Desiderata for a Modified Quantum Dynamics[1]

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1. The Motivation for Modifying Quantum Dynamics

A cluster of problems — the "quantum mechanical measurement problem," the "problem of the reduction of the wave packet," the "problem of the actualization of potentialities," and the "Schrödinger Cat problem" — are raised by standard quantum dynamics when certain assumptions are made about the interpretation of the quantum mechanical formalism. Investigators who are unwilling to abandon these assumptions will be motivated to propose modifications of the quantum formalism. Among these, many (including Professor Ghirardi and Professor Pearle) have felt that the most promising locus of modification is quantum dynamics, and in their presentations (this Volume) they have suggested stochastic modifications of the standard deterministic and linear evolution of the quantum state. Others who have followed this avenue of investigation are F. Károlyházy, A. Frenkel, and B. Lukács (Károlyházy et al. 1982), N. Gisin (1984, 1989), A. Rimini and T. Weber (in Ghirardi et al. 1986), L. Diósi (1988, 1989), and J.S. Bell (1987, pp.201-12). At a workshop at Amherst College in June 1990 Bell remarked that the stochastic modification of quantum dynamics is the most important new idea in the field of foundations of quantum mechanics during his professional lifetime. My own attitude is somewhat cautious and exploratory. The stochastic modification of quantum dynamics ought to be examined intensively, but the possibility should be kept in mind that it may fail, in which case the aforementioned assumptions about the interpretation of quantum mechanics will have to be reassessed. Many, and perhaps all, of the investigators listed above share this exploratory and empiricistic attitude.

It will be useful for later discussion to review briefly the standard dynamics of quantum mechanics and to state its implications for a schematized formulation of the measurement process. According to quantum mechanics, the state of a physical system is represented by a normalized vector of an appropriate Hilbert space (the representation being many-one, for two normalized vectors which are complex scalar multiples of each other represent the same state). If the system is closed, then there is a family of time-dependent unitary (and hence linear) operators $U(t)$, with the property $U(t_1)U(t_2)=U(t_1+t_2)$, such that if $s(0)$ is a vector representing the state of the system at time 0, then the state at an arbitrary time t is represented by $s(t)$, where

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$$s(t) = U(t)s(0). \tag{1}$$

Eq. (1), which is slightly more general than the familiar time-dependent Schrödinger equation, is the fundamental dynamical principle of non-relativistic quantum mechanics. Its relativistic counterpart, the Tomonaga-Schwinger equation, will not be needed for our purposes. What is most important for the problem of measurement is the linearity of $U(t)$:

$$U(t)(c_1s_1+c_2s_2+\ldots+c_ns_n) = c_1U(t)s_1+c_2U(t)s_2+\ldots+c_nU(t)s_n, \tag{2}$$

for any vectors $s_1, s_2,\ldots,s_n$ and any scalars $c_1, c_2,\ldots,c_n$.

Suppose now that an object of interest and an apparatus employed to measure some property of the object together constitute a closed physical system (perturbations from the rest of the universe being negligible). Then by the dynamical principle of quantum mechanics there is a family of unitary operators $U(t)$ governing the temporal evolution of the states of object-plus-apparatus, as in Eqs. (1) and (2). The apparatus is to serve the purpose of revealing the value of a property of the object which is represented by the hermitian operator A, where

$$As_i = a_is_i \qquad (a_i \neq a_j \text{ if } i \neq j) \tag{3}$$

for some basis s_i in the object's Hilbert space. Then there must be some vector v_o in the Hilbert space of the apparatus (representing a "neutral" apparatus state) such that for some time t the vector $U(t)(s_i \otimes_o)$ is an eigenvector of an operator representing a property of the apparatus, with an eigenvalue b_i from which one can infer a_i. A highly idealized version of this schema of measurement is one in which for each i there is a normalized vector v_i in the Hilbert space of the apparatus such that

$$U(t)(s_i \otimes v_o) = s_i \otimes v_i \tag{4}$$

and

$$Bv_i = b_iv_i \quad (b_i \neq b_j \text{ if } i \neq j). \tag{5}$$

In general, however, the initial state of the object will not be represented by a single one of the eigenvectors of A, but by a superposition of the form

$$s(0) = c_1s_1+\ldots+c_ns_n, \tag{6}$$

with the sum of the absolute squares of the scalar coefficients c_i being unity and with more than one of them non-zero. Then the state of object-plus-apparatus at time t is represented by

$$U(t)((c_1s_1+\ldots+c_ns_n)\otimes v_o) = c_1U(t)(s_1 \otimes v_o)+\ldots+c_nU(t)(s_n \otimes v_o), \tag{7}$$

which is a superposition of n vectors, each representing a state in which the property of the apparatus has a different value b_i. It is at this point that the problems mentioned in the first paragraph are revealed. The purpose of a measurement is to obtain information about a property of an object (typically a microscopic object which cannot be directly scrutinized) by means of a correlation established between that property and a property of the apparatus. But in the state represented in Eq. (7) the apparatus property does not have a definite value, and hence the purpose of the measurement has not been achieved. Thus the "measurement problem" is posed. Furthermore, Eq.

(7) shows that the peculiar indefiniteness of a physical property is not confined to microscopic objects (as in Eq. (6)), but is manifested by a property of a macroscopic apparatus on account of the linearity of the dynamical evolution of object-plus-apparatus. In particular, when the notorious experimental arrangement of Schrödinger (1935) is analyzed quantum mechanically, then in the final stage of the experiment it is indefinite whether the cat is alive or dead — the "Schrödinger cat problem." These problems arising in the context of physical measurement may be considered to be special cases of a more general problem of "the actualization of potentialities," for it is obscure how actual events — such as the emission or absorption of photons, or the replication of a macro-molecule, or the firing of a neuron — can occur if quantum dynamics typically gives rise to states in which these events are merely potential because of the indefiniteness of relevant properties.

The following assumptions concerning the interpretation of the quantum mechanical formalism have the consequence of making the foregoing problems so serious that it is difficult to envisage their solution without some modification of the formalism itself. The assumptions themselves are strongly supported by physical and philosophical considerations, and therefore a high price would be paid by sacrificing one of them in order to hedge standard quantum mechanics against modifications.

(i) The quantum state of a physical system is an objective characterization of it, and not merely a compendium of the observer's knowledge of it, nor merely an intellectual instrument for making predictions concerning observational outcomes.

(ii) The objective characterization of a physical system by its quantum state is complete, so that an ensemble of systems described by the same quantum state is homogeneous, without any differentiations stemming from differences in"hidden variables."

(iii) Quantum mechanics is the correct framework theory for all physical systems, macroscopic as well as microscopic, and hence it specifically applies to measuring apparatuses.

(iv) At the conclusion of the physical stages of a measurement (and hence, specifically, before the mind of an observer is affected), a definite result occurs from among all those possible outcomes (potentialities) compatible with the initial state of the object.

I shall very briefly point out how these assumptions preclude some of the proposals that have been made for solving the problem of measurement and related problems. Assumption (i) stands in the way of an instrumentalist interpretation of the quantum mechanical formalism. Such an interpretation could accommodate an expression of the form of Eq. (7), with many terms corresponding to different observational outcomes, just as well as a characterization of the final state of object-plus-apparatus by a single term; either expression would merely be an instrument for anticipating an observational outcome or the probabilities of various outcomes. Some arguments against such an instrumentalist interpretation are given in Shimony (1989), along with references to other discussions. Assumption (ii) rejects a hidden variables interpretation of quantum mechanics, according to which the indefiniteness of the value a_i in Eq. (6) and of b_i in Eq. (7) applies only to ensembles and not to individual members of the ensembles. The main consideration in favor of Assumption (ii) is the incompatibility proved by Bell (1987, pp.14-21 and 29-39) between quantum mechanics and local hidden variables theories, but Bell himself emphasizes that there is still an option of non-local hidden variables theories, which he does not regard as completely repugnant (1987, pp.173-80). Assumption (iii) rules out all variants of the Copenhagen interpretation, which rejects the impasse of Eq. (7) by rejecting the application of quantum mechanics to the apparatus of measurement. In favor of this Assumption is the immense success of the general physical program of understanding macroscopic systems in terms of microscopic parts, conjoined with the immense success of quantum mechanics in the microscopic domain. Wigner (1971, pp.14-15) emphasizes particularly that we have no theory at present for dealing with the interaction of a quantum system and a classical system. Finally, Assumption (iv) precludes the "many-worlds" interpretation, in which all terms on the right hand side of Eq. (7) are considered to be equally real. The conceptual difficulties of this point of view, which effectively denies the distinction between actuality and potentiality, has been analyzed by many writers, for example Bell (1987, pp.93-100) and Stein (1984).

Henceforth in this paper I shall not question Assumptions (i)-(iv), even though, as stated in the first paragraph, an eventual re-assessment is not ruled out. Given these Assumptions, however, one finds Eq. (7) intolerable as a description of the final physical stage of the measurement process. There must be a further stage in which a selection is made from the superposition, and that further stage must be physical. A modification of quantum dynamics is thereby required.

2. Proposed Desiderata

a. *The proposed modification of quantum dynamics should not be restricted to situations of measurement, for such a restriction would inject an anthropocentric element into fundamental physical theory.* This desideratum would preclude von Neumann's (1955, p. 351) postulate of a special process of reduction occurring when a physical variable is measured, unless that postulate could be shown to be a special case of a more general dynamical law. All the authors mentioned in the first paragraph are committed to satisfying this desideratum.

b. *The modified dynamics must agree very well with quantum dynamics in the domain of sucessful application of the latter.* This desideratum is primarily the demand of experimental adequacy of a proposed new theory, for if standard quantum dynamics makes very accurate predictions of such phenomena as resonance and beats, then the new theory would have to agree closely with quantum dynamics in order to fit these phenomena. One may anticipate, however, some additional content in this desideratum: that the modified dynamics be related to standard quantum dynamics in a systematic way, by some limiting principle, which would be analogous to the "correspondence principle" relating quantum to classical mechanics.

c. *If the proposed modified dynamics is applied to a measurement situation, it should predict definite outcomes in a "short" time, where the vague word "short" is made quantitative by the known reaction time of the experimental apparatus.* This desideratum strongly favors a stochastic modification of quantum dynamics over a deterministic non-linear modification. If the composite system object-plus-apparatus is governed by a non-linear dynamical equation, then one could not preserve Eq. (7), in which a final superposition mirrors the initial superposition of eigenvectors of the object variable A; and one could easily imagine a continuous dwindling away of all coefficients except one, which asymptotically would approach absolute value unity. But it is very difficult to construct a plausible dynamical equation for which this asymptotic behavior occurs in a finite time interval. Difficult is not impossible, however, and Pearle (1985) actually succeeded in constructing such an equation (but it is tailored to the measurement of a particular object variable, contrary to desideratum a). The non-deterministic "jumps" of a stochastic dynamical theory — whether they are sporadic and finite, as in the Spontaneous Localization theory of Ghirardi, Rimini, and Weber (1986), or infinitesimal, as in the Continuous Spontaneous Localization theory of Pearle (1989) — are a promising means for achieving definite measurement outcomes rapidly.

d. *If a stochastic dynamical theory is used to account for the outcome of a measurement, it should not permit excessive indefiniteness of the outcome, where "excessive" is defined by considerations of sensory discrimination.* This desideratum tolerates outcomes in which the apparatus variable does not have a sharp point value, but it does not tolerate "tails" which are so broad that different parts of the range of the variable can be discriminated by the senses, even if very low probability amplitude is assigned to the tail. The reason for this intolerance is implicit in Assumption (iv) of Section 1. If registration on the consciousness of the observer of the measurement outcome is more precise than the "tail" indicates, then the physical part of the measurement process would not yield a satisfactory reduction of the initial superposition, and a part of the task of reducing the superposition would thereby be assigned to the mind. For this reason, I do not share the acquiescence to broad "tails" that Pearle advocates (1990, pp.203-4), with the concurrence of Bell and Penrose (*ibid.*, p.213, footnote 30).

e. *The modified dynamics should be Lorentz invariant.* This desideratum has not been achieved by any of the proposed stochastic theories, and it evidently will be very difficult to satisfy. A discussion both of the difficulties and of some progress towards solving them is given by Pearle (1990, pp.204-12) and Fleming (1989).

f. *The modified dynamics should not lose the "peaceful coexistence" with special relativity that standard quantum mechanics possesses — that is, the impossibility of capitalizing upon the entanglement of the state of spatially separated systems to send a superluminal message.* Gisin (1989) has shown that a large class of non-linear deterministic modifications of quantum dynamics violate this desideratum. His argument provides a consideration supplementary to desideratum c for preferring stochastic theories.

g. *The modified dynamics should preclude the gestation of Schrödinger's cat, and in general the occurrence — even for a brief time — of states of a system in which a macroscopic variable is indefinite.* This desideratum is less strongly entrenched than the others discussed so far, because one could presumably achieve agreement with our failure to observe such states by supposing that they are highly unstable and decay very rapidly into states where macroscopic variables have sharp variables (to the extent required by desideratum d). Incidentally, it is fascinating, and perhaps fruitful, to consider the experimental search for very short-lived superpositions of radically differing states in mesoscopic systems.

h. *The modified dynamics should be capable of accounting for the occurrence of definite outcomes of measurements performed with actual apparatus, not just with idealized models of apparatus.* The Spontaneous Localization theory of Ghirardi, Rimini, and Weber (1986) has been criticized for not satisfying this desideratum. In the measuring apparatus that they consider, the macroscopic variable which is correlated with a variable of a microscopic object is the center of mass of a macroscopic system, and spontaneous localization ensures that within about ten nanoseconds this variable will be quite sharp. (At the 1990 PSA meeting I incorrectly stated that the macroscopic system had to be rigid in order to obtain such rapid localization, and my error was pointed out by Professor Ghirardi.) Albert and Vaidman (Albert 1990, 156-8) note that the typical reaction of a measuring apparatus in practice is a burst of fluorescent radiation, or a pulse of voltage or current, and these are hard to subsume under the scheme of measurement of the Spontaneous Localization theory.

3. The "Quantum Telegraph": A Promising Locus of Investigation

A great weakness in the investigations carried out so far in search of modifications of quantum dynamics is the absence of empirical heuristics. To be sure there is one grand body of empirical fact which motivates all the advocates of stochastic modifications of quantum dynamics and most of the advocates of non-linear modifications: that is, the occurrence of definite events, and in particular, the achievement of definite outcomes of measurement. But this body of fact is singularly unsuggestive of the details of a reasonable modification of quantum dynamics. What is needed is phenomena which are suggestive and even revelatory. No more promising phenomena for this purpose have been found than the intermittency of resonant fluorescence of a three-level atom.

H. Dehmelt (1975) proposed to study fluorescent radiation from a trapped atom (confined to a small region by techniques of which he was a pioneer) exposed to two laser beams, one labeled "strong" and one "weak." The first is tuned to the frequency of a transition from the ground state 0 to an excited state 1, and the second to the frequency of a transition from 0 to an excited state 2. The 1-0 transition is dipole-allowed, so that the state 1 has a lifetime of about 10^{-8} s, whereas the 2-0 transition is dipole-forbidden and the lifetime of 2 is about 1 s. Dehmelt anticipated that there would be fairly long periods (of the order of a second) in which the atom undergoes cycles of excitation and spontaneous emission about 10^{-8} s in duration. During such a period the radiation from the single trapped atom would be visible to the naked eye; Cook (1990, p. 367) says, "With a 10 x magnifying lens a point source of this strength would appear as bright as one of the stars in the Big Dipper"! Every few seconds, however, Dehmelt conjectured, the atom would absorb a photon from the weak laser beam and would be excited to state 2, where it would remain for a fairly long period, "shelved", in his descriptive term. Consequently, the fluorescent radiation from this three-level atom would be intermittent, with a pattern of alternating light and dark periods that has been described as the "quantum telegraph." (Of course, unlike the dots, dashes, and spaces of Morse telegraphy, the periods of light and dark would be of random durations.)

Dehmelt's reasoning seemed implicitly to accept the idea of quantum jumps from one state to another. It is reminiscent of the old Bohr theory of atomic transitions (1913), though to an advocate of a stochastic modification of quantum dynamics it could be construed as an intimation of the theory of the future. In any case, it was criticized for neglecting the superposition principle and the linearity of quantum dynamics, which seem to be inconsistent with "shelving" (Pegg, Loudon, and Knight 1986). But if the atom is always in a superposition of states 0, 1 , and 2 except when a photon is detected (at which point emission has occurred with certainty and the state is "reset" to 0), then it is straightforward to show that there is negligible probability of a dark period longer by an order of magnitude than the natural lifetime of state 1. It follows that the phenomenon of the quantum telegraph should not appear.

Dehmelt's intuition was confirmed by experiment (Bergquist et al. 1986, Nagourney et al. 1986, Sauter et al. 1986, Itano et al. 1987). These results are among the most dramatic in the history of optics. And they have given rise to a number of sophisticated analyses, attempting to show the consistency of the quantum telegraph with standard quantum mechanics (e.g., Cohen-Tannoudji and Dalilbard 1986, Porrati and Putterman 1989, Erber et al. 1989, Cook 1990). For the most part these analyses agree with each other, but there are some differences in emphasis and detail. I shall summarize the main ideas without examining the differences, since this procedure will suffice for the heuristic purposes of the present paper.

First, the system of interest is taken to be the atom together with the scattered part of the radiation field (which is discriminated sufficiently from the incident laser beams because of the precisely defined directions of these beams). The states of interest will be represented by superpositions of the form

$$|\Psi(t)> = c_1(t)|1>\otimes|0>_F + c_2(t)|2>\otimes|0>_F + \sum c_{kp}(t)|0>\otimes|kp>_F, \qquad (8)$$

where $|0>$, $|1>$, $|2>$ respectively represent the ground state and the two relevant excited states of the atom, $|0>_F$ represents the state of the scattered radiation field with no photons, and $|kp>_F$ represents a state with a single photon of wave vector k (of variable direction but with magnitudes restricted by the energies of the 1-0 and 2-0 transitions) and polarization p. These states evolve from an initial state consisting only of the first two terms of Eq. (8), with coefficients $c_1(0)$ and $c_2(0)$.

Second, for simplicity it is assumed that a perfect photo-detector is in place, to respond to any photon in one of the permitted modes kp. A detection of a photon would "reset" the state to a superposition of the first two terms of Eq. (8).

In addition to such normal "positive" measurements, there is a recognition of "null measurements": i.e., the non-detection of a photon by the perfect photo-detector after a time interval which is long compared to the lifetime of the short-lived state 1. Non-detection has the effect of projecting the vector of Eq. (8) onto the two-dimensional space spanned by $|1>\otimes|0>_F$ and $|2>\otimes|0>_F$, so that the last term of Eq. (8) is projected out and the first two terms are preserved but with renormalization.

The questions of exactly when the projection occurs, and what the state looks like before the projection is fully accomplished, are evaded by making use of the enormous difference in order of magnitude of the lifetimes of states 1 and 2. The statistics of light and dark periods are therefore insensitive to answers to these two questions.

Once this projection is accomplished, the usual unitary evolution of the state will automatically account for a rapid diminution of the coefficient $c_1(t)$ relative to $c_2(t)$, thereby greatly extending the period of darkness to a length comparable to the natural lifetime of state 2.

Finally, an epistemic concept of probability is invoked. For example, Porrati and Putterman (1988, p. 3014) write, "In our picture the measurement of a period of time during which no photons are recorded changes our information about the system and thus the wave function. This null measurement increases the probability of successive periods of darkness." Cook (1990, p. 407) uses the locution "Bayesian transitions" to describe the consequences of null measurements, and he contrasts his point of view with Dehmelt's original suggestion as follows: "It is interesting that the quantum formalism attributes electron shelving to the lack of fluorescence, whereas the intuitive picture of the process attributed the lack of fluorescence to electron shelving."

A strenuous objection must be brought against the foregoing scheme of ideas, in spite of the elegance of the theoretical analysis based upon them and the agreement of this analysis with experiment. The scheme takes for granted that a photo-detector definitely has or has not registered the arrival of a photon in a certain interval of time. This assertion does not make a commitment to a definite instant beginning the interval and a definite instant ending it; the time-energy uncertainty relation and the operational uncertainties of the detector can be fully respected. The point is rather that a reduction of the wave packet has been assumed at the level of a macroscopic measuring apparatus, and the analogue of Schrödinger's cat — that is, a superposition of photon detected and photon not detected — has tacitly been excluded. This assumption underlies the Bayesian locutions about probabilities conditional upon the occurrence or non-occurrence of a certain event. Of course, working physicists regularly assume that at the level of macroscopic apparatus the superposition principle does not preclude definite outcomes. The opportunistic employment of the superposition principle in the early stages of a physical process and its suspension at the final stage is, in fact, a part of the ordinary practice of quantum mechanics, and as Bell forcefully reminded us (1990, p. 18), "ORDINARY QUANTUM MECHANICS (as far as I know) IS JUST FINE FOR ALL PRACTICAL PURPOSES." But the purpose of Section 1 of this paper was to review the argument that the opportunistic employment of the superposition principle is not understood from the standpoint of first principles.

My proposal is to avoid a merely "practical" explanation of the quantum telegraph in terms of ordinary quantum dynamics, but instead to let this remarkable phenomenon guide us heuristically to a modified dynamics. Two propositions seem to me to suggest themselves quite strongly. The first is that a stochastic modification of quantum dynamics is a natural way to accommodate the jumps from a period of darkness to a period of fluorescence. The second is that the natural locus of the jumps is the interaction of a physical system with the electromagnetic vacuum. Whether stochasticity is exhibited when the system in question is simple and microscopic, like a single atom, or only when it is macroscopic and complex, like the phosphor of a photo-detector, is not suggested preferentially by the quantum telegraph, for the simple reason that the single trapped atom and the photo-detector are both essential ingredients in the phenomenon. But whichever choice is made points to a stochastic modification of quantum dynamics that has little to do with spontaneous localization. There is hope, therefore, for a stochastic theory that will escape the criticisms leveled by Albert and Vaidman against the localization theories of Ghirardi, Rimini, and Weber, and of Pearle. I must admit, however, that the envisaged theory which I prefer to those of Professors Ghirardi et al. and of Pearle has one serious disadvantage relative to theirs — it does not exist, whereas theirs do!

4. Two Concluding Remarks

The search for a reasonable modification of quantum dynamics was motivated by a cluster of problems arising from the linearity of the standard time evolution operators. The implications of a modified dynamics, however, may reach far beyond the original motivation. In particular, a stochastic modification of quantum dynamics can hardly avoid introducing time-asymmetry. Consequently, it offers an explanation at the level of fundamental processes for the general phenomenon of irreversibility, instead of attempting to derive irreversibility from some aspect of complexity (which has the danger of confusing epistemological and ontological issues). Thus a stochastic modification of quantum dynamics is a promising way to satisfy the thesis of R. Penrose (1986) that the problem of the reduction of the wave packet is inseparable from the problem of irreversibility.

Finally, to the list of eight desiderata listed in Section 2 for a modification of quantum dynamics I want to add a ninth, highly personal one: that a satisfactory theory be found by some one during my lifetime.

Notes

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