

1. These postulates may be regarded as distinct dynamic superselection principles, in that each postulate denies the existence (or persistence) of superpositions asserted to exist by OQT. This is somewhat analogous in form to generally accepted superselection principles which deny the possibility of superpositions of states of angular momenta that are an integer and half-integer multiple of $\hbar$, or of states of different total charge (Wick et al., 1952).

2. Any version of PQT must satisfy what may be called a principle of 'local-global' phase invariance. If two systems, A and B, have not yet interacted, then the phase of the state of A may be changed globally without this affecting the state of A + B. In this way, global phase invariance can be applied locally, to a part of A + B. Both OQT and PQT comply with this application of 'local-global' phase invariance. In addition PQT (but not OQT) asserts that if A and B interact and separate spatially and A interacts with C so that A + C undergoes a probabilistic transition at time t, then after t, the phase of the state of A + C can be arbitrarily changed globally, without this affecting the state of (A + C) + B.

This principle of local-global phase invariance provides a basis for counting propensitons (not at all the same as counting 'particles'). Given a composite system S, if the state of S can be factorized into no more than n states $\psi_1 \ldots \psi_n$, such that local-global phase invariance can be applied to each ψ_r at time t then, at this time, S is made up of just n distinct propensitons.

3. A decisive feature of (6A) to (6F) is that they each assert that probabilistic events occur whenever energy in the form of rest mass is converted into other forms of energy, or *vice versa*. This may seem to be a not altogether implausible postulate when it is put into historical context. From its inception, QT was developed in response to problems concerning the interaction of radiation and matter. This is true of Planck's original quantum theory of black-body radiation; it is true of Einstein's photon hypothesis of 1905, in terms of which hitherto puzzling aspects of the photoelectric effect were explained; it is true of Bohr's 1913 quantum theory of the atom, which explained the manner in which atoms absorb and emit radiation (in accordance ith the Balmer series); and it is true of subsequent contributions to the development of QT made by Heisenberg, Schrödinger, Dirac and others (Jammer, 1966). If QT is understood in this way, as concerned quite fundamentally, and from the outset, to solve problems concerning the interaction between matter and radiation, then

the postulate that probabilistic events occur when rest mass is converted into or created out of radiant (or other) forms of energy, can be seen to be a rather natural development of QT, in no way arbitrary or *ad hoc.*

4. One feature of PQT may be held to be problematic. PQT postulates *instantaneous* collapse of wave packets, as a real physical phenomenon. (The collapse is instantaneous in the centre of mass frame of the system that becomes 'actualized' with the occurrence of the probabilistic event.) Such instantaneous collapse conflicts with special relativity.

This feature of PQT is not however as damaging as it may at first sight appear to be. Five points deserve to be made.

First, OQT (in its relativistic versions) evades this conflict with special relativity—insofar as it does—only by being extremely *imprecise* as to what does occur when measurements are made. It is this lack of precision which makes it possible to hold, within the framework of the orthodox viewpoint, that the collapse of the wave packet, associated with measurement, is not a real physical process, and therefore not a process whose instantaneous occurrence can conflict with special relativity (SR). PQT, we may say, as a result of being much more precise than OQT, makes explicit a non-relativistic feature of quantum theory that is only implicit in the vaguer, more ambiguous OQT. It deserves to be noted that attempts that have been made to provide a more precise, Lorentz invariant theory of wave packet collapse within the framework of OQT have not met with success (Aharonov and Albert, 1981).

Second, granted that wave packet collapse is a real physical phenomenon, recent experimental results of Aspect et al. (1982) reveal that this phenomenon occurs in a faster-than-light way. To this extent, the non-relativistic collapse of the wave packet, predicted by PQT, has been experimentally corroborated. (Aspect et al., however, interpret their result differently, as confirming the anti-realist feature of OQT.)

Third, I have shown elsewhere (Maxwell, 1985) that probabilism in general is incompatible with SR. But if this is the case, then it can be no defect whatsoever of probabilistic PQT that it is incompatible with SR. Once again, we see that OQT only evades this incompatibility because of its ambiguity concerning the crucial issue of whether or not the quantum domain is fundamentally probabilistic in character.

Fourth, PQT is incompatible with SR in only an extremely subtle way. It is only the manner in which physical potentialities evaporate (as one may put it) with the occurrence of probabilistic events, that contradicts SR. The dynamical evolution of quantum systems is otherwise, according to (relativistic) PQT, fully Lorentz invariant. If SR is interpreted phenomenalistically, as prohibiting instantaneous *signals*, then SR and PQT become compatible insofar as instantaneous wave packet collapse cannot be used to transmit signals.

Fifth, the subtle way in which PQT conflicts with SR appears to be related to the dramatic way in which QT more generally conflicts with general relativity (GR) in connection with Hawking radiation of black holes. Both kinds of conflict arise in connection with the conversion of rest mass into radiant energy.

GR implies that a non-rotating black hole cannot lose mass. Hawking (1974) showed that QT implies that at the event horizon of a black hole, the gravitational field causes photon pair creation in such a way that one photon of each pair escapes to infinity, thereby decreasing the rest mass of the black hole. This quantum process leads to the eventual 'evaporation' of the black hole, in sharp conflict with GR.

Once it is conceded that the conversion of rest mass into radiant energy can (in certain circumstances) lead QT to contradict GR, it is perhaps not so very implausible to suppose that the same physical process can lead QT to contradict SR (in a fashion which experiment corroborates and does not refute). That PQT does subtly contradict SR in this way may well indicate that PQT contains important clues as to how QT and GR are to be unified.

8 EXPERIMENTAL SUCCESS OF OQT ENSURES EXPERIMENTAL SUCCESS OF PQT

In what follows, PQT is to be understood as the dynamical equations of QT interpreted and restricted in scope by postulate (5) and one or other of (6A) to (6F), understood as different more precise versions of (2B).

Putting on one side for the moment the few special conceivable experiments for which OQT and PQT give slightly different predictions, I now show that PQT recaptures all the experimental success of OQT, even though PQT (like Newtonian mechanics and Maxwellian electrodynamics) makes no reference to observables or measurement in its basic postulates.

It is, to begin with, not hard to see how PQT can reproduce the experimental predictions of OQT as far as *position* measurements are concerned at least. A quantum position measurement invariably involves the detection of a quantum object by means of the occurrence of an inelastic collision, which creates a new particle state capable of providing a permanent, detectable record of what has occurred. Thus, for example, an atom is ionized, creating a detectable dot in a cloud or bubble chamber; a silver bromide molecule is dissociated, creating a detectable dot of silver in a photographic emulsion after development. Analogous remarks hold for scintillation and geiger counters. All such processes, associated with position measurements, with the detection of quantum objects, are precisely of the kind that are, according to PQT, associated with the probabilistic actualization of propensities.

It becomes clear that PQT is able to predict the results of measuring all other observables besides position once one realizes that measurements of all other observables invariably involve position measurements, the detection of quantum objects, of the kind just indicated. It is of decisive importance, here, to distinguish *preparation* and *measurement*. Preparation arranges for quantum objects to have some definite quantum state in some specific spatial region: quantum objects are not detected, and no probabilistic events need occur. Measurement, on the other hand, invariably involves the detection of quantum objects—and thus processes of the kind just indicated. A measurement of spin, momentum or energy typically involves first, a preparation procedure to ensure that eigenstates of the observable can be associated with distinct spatial regions, and then, second, a position measurement to detect the quantum object in one or other region. PQT, in predicting the outcome of inelastic collisions that create new particle, stationary states, is thus able to predict the results of measuring *all* quantum observables (via the detection of quantum objects, the measurement of position). PQT, indeed, does much better justice to the realities of quantum measurement than OQT (yet another indication of its superiority). Whereas the formalism of OQT suggests that all observables are on an equal footing, PQT makes it quite clear that this is not the case at all.

Finally, we have every reason to hold that PQT recaptures in detail *all* the experimental success of OQT, even though PQT treats measurement in a purely quantum mechanical way, and makes no use of classical physics for a specification of physical states of measuring instruments, in the manner of OQT. Because OQT and PQT share all the same dynamical equations, *the very empirical success of OQT itself ensures this result.* If physical processes associated with quantum measurements cannot be accurately predicted (in principle at least) by quantum scattering theory, as developed in the literature, but reinterpreted in terms of PQT, then this would imply that OQT itself is empirically defective.

Essentially only two reasons exist for holding that orthodox quantum collision theory does not apply to measurement. First, probabilistic events that involve wave packet collapse are it seems to be associated with measurement: no such events are to be associated with quantum wave packed collisions, according to orthodox quantum collision theory. Second, OQT is interpreted to be about the results of performing measurements on quantum systems: hence OQT cannot, without incoherence, be applied to the process of measurement itself. PQT solves both these problems of principle. First, according to PQT, inelastic wave packet collisions do indeed quite generally involve probabilistic events and wave packet collapses of precisely the kind to be associated with measurement. Second, PQT reinterprets the ψ-function to contain probabilistic information about the outcome of inelastic wave packet collisions: all measurements are just special cases of such inelastic wave packet collisions. Thus the decisive objections to applying *orthodox* collision theory to measurement do not arise when *propensity* collision theory is applied to measurement. In moving from OQT to PQT, (i) quantum wave packet collision theory, and (ii) the theory and role of measurement in quantum theory, are *both* adjusted, so that the former becomes straightforwardly applicable to the latter. Formidable technical problems may well arise, having to do with solving Schrödinger's equation for many interacting systems; but problems of principle do not arise. (PQT can of course avail itself of the orthodox account of measurement as a matter of practical convenience, in order to simplify calculations: the vital point is that PQT, unlike OQT, does not need to do this as a matter of conceptual necessity.)

9 CRUCIAL EXPERIMENTS

The six versions of PQT put forward here are by no means equally easy to distinguish from OQT on experimental grounds. The version that departs most radically from OQT on experimental grounds is PQT based on (6A). It may well be that existing inelastic wave packet scattering data already refute (6A).

At the opposite extreme, PQT based on (6F) may well be in practice (even if not in principle) indistinguishable experimentally from OQT.

Two kinds of crucial experiment are of decisive importance. The first has to do with potential particle interference, the second with decaying systems—with the rates at which such systems decay, and possible deviations from exponential rates of decay.

The first kind of experiment can be illustrated by the following thought experiment. A particle, about to decay into two equal fragments, moves towards a three-slitted screen. The particle has a certain propensity to decay before encountering the screen, at region A, and a certain propensity to decay after passing through the screen, at region B. According to OQT, the particle passes through the slits of the screen as a *superposition* of the undecayed state (which passes through the central slit) and the decayed state (which passes through the two outer slits in the form of two decay fragments). PQT based on (6A) asserts that this superposition does not exist if time of flight from A to B $\Delta t > \hbar/\Delta E$, since in this case the superposition of undecayed and decayed states jumps probabilistically into one or other state. If the half life of the decay is comparable to the time of flight from A to B, then PQT based on (6D) predicts that the superposition does not exist in half of an ensemble of similarly prepared systems. Let subsequent position measurements of decay fragments (by means of a photographic film) be such that decay at A or B are indistinguishable. In this case interference is possible, since as the relative distance between the film and A and B vary, so wave packets of decay fragments interfere constructively or destructively, in this way creating interference bands on the film when the experiment is repeated many times. OQT predicts that such interference bands exist whereas versions of PQT predict that they do not or only exist weakly.

Another version of this first kind of experiment would involve arranging for a photon to encounter a nucleus in such a way that there is a probability $= 1/2$ that the photon persists, probability $= 1/2$ that an electron/positron pair is created. The experimental arrangement is such that these two channels are then reflected back to the region of the interaction in such a way that interference effects arise if *both* channels exist. In such circumstances OQT predicts interference whereas appropriate versions of PQT predict no (or weak) interference.

A second kind of crucial experiment exploits two different ways in which, according to OQT, any quasi-stable system can decay. Type 1 decay occurs when the conditions are such that nothing exists to subject the system to measurement: in this case, according to OQT, the system persists as a superposition of the undecayed and decayed states until a measurement is eventually performed. Type 2 decay occurs when measurements capable of detecting whether or not the system has decayed, are performed at intervals Δt; in this case, according to OQT, the system returns to its initial undecayed state every Δt until the system is eventually detected to have decayed.

OQT predicts that type 1 and 2 decays proceed at very nearly the same rates. But not quite. For times considerably longer than Δt, type 2 decay is invariably exponential (Maxwell, 1973). Type 1 decay must however, according to OQT, depart slightly from the exponential for long times (Fonda et al., 1978). This difference makes the second kind of crucial experiment possible. Leaving (6C) on one side, the remaining five versions of PQT predict that, in appropriate circumstances, systems decay in a type 2 way when OQT predicts type 1 decay. This difference arises whenever conditions are such that probabilistic events occur, according to the relevant version of PQT, even though no measurement is performed. In such circumstances, for long times, the relevant version of PQT predicts exponential decay, whereas OQT predicts slight departure from exponential decay. Accurate determination of whether or not decay is exponential for long times in various physical conditions can therefore decide between OQT and at least five versions of PQT. Attempts have been made to verify non-exponential decay, but the experimental results so far appear to be inconclusive: see Butt and Wilson (1972).

OQT predicts also that type 1 decay is non-exponential for short times (Fonda et al., 1978). This carries with it the implication that rapid repeated measurement can effect the rate of decay. There is here the possibility of another kind of experiment capable of distinguishing between OQT and versions of PQT: for a discussion of the theoretical and experimental issues involved here, see Fonda et al. (1978) and Ghirardi et al. (1979).

It deserves to be noted that OQT already faces one serious problem in connection with decay: OQT implies that a continuously observed system cannot decay at all! For a discussion of this problem, and how OQT may be modified so as to overcome it, see Sudbery (1984).

10 WHY HAS QUANTUM PROPENSITON THEORY BEEN OVERLOOKED?

Whereas OQT fails to solve the problem of what sort of entities quantum objects can be in virtue of their ostensibly contradictory wave-like and particle-like properties, PQT provides a precise, consistent solution to the problem: quantum objects are varieties of a distinctively quantum mechanical kind of *discrete propensiton.* Granted that the quantum world is fundamentally probabilistic (a reasonable hypothesis) this characterization of quantum objects as discrete propensitons arises in wholly natural way. Whereas OQT is grossly *ad hoc*, vague, ambiguous and non-explanatory, PQT is, in comparison, non-*ad hoc*, powerfully explanatory and precise (even granted the uncertainty as to which of (6A) to (6F) should be adopted). PQT is free of the seven very grave difficulties that plague OQT. Furthermore, crucial experiments appear to be possible capable of deciding between OQT and versions of PQT. The case for taking PQT sufficiently seriously to develop it further theoretically, and put it to the test experimentally, would seem to be overwhelming. Why, then, has this propensiton approach been ignored for the last sixty years, despite the flood of literature on problems concerning the interpretation of QT?

A part of the answer to this question must be that the propensiton approach advocated here has not been entirely overlooked. Thus de Broglie, Vigier, Landé and Popper have all sought to interpret QT in ways which combine realism and probabilism—the key idea of the propensiton approach. Unfortunately these thinkers have persisted in the attempt to understand quantum objects in terms of classical objects and properties, thus violating a key tenet of this paper—assumption (I) of section 3. Thus de Broglie's theory of the double solution conceives of quantum objects as *particles* guided by pilot *waves* (de Broglie, 1964). Landé (1965) holds quantum objects to be *particles.* And so does Popper, despite having done more than anyone to introduce the propensity idea into quantum physics. This is in part because, for Popper, propensities are *relational* properties rather than intrinsic and fundamental properties of quantum objects *per se.* As he has put it '*Propensities are properties of neither particles nor photons nor electrons nor pennies.* They are *properties of the repeatable experimental arrangement.*' (Popper, 1967). The result, as Feyerabend (1968) has argued, is that Popper ends up, despite his intentions to the contrary, defending a position not so very different from Bohr's.

Scattered throughout the literature there are remarks—by Born, Heisenberg, Dirac, Eddington, Jeans, Landé (see Popper, 1982, pp. 130–35) and Margenau (1954)—that can be regarded as anticipating the propensity viewpoint proposed here. These remarks all fail, however, to take seriously the need to specify micro realistic conditions for probabilistic events to occur. They thus indicate variants of OQT, rather than PQT.

Ironically enough, elsewhere in the literature, in connection with decay, a number of authors express the view that measurement-type interactions occur even when only purely quantum, micro phenomena are involved: see Fonda et al. (1978, p. 623). In a recent paper Sudbery remarks that it is 'universally' assumed 'in textbooks and research papers alike' that decaying systems decay at some definite time even when not subject to measurement (Sudbery, 1984, p. 529). In other words, the key physical postulate of PQT—that inelastic interactions involve probabilistic transitions—is widely taken for granted by physicists as far as decay processes are concerned, even though this clashes with OQT. One is almost inclined to say that the theory that physicists employ in practice is PQT obscured by the rhetoric of OQT.

All this only deepens the mystery as to why PQT was not explicitly advocated long ago, soon after Schrödinger's epoch making work. The solution to the mystery can, in outline, be put like this.

If, around 1926, the physics community had conceived of physics in terms of *conjectural elemental essentialism*, and had fully appreciated the point that there is an intimate link between the nature of physical objects and properties on the one hand, and the nature of dynamical laws on the other hand (assumption (I) of section 3), then PQT would almost certainly have been put forward soon after Schrödinger's work—perhaps by Schrödinger himself. This would have occurred as soon as the fundamentally probabilistic character of the quantum world had been recognized. Unfortunately, very different instrumentalist and positivist philosophies of physics prevailed at the time. Bad philosophy, in short, prevented physicists from developing PQT soon after 1926; subsequently, orthodoxy hardened into an almost uncriticizable dogma.

In a little more detail, the failure of the physics community to consider PQT during the years 1926–1935 can be explained in the following way. In order to entertain PQT as a viable possibility, it is absolutely essential to distinguish sharply between abandoning *determinism* and abandoning *micro realism* as one moves from the classical to the quantum domain. It is only if we decisively distinguish these two issues that we are able to consider *abandoning* determinism but *retaining* micro realism—which is what PQT presupposes. Quite disastrously, everyone during the years 1926–1935 conflated these two distinct issues. On the one hand, Bohr, Heisenberg and Born argued for the abandonment of determinism-and-micro-realism; on the other hand Einstein and Schrödinger argued for the retention of determinism-and-micro-realism (Jammer, 1974). Because of the universal conflation of these two quite distinct issues, no one was able to argue for the abandonment of determinism and the retention of micro realism—for the development of probabilistic micro realism, in other words. Gradually around 1934/35 Einstein and Popper did discover how to distinguish these two very different issues. But by then it was too late: the Copenhagen position had become an unassailable dogma.

A part of the reason for the general failure to distinguish 'determinism versus probabilism' from 'micro realism versus instrumentalism' was this. Everyone at the time tended unthinkingly to take subjectivist interpretations of probability for granted. Both the Bohr camp and the Einstein camp tended to assume that a probabilistic physical theory could not be about *reality*, but could only be about *our incomplete knowledge of reality*. Thus abandonment of determinism seemed to everyone to carry with it the implication that micro realism must be abandoned as well. Einstein and Schrödinger, reluctant to abandon realism, felt forced to hold on to determinism as well; Bohr and Heisenberg, seeing forcefully the need to abandon determinism, felt compelled to abandon realism as well. Thus no one was able to envisage the obvious option: probabilistic micro realism, or the *discrete propensiton*!

There is, however, a deeper reason for the general failure of the physics community to consider this possibility of a new kind of probabilistic physical entity. Again and again in the history of physics we encounter the failure of physicists to conceive of new physical objects and properties appropriate to new physical theories.

Before Newton, the new natural philosophy had been closely associated with the attempt to understand Nature in terms of corpuscles interacting by contact (Dijksterhuis, 1961; Burtt, 1932). A physical theory, in order to be an acceptable and comprehensible contribution to physics, had to be capable of being interpreted in terms of this corpuscular idea. Thus, when Newton's law of gravitation appeared, natural philosophers did not set out to invent a new kind of object, with new kinds of physical properties, appropriate to the new law. Quite to the contrary, many of Newton's contemporaries in effect took it for granted that the law could only be acceptable if explicable in corpuscular terms. Insofar as they judged this to be impossible, they found Newton's law to be incomprehensible, or without explanatory power. Thus Huygens, in a letter to Leibniz, writes: 'Concerning the Cause of the flux given by M. Newton, I am by no means satisfied [by it], nor by all the other Theories that he builds upon his Principle of Attraction, which to me seems absurd . . . I have often wondered how he could have given himself all the trouble of making such a number of investigations and difficult calculations that have no other foundation than this very principle' (Koyré, 1965, pp. 117–8). In a sense, Newton himself agreed, as is indicated by his remark: 'That gravity should be innate, inherent, and essential to matter, so that one body may act upon another, at a distance through a vacuum, without the mediation of anything else . . . is to me so great an absurdity, that I believe no man who has in philosophical matters a competent faculty of thinking can ever fall into it' (Burtt, 1932, pp. 265–6). The manifest impossibility of interpreting the law of gravitation in corpuscular terms led Newton to adopt an instrumentalist or positivist interpretation of the law, according to which the law merely describes how objects move, without specifying the cause of such motions, or providing any kind of explanation for the motions. In other words, the failure of an utterly misguided attempt at a realist or essentialist interpretation of the law, led straight to instrumentalism and positivism.

Subsequently, however, Boscovich and others were able to conceive of an object with properties rather more appropriate to Newtonian theory—namely, the point-particle, possessing inertial mass, and being surrounded by a spherically symmetrical, centrally directed force-field, varying continuously with distance, but otherwise invariant. This genuinely Newtonian object can be regarded as a generalization of the pre-Newtonian solid corpuscle (retained by Newton himself). It accords beautifully with Newton's law of gravitation, having been designed in part just for that purpose.

This pattern of confusion arises again in the late nineteenth and early twentieth century, in connection with Maxwell's new theory of electromagnetism. Instead of trying to invent a new kind of object—the electromagnetic field—appropriate to Maxwell's equations of electromagnetism, Maxwell himself, Kelvin and others devoted endless effort to the attempt to understand the new theory in terms of old, pre-Maxwellian objects—namely, the material aether, in turn to be understood, presumably, in terms of Boscovichian point-atoms, or even pre-Boscovichian corpuscles. The failure—indeed the frequent absurdity—of these (utterly misguided) attempts at a realist or essentialist interpretation of electromagnetism led many to adopt instrumentalist and positivist viewpoints.

It was only when special relativity became accepted that physicists began to appreciate what Faraday had seen all along—namely that the electromagnetic field is a new kind of object with new properties (a generalization of the Boscovichian force-field), which does not need to be understood in terms of old, inappropriate particle-like objects and properties. Indeed, instead of trying to understand the electromagnetic field in terms of some matter-like substance, one should rather try to understand matter in terms of the field.

The lesson from history is I hope clear. The same pattern of confusion arises in connection with quantum theory. Instead of trying to invent a new kind of physical object (the discrete propensiton!) appropriate to the character of the new theory, physicists rather persisted in the attempt to interpret the new theory in terms of old, inappropriate, deterministic objects—the point-particle and the field—lapsing into instrumentalism and positivism when this utterly misguided attempt failed.

What is needed, in order to avoid further repetitions of this pattern of confusion is the general adoption of what I have called *conjectural elemental essentialism*, which carries with it the implication that to talk of theoretical objects and their properties *is* to talk of the dynamical laws that the objects obey (a change in our ideas of the latter thus automatically necessitating a change in our ideas of the former). In this way we may in future avoid what is so striking a feature of the history of theoretical physics: great imaginativeness and inventiveness concerning equations and theories, combined with immense conservatism and stupidity concerning physical *objects* and their *properties*. (More fundamentally, we need the adoption of what I have called elsewhere *aim oriented empiricism*, to be implemented within the general framework of the *philosophy of wisdom*: see Maxwell, 1984.)

It deserves to be noted that the one great exception to the above pattern of confusion is Einstein's invention of general relativity: here, from the outset, there is harmony and accord between the new theory, and the new object the theory is taken to describe—curved Riemannian space-time. (But this exception is hardly surprising, since Einstein came close, instinctively, to pursuing natural philosophy in accordance with aim oriented empiricism and the philosophy of wisdom.)

II CONCLUSION

Two and a half thousand years ago the presocratic philosophers first tried to explain and understand the world in terms of some kind of elemental stuff, invariant through all change and diversity. For Anaximander, everything was diverse, lawful manifestations of the *apeiron* or boundless; for Heraclitus everything was lawfully regulated fire or process; for Democritus everything was the outcome of intrinsically unchanging atoms in relative motion in the void. After Plato and Aristotle, the astonishing endeavour of the presocratics fell into decay, and was abandoned. It was resurrected in the seventeenth century by those who created modern science: Galileo, Kepler, Descartes, Huygens, Boyle, Newton. From that time until the present, the basic idea of the presocratics has been the fundamental guiding idea of physical science: to explain and understand change and diversity in terms of that which is elemental and invariant. But it is above all in the twentieth century, and especially in the last decade or so, that giant strides have been made towards fulfilling the presocratic vision. Grand unified theories, quantum gravity and superstring theory are, for the first time ever, groping attempts at a unified scientific theory of everything. And here we come to the paradox. For just when the two and a half thousand year old research programme of the presocratics seems close to completion, the physics community has lost interest. The orthodox version of QT is, as we have seen, hopelessly inadequate from the standpoint of enabling us to explain and understand complex macro phenomena in terms of elemental micro phenomena. Insofar as the physics community, by and large, accepts OQT as unproblematic, *and does not actively seek a better alternative*, it has lost interest in the noble quest of the presocratics. As Einstein realized with anguish, the soul of natural philosophy has been betrayed. The quest to understand has disintegrated into expert puzzle solving, the hunt for Nobel prizes and defence contracts.

What I have tried to do in this paper is point to an alternative approach to understanding the quantum world which keeps alive, and does not betray, the presocratic endeavour. My hope is that others, better qualified than myself, will take up and develop the basic idea, so that it may be formulated with precision and put to the test of experiment.

12 APPENDIX

Our inability to conceive of quantum objects in classical terms—as classical particles, waves or fields—has led many to conclude that there is something inherently inexplicable about the nature of quantum objects which must prevent us from developing a fully realistic version of QT with its own consistent, self-contained quantum ontology. A central claim of this paper is that precisely the reverse of this is true. In order for quantum objects to be fully explicable and understandable it is absolutely essential that they differ radically from all classical objects—granted merely that the quantum world is fundamentally probabilistic in character. It is being understandable in classical terms—as classical particles or waves—which would render probabilistic quantum objects utterly inexplicable and incomprehensible!

Quantum objects are, I have argued, unproblematic varieties of the *discrete propensiton.* In order for this solution to the wave/particle problem to be satisfactory, I need to show that the *discrete propensiton* as I have characterized it in section 3 arises in an entirely natural, non-arbitrary way as we generalize the notion of physical object and property in moving from determinism to probabilism. I begin with a characterization of deterministic properties and objects in the following eight points (see also Maxwell 1968, 1976a, 1982, 1985).

(1) Any classical, deterministic physical property—such as rigidity, elasticity, gravitational charge, electric charge, inflammability or opacity—determines how something *changes* (or resists change) in certain circumstances. Thus, if an object is inflammable then, of necessity, it bursts into flames when the relevant physical conditions are satisfied (exposure to a naked flame, etc.). If it does not burst into flames in these circumstances then, *ipso facto,* it is not inflammable. Again, if two objects possess the property of Newtonian gravitational charge, g_1 and g_2, (equal to inertial masses m_1 and m_2), then of necessity, in the absence of other forces, the two objects accelerate towards each other in accordance with $F = Gg_1g_2/d^2$ and $F = ma$. If they do not, then *ipso facto,* they do not possess Newtonian gravitational charge. Yet again, the classical electromagnetic field can be regarded as having, at any given point and instant, a value of electric and magnetic field intensity, which determines the way a test particle would accelerate were it to occupy the given point at the given time. In this way, the physical properties of the electromagnetic field determine necessarily how charged test particles change their state of motion.

(2) Properties of the kind indicated determine how objects change (in

appropriate circumstances) with *necessity*, as long as the relevant property is possessed by the object in question. David Hume (1959) is wrong. It *is* possible for there to be necessary connections between successive states of affairs (Maxwell, 1968). All that we require is a state of affairs made up of objects with invariant, necessitating, deterministic properties (of the kind just indicated). We cannot *know* (for certain) that necessary connections between successive states of affairs really exist, just because we can never *know* that the relevant necessitating properties really exist. But equally, we cannot *know* that necessary connections, and necessitating properties, do not exist.

(3) Classical theories, when understood in the usual way, do not attribute necessitating properties to physical objects. Rather they assert that certain physical objects obey *contingent regularities.* Thus Newton's law of gravitation, as ordinarily understood, does not attribute the necessitating property of gravitational charge to particles; rather it asserts that particles obey the law-like but *contingent* regularity $F = Gm_1m_2/d^2$ (and $F = ma$.). Classical theories can however be reinterpreted so that they do attribute necessitating properties to physical objects. Thus Newton's law of gravitation can be reinterpreted *essentialistically*, to assert: 'All particles have (Newtonian) gravitational charge $g = m$ (where m is the inertial mass of the particle)'. Here, it is built into the *meaning* of 'Newtonian gravitational charge g' that if bodies possess this property then, of necessity, they obey Newton's law $F = Gm_1m_2/d^2$ (and $F = ma$.). The outcome of interpreting Newtonian theory in this way is that the law becomes an analytic statement—a statement true in virtue of the meaning of the constituent terms. And quite generally, interpreting a classical theory *essentialistically*, so that it can be used to attribute necessitating properties to physical objects, renders all the law-like statements of the theory *analytic statements.* But no loss of empirical content is involved in interpreting physical theories in this way—a crucial point to appreciate. The whole empirical content of an essentialistically interpreted theory is contained in the assertion that all physical objects (of the specified type) do in fact possess the relevant physical properties, in virtue of which, according to the theory, the laws are of necessity obeyed. Thus the whole empirical content of Newton's theory of gravitation, essentialistically interpreted, is concentrated in the statement that all objects possess Newtonian gravitational charge, equal in value to inertial mass. It is *this* statement that is refuted with the discovery of objects moving under the influence of gravitation in a way which violates Newton's law. (In a sense, general relativity, if true, does not refute the essentialistic version of Newton's law of gravitation: rather, it shows that strictly nothing exists to which Newton's law is applicable.)

(4) Essentialistically interpreted physical theories provide an *explanation* for the existence of the lawful regularities they postulate. The regularities exist because physical properties exist which make such regularities inevitable. If essentialistic Newtonian theory is true, then all objects really do possess

Newtonian gravitational charge, and it is inevitable, necessary, that all objects obey Newton's law of gravitation. By contrast, non-essentialistic theories can provide no explanation as to why postulated lawful regularities are observed. Theories so interpreted are incapable of postulating the *existence of anything responsible for* lawful regularities. As restricted regularities are derived from more and more comprehensive or universal ones, so the mystery as to why such regularities should obtain in nature at all can only deepen.

(The point made here—that essentialistic theories have greater explanatory power than non-essentialistic theories—is of course wholly in addition to, and independent of, the point made earlier, that conceptually coherent, *non-ad hoc* theories are, other things being equal, more explanatory than incoherent, *ad hoc* theories, such as OQT.)

(5) The greater explanatory power of essentialistic theories (of the kind just indicated) makes it desirable to commit theoretical physics as a whole to the aim: to discover those few basic invariant essentialistic properties (possessed by a few different sorts of basic physical entities) which we conjecture to exist and to be responsible for all change and diversity in the world. The view that physics ought to have this aim of discovering a true, unified, comprehensive, *essentialistic* physical theory, unifying all forces and applicable to all phenomena, may be called *conjectural elemental essentialism*. This paper in effect seeks to indicate one way in which OQT can be modified so that it accords rather better with conjectural elemental essentialism.

(6) Classical deterministic physical properties have associated with them *two kinds of change*. First, there is the change which occurs when the property is 'actualized': the inflammable wood burns, the elastic ball bounces, the gravitationally charged objects accelerate towards each other. Second, values of the property may themselves change: the inflammable wood may gradually become less inflammable (as it becomes wet), the ball may become less elastic. Newtonian theory postulates that gravitational charge is *invariant*: and it is of course the task of theoretical physics to discover properties that are invariant through as wide a range of changes as possible. There is always the possibility, however, that gravitational charge changes (as indeed it does given relativity).

(7) Classical deterministic physical properties are of two kinds. The first kind are properties which are actualized discontinuously or *discretely*, when special physical conditions arise, such as when the inflammable object is exposed to a naked flame, or elastic objects collide. The second kind are properties which are actualized *continuously*, as in the case of Newtonian gravitational charge (granted that there is more than one object in the universe).

(8) The nature or character of any classical deterministic *object* is entirely given or determined by the nature of the *properties* possessed by the object. There is nothing to the object over and above the properties it possesses. The nature of the Newtonian point-particle or Maxwellian electromagnetic field is

entirely specified by the physical properties these objects possess—and hence by the dynamical laws these objects obey.

All these points concerning classical deterministic properties and objects carry over to fundamentally probabilistic properties and objects, to *propensities* and *propensitons*. The *only* difference is that when a deterministic property is actualized there is just one possible outcome, whereas when a propensity is actualized there are n possible outcomes. A specific *value* of a propensity P specifies n probabilities $p_1 \ldots p_n$, and attributes a definite probability p_r to each possible outcome O_r, with $\sum_{r=1}^{n} p_r = 1$.

Just as classical, deterministic properties determine how things change (point (1)), so too propensities determine how things change in certain circumstances, but probabilistically and not deterministically. Again, just as there can be necessary causal connections between successive states of affairs, given deterministic (essentialistic) properties (point (2)), so too there can be *probabilistic* necessary causal connections between successive states of affairs given that propensities and propensitons exist. Yet again, just as classical deterministic properties can change in two kinds of ways (point (6)), so too propensities (and propensitons) can change in two kinds of ways: the propensity can be actualized with the occurrence of a probabilistic event, and the value of the propensity itself can change. (In the case of a die, this second kind of change would take place if the die, itself a magnet, moves through a varying magnetic field.)

Finally, and most important, just as classical deterministic properties are of two kinds (point (7)), so too are propensities (and propensitons). On the one hand, corresponding to inflammability or rigidity, there are discrete propensities (and discrete propensitons), actualized probabilistically at *discrete* times, when appropriate physical (propensiton) conditions arise. On the other hand, corresponding to Newtonian gravitational charge, there are continuous propensities (and propensitons) actualized continuously in time.

Corresponding to these two kinds of propensities and propensitons (derived from the two kinds of classical properties and objects), there are two kinds of fundamentally probabilistic dynamical theories, namely *discretely probabilistic* theories (which assert that values of propensities evolve deterministically until the physical conditions arise for a probabilistic actualization to occur, when an instantaneous probabilistic event occurs, determined probabilistically by the values of the relevant propensities at that instant), and *continuously probabilistic* theories (which assert that probabilistic events occur continuously in time).

The vital point to appreciate is that the three kinds of dynamic theories that have been considered—deterministic, discretely probabilistic and continuously probabilistic—deserve to be regarded as equally viable from an *a priori* standpoint. Equally, the three kinds of *objects* that correspond to these three kinds of theories—deterministic object, discrete propensiton, and continuous propensiton—deserve to be regarded as equally intelligible or understandable, even if we may be more familiar with (approximately) deterministic objects. There is nothing intrinsically *ad hoc* or inexplicable about the instantaneous probabilistic transitions of discretely probabilistic theories (whether these arise in connection with QT or some other theory): such transitions are an inherent feature of this kind of theory. Furthermore, to demand that such instantaneous probabilistic transitions (e.g. those associated with PQT) must be explained in terms of some continuous evolution or theory is just to refuse to recognize the discrete propensiton, and the discretely probabilistic theory, as viable possibilities.

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