I - Introduction

The usual highly successful interpretation of quantum theory divides the world into two parts, the observer, and the external part. It assigns state functions, \( \psi \), which are elements of a Hilbert space, to the external part, and asserts that \( \psi \) gives information only concerning the probabilities of results of various observations which can be made upon the external system by the observer. It further asserts that \( \psi \) is a complete description of the external system, in the sense that the information it gives is maximal. On the other hand, it asserts that, so long as the system remains isolated from the observer, \( \psi \) changes in a causal manner. Thus there are two fundamentally different ways in which the state function can change:

**Process 1**: The discontinuous change brought about by the observation of a quantity with eigenvalues \( \lambda_1, \lambda_2, \ldots \) in which the state \( \psi \) will be changed to the state \( \psi_1 \) with probability \( |\langle \psi_1 | \psi \rangle|^2 \).

**Process 2**: The continuous, deterministic change of state of the (isolated) system with time according to a wave equation, \( \frac{\partial \psi}{\partial t} = A \psi \), where \( A \) is a linear operator.

However, this scheme encounters difficulties if
Notebook (performs his detection). Having observed the notebook entry he turns to A and informs him in a patronizing manner that since his (B's) wave function just prior to his entry into the room, which he knows to have been a complete description of the room and its contents, had non-zero amplitude over other than the present result of the measurement, the result must have been decided only when A entered the room, so that A, his notebook entry, and his memory about what occurred one week ago had no independent objective existence until the intervention by B. In short, B implies that A owes his present objective existence to B's generous nature which compelled him to cooperate in his endeavor. However, to B's continuation, A does not react with anything like the respect and gratitude he should exhibit towards B, and at the end of a somewhat heated reply, in which A conveys in a colorful manner his opinion of B and his beliefs, he rudely punctures B's ego—by observing that if B's veto is correct, then he has no reason to feel complacent, since the whole present situation may have no objective existence, but may depend upon the future actions of yet another observer.

At this point several alternatives appear which avoid the paradox:

Alternative 1: To postulate the existence
Alternative B. To deny the possibility that A could ever be in possession of the
state of A+B. This one might argue that if the state of A+B constitutes
the function of A+B, then one might argue that the function of the state of A+B might cease to
exist after a discrete interaction. This argument is not valid.

The first objection to this

operation is on common sense. This is to say that whatever the state is
that is observed, there is a complete set of commuting operators which
commute with it. There is no complete set of commuting operators which
commute with A. If there are not any such operators, then the observation of
the function of A+B will not always give us the function of A+B. In
the theory of the possibility of any state functions,

the second objection is that it is not possible to know
whether we or not the system is in the system is described.

Note that this theory about what is
not possible for the system is described.

This theory requires external postulates about what is
not measurable. This is the standard

theory. The only cases of animal

progress is subject to being

earth processes.
it is contemplated that the universe contains more
than one observer. Let us consider the case of
one observer A, who is performing measurements
upon a system S; the totality (A+S) in turn
forming the object system for another observer B.

We wish to consider the consequences of B's use of
a quantum mechanical description of A+S. If
we are to deny this possibility to B, then we must
be prepared to state what constitutes an "observation"
or measuring apparatus in distinction to an ordinary
physical system to which quantum mechanics is
applicable, and we must then attribute to observers,
or measuring apparatus, a preferred position—a
kind of mystical aloofness from the natural laws.

On the other hand, if we do allow B to give
a quantum description to A+S, by assigning a
state function ##\psi_{A+S}##, then so long as B does not
interact with A+S its state changes causally
according to process 1, even though A may be
performing measurements upon S. From B's point
of view nothing resembling process 1 can occur (there
are no discontinuities), and the question of

the validity of A's use of process 1 is raised.

That is, apparently either A is incorrect in assuming
process 1, with its probabilistic implications, to apply
to his measurements, or else B's state function is
an inadequate description of what is happening
in A+S.

To better illustrate the situation we consider
the following hypothetical drama. Isolated somewhere
out in space is a room containing an observer, A,
who is about to perform a measurement upon a system S. After performing his measurement he will record the result in his notebook. We assume that he knows the state function of S (perhaps as a result of a previous measurement) and that it is not an eigenstate of the measurement he is about to perform. A being an orthodox quantum theorist then believes that the outcome of his measurement is undetermined and that the process is correctly described by Process 1. In the meantime, however, there is another observer, B, outside the room, who is in possession of the state function of the entire room, including S, the measuring apparatus, and A, just prior to the measurement. B is only interested in what will be found in the notebook one week hence, so he computes the state function of the room for one week in the future according to Process 2.

One week passes, and we find B still in possession of the state function of the room, which he finds he is also an orthodox quantum theorist. He believes to be a complete description of the room. If it is now the case that B's state function tells exactly what is in the notebook, then A is incorrect in his belief about the indeterminacy of the outcome of his measurement (because B could predict this state function even before the measurement takes place). We therefore assume that B's state function contains non-zero amplitude over several of the possible notebooks entries. At this point B opens the door to the room and looks at the
of only one observer in the universe. This is
the solipsist position, in which each of us
must hold the view that we alone are the
only valid observer, with the rest of the universe
and its inhabitants obeying at all times Process 2
except when under our observation. This view is
quite consistent, but one must feel uneasy
when, for example, writing textbooks on quantum
mechanics, describing process 2 for the consumption
of other persons to whom it does not apply.

Alternative 2: To limit the applicability of
quantum mechanics by asserting that the
quantum mechanical description (or observers)
or measuring apparatus, or more generally
systems approaching macroscopic size...

If we try to limit the applicability so as to
exclude measuring apparatus, or in general
systems of macroscopic size, we are forced with the
difficulty of sharply defining the region of validity.
For what in might a group of n particles be
considered as forming a measuring device so that the
quantum description fails? And to draw the line
at human or animal observers, i.e., to assume that
all mechanical apparatus obeys the usual laws, but that
they are somehow not valid for living observers, is to
do violence to the principle of psycho-physical
paradigm, and constitutes a view to be avoided if
possible. To do justice to this principle we must
insist that we be able to conceive of mechanical
devices (such as servomechanisms), obeying
natural laws, which we would be willing to call
observers.

Alternative 4: To abandon the position that
the state function is a complete description
of a system. The state function is to be
regarded not as a description of a single
system, but of an ensemble of systems, so
that the probabilistic assertions arise naturally
from the incompleteness of the description.

It is assumed that the correct complete description,
which would presumably involve further, Chisholm, parameters
beyond the state function alone, would lead to a
deterministic theory, from which the probabilistic
aspects arise as a result of our ignorance of these
extra parameters in the same manner as in
classical statistical mechanics, held by Einstein, among others, and which quite
appealing suffers from the fact that no one has
yet presented a completely satisfactory theory along
such lines.

Alternative 5: To assume the universal
validity of the quantum description, and
to treat all observation processes on equal
footing with all other natural processes, by
the abandonment of Principle 1 (i.e. to assert
the general validity of pure wave mechanics,
without any statistical assertions, in which,
Thesis: We show that the concept of "universal wave function" and associated correlation machinery provides a logically self-consistent description of a universe in which several observers are at work.
It is immediately evident that Alternative 5 is a theory of many advantages. It has the virtue of logical simplicity, and it is complete in the sense that it is applicable to the entire universe. All processes are considered equally (there are no "measurement processes" which play any preferred role), and the principle of psycho-physical parallelism is fully maintained. Since the universal validity of the state function is asserted, one can regard the state function itself as the fundamental entity, and one can consider the state function of the whole universe. In this sense this theory can be called the theory of the "universal wave function," since it can be based upon this alone. There remains, however, the question of whether or not such a theory can be put into correspondence with our experience.

It will be our purpose to show that this can, in fact, be done in a satisfactory manner. We shall be able to introduce ideal observers, which can be conceived as automatically functioning machines (servomechanisms) possessing recording devices (memory) and which are capable of responding to their environment into the theory, the behavior of which shall always (cont'd)
be treated entirely within the framework of wave mechanics. Furthermore, we shall be able to deduce the probabilistic assertions of Process 1 as subjective appearances to such actual observers, thus placing the theory in correspondence with experience. We are then led to the novel situation in which the formal theory is objectively continuous and causal, while subjectively discontinuous and probabilistic. While this point of view thus shall ultimately justify our use of the statistical assertions of the orthodox view, it enables us to do so in a logically consistent manner, allowing for the existence of other observers.

At the same time, it gives a deeper insight into the meaning of quantized systems and the role played by quantum-mechanical correlations.

The key to the possibility of such an interpretation lies in the proper exploitation of the correlations between subsystems of a composite system, which is described by a wave function. A subsystem of such a composite system does not, in general, possess an independent state function. That is, in general, a composite system cannot be represented by a single pair of subsystem states, but can be represented only by a superposition of such pairs of subsystem states. For example, the Schrödinger wave function for a pair of particles,

\[ \psi(x_1, x_2) \]

cannot generally be written in the form

\[ \psi(x_1, x_2) = \psi(x_1) \psi(x_2) \]

but only in the form

\[ \psi(x_1, x_2) = \sum \psi_i(x_1) \psi_i(x_2) \]

In the latter case, there is no single state for particle 1 alone or particle 2 alone, but only the superposition of such cases.
In fact, for any arbitrary choice of state for one subsystem, there will correspond a substate for the other subsystem, which will generally be dependent upon the choice of state for the first subsystem, so that the state of one subsystem is not independent, but correlated to the state of the remaining subsystem. Such correlations between systems arise from interaction of the systems and from our point of view, all measurement and observation processes are to be regarded simply as interactions between observer and object system which produce strong correlations.

It is then a consequence of regarding the observer as a subsystem of the composite system observer + object-system, that after interaction, there will not, in general, exist a single observer state, but a superposition, each element of which contains a definite observer state and a corresponding relative object-system state. Furthermore, in a general consequence of the superposition principle for linear wave equations, that if the observation is performed upon an object system which is not on eigenstate of the measurement, that the result will be a superposition of states, each of which describes an observer which has obtained a different result of observation, and for which the relative system state is nearly the eigenstate corresponding to the observed result. The whole superposition being combined with approximacy the coefficients of the expansion of the original object-system state in terms of the eigenfunctions of the measurement.
Thus each element of the resulting superposition describes an observer who perceived a definite result, and to whom it appears that the object system state has been transformed into the corresponding eigenstate. In this sense, the usual attentions of Process 1 appear to hold on a subjective level to each observer described by an element of the superposition. We shall see also that correlation plays an important role in preserving consistency when several observers are present and allowed to interact with one another as well as with the object-system with.

In order to develop a language for interpreting our pure wave mechanics for composite systems we shall find it useful to develop quantitative definitions for such notions as the "nearness" of a state function \( \Psi \) to an eigenfunction of an operator \( \mathbf{A} \), i.e., the "sharpness" of definiteness of \( \mathbf{A} \), and the degree of correlation between subsystems of a composite system, or between a pair of operators in the subsystems, so that we can use these concepts in an unambiguous manner. The mathematical development of these notions will be carried out in the next chapter (17) using some concepts borrowed from Information Theory. We shall develop these general definitions of information and correlation, as well as some of their more important properties. While we shall use the language of probability theory in this chapter to facilitate the exposition, we shall nevertheless subsequently apply the mathematical definitions directly to state functions by replacing probabilities by square amplitudes, without.
however, making any reference to probability models.

We shall then investigate the Quantum
formalism of composite systems (Chap. IV), particularly
the concept of relative state functions, and the
meaning of the representation of subsystems by
non-interfering mixtures of states characterized by
density matrices. We shall also see that the
existence of a strong correlation between an operator A
in one subsystem and an operator B in the other
implies the possibility of a representation of the
composite system state as a superposition for
each element of which both A and B have nearly
definite values. The degree of this definiteness, improving
with the degree of correlation. Finally, we shall
see that there is a characteristic correlation between
the subsystems of a composite system which has
some interesting properties.

This will be followed by an investigation
of abstract measuring processes (Chap. IV) considered
simply as correlation inducing interactions between
subsystems of a single isolated system, and the
representation of the resulting state as a superposition
of states for which the two subsystems have nearly
definite values for the measured quantity. Ideal
observers are then introduced and treated in
similar fashion, and the validity of Process 1 as a
subjective phenomenon is deduced. The consistency
of allowing several observers to interact is also shown.

The abstract treatment is then supplemented in
Chap. V, with a discussion of real processes. The
existence and meaning of macroscopic objects
We do not wish to restrict ourselves to numerical valued random variables, but to abstract valued random variables - hence our general set construction.
of fairly well defined boundaries and shapes. From this viewpoint, their atomic constitution and the wave mechanics of their constituent particles is discussed. In addition, some other implications of the investigation are mentioned.

The final chapter summarizes the situation and describes further the advantages of the theory, as well as the difficulties of the other alternatives.
If we are to deny the possibility of B's use of a quantum mechanical description (wave function for A+S), then we must be supplied with some alternative description for systems which contain observers (or measuring apparatus). Furthermore, we would have to have a criterion for telling precisely what type of systems would have the preferred positions of "measuring apparatus" or "observer" and be subject to the alternate description. Such a criterion is probably not capable of rigorous formulation.

Statement 2:

On else B's state function, with its purely causal character, is an inadequate description of what is happening to A+S which this equally orthodox quantum theorist believes to be a complete description of the room and its contents. If B's state function calculation tells beforehand exactly what is going to be in the notebook, then A is incorrect in his belief about the indeterminacy of the outcome of his measurement. We therefore assume that B's state function contains non-zero amplitudes over several of the notebook entries.
Alternative 3: let us deny the possibility that B could ever be in possession of the state function of A+S. Thus one might argue that a determination of the state of A would constitute such a drastic intervention that A would cease to function as an observer.

The first objection to this view is that no matter what the state of A+S is, there is in principle a complete set of commuting operators for which it is an eigenstate, so that, at least, the determination of these quantities will not affect the state nor in any way disrupt the operation of A. There are no fundamental restrictions in the usual theory about the knowability of any state functions, and the introduction of any such restrictions would therefore require extra postulates.

The second objection is that it is not particularly relevant whether or not B actually knew the precise state function of A+S. If he merely believes that the system is described by a state function, which he does not presume to know, then the difficulty still exists. He must then believe that this state function changed deterministically, and hence that there was no probability in A's determination.
Alternative 5: To assume the universal validity of the quantum description, by the complete abandonment of Process 1. The general validity of pure wave mechanics, without any statistical assertions, is assumed for all physical systems, including observers and measuring apparatus. Observation processes are to be described completely by the state function of the composite system which includes the observer and the object system, and which at all times satisfies the wave equation (Process 2).

all of physics is presumed to follow from this function alone.

The present thesis is devoted to showing that this concept of a universal wave mechanics, together with the necessary correlation machinery for its interpretation, forms a logically self-consistent description of a universe in which all observers are at work, and which can be put into correspondence with our experience.
We shall be able to introduce into the theory systems which represent observers. Such systems can be conceived as automatically functioning machines (mechanisms) possessing recording devices (memory) and which are capable of responding to their environment. The behavior of these observers shall always be treated within the framework of wave mechanics. Furthermore, we shall deduce the probabilistic assertions of Process 1 on subjective appearance to such observers, thus placing the theory in correspondence with experience.

In order to bring about this correspondence with experience for the pure wave mechanical theory, we shall exploit the correlations between subsystems of a composite system which is described by a state function.

It is, however, an inescapable consequence that if one regards an observer as a subsystem of the composite system that after the interaction has taken place there will not, in general, exist a single observer state. There will, however, be a superposition of the composite system states, each element of which contains a definite observer state and a definite object system state. Furthermore each of these relative object-system states will be, approximately, the eigenstates of the observation corresponding to the value obtained for the observer which is devised by the same element of the superposition.