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Measurement and Fundamental Processes in Quantum Mechanics

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Abstract In the standard mathematical formulation of quantum mechanics, measurement is an additional, exceptional fundamental process rather than an often complex, but ordinary process which happens also to serve a particular epistemic function: during a measurement of one of its properties which is not already determined by a preceding measurement, a measured system, even if closed, is taken to change its state discontinuously rather than continuously as is usual. Many, including Bell, have been concerned about the fundamental role thus given to measurement in the foundation of the theory. Others, including the early Bohr and Schwinger, have suggested that quantum mechanics naturally incorporates the unavoidable uncontrollable disturbance of physical state that accompanies any local measurement without the need for an exceptional fundamental process or a special measurement theory. Disturbance is unanalyzable for Bohr, but for Schwinger it is due to physical interactions' being borne by fundamental particles having discrete properties and behavior which is beyond physical control. Here, Schwinger's approach is distinguished from more well known treatments of measurement, with the conclusion that, unlike most, it does not suffer under Bell's critique of quantum measurement. Finally, Schwinger's critique of measurement theory is explicated as a call for a deeper investigation of measurement processes that requires the use of a theory of quantum fields.

Keywords Measurement · Quantum mechanics · Quantum field theory · Disturbance · Process

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1 Introduction

In its standard formulation, quantum mechanics takes measurement, which typically involves not simple but rather complex physical situations, as a fundamental process rather than a special case of interaction within the generic class of processes as in classical mechanics: when a measurement is made of a property of the system which is *not already* strictly determined, the quantum state of a measured system—unlike in all other situations involving a closed joint system—is taken to change discontinuously rather than continuously [1]. Most famously, John Bell was concerned about this state of intellectual affairs, which he argued was due to a lack of conceptual precision [2,3]. In contrast to Niels Bohr's influential, early view of quantum measurement presented in his Como lecture of 1927 as having a novel character arising from unpredictable, unavoidable disturbance that requires no further explanation than the quantum postulate, Julian Schwinger argued that the quantum disturbance effect is manifest in measurement because all physical interaction is carried out via *fundamental particles*, which are field quanta [4].

Measurement is a physical *process* involving several systems and does not involve just one time point, as does an event or state specification. Indeed, in the basic mathematical formulation of John von Neumann following work of Paul Dirac and others, measurement is a process, "*Prozess I*," of non-unitary state evolution and is distinct from the remaining, otherwise always occuring process (*Prozess II*) which for closed systems (the only ones considered here) corresponds to a unitary state evolution [1]. Although it would be more desirable for a number of reasons to have a single fundamental evolution of quantum state, for example, Process II alone, this appears to be impossible (except, perhaps in a modal interpretation) in the theory: because any process of type I has a time-evolution operator representation which non-unitary, it cannot (within the closed system context for the joint apparatus–measured-system pair) be reduced to any product of specific processes of type II, i.e., having time-evolution operator descriptions that are unitary, cf. [5].

Here, the measurement process will be considered in light of the conception of measurement of Bohr and a differing articulation of its emphasis on disturbance given by Julian Schwinger, as well as later criticisms of Bell of measurement theory in quantum mechanics. This analysis demonstrates that it behooves us to reconsider our approach to measurement, in particular, whether the physical process can be fully captured within basic quantum mechanics. In particular, the argument of Schwinger that one must take the role of field quanta into account even at the level of the quantum mechanics of simple systems serves both to support the basic quantum mechanical treatment of measurement within quantum mechanics proper and to suggest the need to move beyond quantum mechanics to a theory of quantum fields to describe it.

2 Bohr: Measurement as Disturbing

Although it can refer any non-static situation in which there is duration, in specific situations the term 'process' is most often applied in quantum theory to interactions, for example, the light emission process, the light absorption process, and the various scattering processes of particle physics. At its most abstract, a process is a succession of events involving physical entities which, when the process is non-trivial, change state. At a minimum, there is an initial set and final set of states between which there is change in at least one of the states of one of the entities. Because measurements are processes, let us first consider the use of the notion of process in the context of quantum measurement specifically. In measurement processes as often treated in quantum theory of measurement, the physical systems involved are (at least) a quantum object system S and a quantum apparatus system A.[1]

One of the first measurement situations considered in the history of the foundations of quantum theory—that of an idealized light microscope being used to measure an electron's position and momentum (cf. [8], Ch. 2, Sect. 2)—was offered by Werner Heisenberg and analyzed in some detail by Bohr in his 1927 Como lecture [6], cf. [7]. The term 'process' was used by Bohr in his discussions of fundamental quantum theory, including this one. Bohr held the discovery of the "elementary quantum of action" to reveal "a feature of wholeness inherent in atomic processes" which he was to more strongly emphasize later [9], where this quantum of action is considered *indivisible*, something which differentiates these processes from classical ones: the essence of quantum theory "may be expressed in the so-called quantum postulate, which attributes to any atomic process an essential discontinuity, or rather individuality, completely foreign to the classical theories and symbolised by Planck's quantum of action" [6]. In Bohr's treatment of measurement, the microscope as apparatus is not to be treated as a quantum mechanical system A, but rather is to be treated classically. Yet, measurements of entities such as S at the atomic scale do violate a *principle of continuity* belonging to classical physics: in classical physics, when a physical system is at some time in one state and at a later time in another state, there is a continuum of intervening states through which the system passes, whereas in quantum theory the state can be seen to change directly from one state to another, distant state. Because measurements in quantum mechanics do not take place at the atomic scale alone, for him, any attempt at a purely quantum mechanical analysis of measurement as a process is improper, due to the need in any measurement analysis for the inclusion of the specification on the entirety of the experimental arrangement, including those 'sufficiently heavy to be given a classical account."

Bohr argues further that the "impossibility of neglecting the interaction with the agency of measurement means that every observation introduces a new uncontrollable element" [6]. As Abner Shimony explained Bohr's picture of measurement in discussion with Bell, "In any measuring process, Bohr insists upon a sharp distinction between object and subject. The apparatus is considered to be situated on the subject's side of this division. Hence it is characterized in terms of the concepts of everyday life (of which the concepts of classical physics are refinements)" [10]. Moreover, for Bohr, "the quantum postulate implies a renunciation as regards the causal space-time co-ordination of atomic processes" because there is a "complementary character of the description of atomic phenomena which appears as an inevitable consequence of the contrast between the quantum postulate and the distinction between object and

[1] The role of a consciousness is sometimes also mentioned, but such a characterization is then not purely physical and is not considered here.

agency of measurement, inherent in our very idea of observation" [6]. For him, this clearly should have consequences for the specification of state and state change during the measurement process.

As Bohr explained during his analysis of the Heisenberg microscope experiment, which involves measuring the position of an electron with light and which takes place near the atomic spatial scale, the traditional notions of position and momentum remain applicable but are also limited:

> "…a discontinuous change of energy and momentum during observation could not prevent us from ascribing accurate values to the space-time co-ordinates, as well as to the momentum-energy components before and after the process. The reciprocal uncertainty which always affects the values of these quantities is…essentially an outcome of the limited accuracy with which changes in energy and momentum can be defined, when the wave-fields used for the determination of the space-time co-ordinates of the particle are sufficiently small." [6]

Significantly, although observation is considered a process, it is Bohr's view the duration of this process can be made arbitrarily small: "Just as in the case of the determination of position, the time of the process of observation for the determination of momentum may be made as short as is desired if only the wavelength of the radiation used is sufficiently small" [6].

On the whole, we see that Bohr's approach to measurement consists largely in the articulation of fundamental limitations on the descriptions which can be attributed to quantum states and their measurement as a matter of principle. By contrast, later Schwinger would provide instead a specific basis, as discussed in Sect. 4 below, for the limitations on measurement accuracy in quantum mechanics, and for the inappropriateness of describing the measurement process within quantum mechanics, that is not limited by principle but rather by the quantum fields necessarily present in any physical interaction.

3 Modeling Measurement

Let us now consider the nature and scope of the attempts at modeling measurement that have been carried out despite Bohr's claim that a fully quantum theory of measurement is bound to fail. First, note that, although the general claim that the duration of measurement can be made as small as desired was later challenged and despite the fact that the only explicit quantum mechanical model for some sort of successful measurement without discontinuous state evolution was one taking infinite time (provided by Coleman and Hepp, cf. [11]), the main thrust of these challenges was dispelled in 1961 by Yakir Aharonov and David Bohm [12]. Given that all completed measurements are performed in finite time, it is natural to require of a conception of measurement that it allow them to be described.

Second, note that measurements typically involve complex apparatus extending over ranges of spatial scale. Insight into their essential nature can be expected to be gained by closer inspection of the structure and the functioning of apparatus and their components, particularly those at the atomic and sub-atomic scales [13]. Despite

Bohr's focus on the atomic scale—presumably because it is where the novelty of quantum mechanics is centered and because it is at that scale that the theory is necessary for the description of phenomena—he also required classical concepts and systems in his description of the measurement process. For Bohr, measurements also necessarily involve apparatus that is large enough that a general correspondence principle—namely, that in the limit of large size physical systems are describable classically to an increasingly good approximation—to come into play to provide outcomes provided in classical terms [14]. In particular, in relation to the measurement situation, Bohr says that "In actual experimental arrangements, the [unambiguous description the apparatus and measurement results] is secured by the use, as measuring instruments, of rigid bodies sufficiently heavy to allow a completely classical account of their relative positions and velocities" [15]. It was noticed by others later that these large apparatus are also commonly initially prepared in metastable states. These considerations informed fully quantum mechanical models of measurement, despite Bohr's rejection of them as a matter of principle.

Beyond the artificial apparatus, such as that of Stern–Gerlach, used to measure features of quantum systems, there are natural systems that are known to measure, the examination of which should also provide insight into the process, cf. [13]. Indeed, our sensory apparatus conjoined with the larger human nervous system are such systems. The human vision system is particularly important to our observation of nature; Shimony has already pointed out that, in this case, the photoreceptor protein of the rod cells of the retina, namely rhodopsin, absorbs a photon initiating a chemical cascade that is then followed by an electrical pulse in the optic nerve. Rhodopsin has two components, "retinal, which can absorb a photon, and opsin, which acts as an enzyme that effects the binding of about five hundred mediating molecules when it is triggered by the excited retinal" [16]. At the molecular level of this "front-end" portion of the system, this apparatus is relatively complex. The presence of distinct, alternative physical states corresponding to different conformations of a molecule, which can superpose and then enter a specific state when in contact with the remainder of the nervous system with which it is in contact, is central to the functioning of this light detection process, which takes place in a biochemical and electric environment. Moreover, the larger sub-system beyond rhodopsin has as one of its effects the "amplification" of the initial "signal" produced by the initial encounter of light with the eye.

Artificial systems used in optical physics—for example, avalanche photodiodes (APDs) connected to voltage descrimating electronics—share certain similarities to the human vision system. Both of these examples appear to us to yield measurements which are completed in a way that the more pedagogical example of a Stern–Gerlach magnet followed spatial beam direction but without a downstream beam-occupation detector, are not. Yet, it has been argued by some that signal amplication is not required for measurement to occur, cf. [17]; despite the presence of some common properties in many or most familiar measurement situation, one must ask whether they are indeed *necessary* to successful data yielding situations. The commonly recognized measurement-like situations, such as this, involve not only a significant number of degrees of freedom but can also be viewed as involving of a number of distinct parts, the essential characteristics of which could be sought out.

However, the theory of measurement has most often been approached very formally. In standard versions, this process is analyzed in terms of a measured system S and a measuring system A, the latter being such that its state including a “pointer” variable in some sense directly knowable by contrast with the former, something making the measurer necessary in the first place. In von Neumann’s measurent theory, neither the measuring system nor the measured system ends up in a state which has a classical description such as desired on Bohr’s approach, although it allows for the description of a chain of intermediate stages of interaction leading from the system that is the object of measurement to any desired physical recording system, such as that of a computer memory or part of the human brain, which ends up in a state reflecting that of the object system with the occurrence of Process I upon it. How the data corresponding to this pointer value appears in the mind of the observer is an epistemic question; von Neumann simply required that there be psycho-physical parallelism, that is, that there be consistent development of the pertinent physical and mental states, for example, those of the observer’s brain. Measurements, in such situations, thus involve an interaction between object and apparatus affecting the pointer of the apparatus and systems between it and eventually any involved observer’s brain. More specifically, in the contemporary quantum theory of measurement, experiments are often understood schematically as follows, cf. e.g. [18], p. 28. A system S is intially prepared, through a series of physical interactions, such as state filtering, in some well identified quantum state, after which it is measured through interaction with a measurement apparatus A. The apparatus A is required to enter a state corresponding to the value of the pointer property Z of A—the strictness of the (at least implicit) eigenvalue–eigenstate relation varies from interpretation to interpretation—which becomes correlated with the value of the measured property (non-degenerate observable) E of S.

Let us consider here, for simplicity, the case that the property to be measured, E, is representable as a discrete observable $E = \sum_i a_i |\psi_i\rangle\langle\psi_i|$, where $\{|\psi_i\rangle\}$ is an orthonormal basis for the Hilbert state space relevant to the system property. A minimal requirement required of a measurement is that a “calibration condition” be satisfied, namely, that if a property to be measured is a “real” one, then it should exhibit its value unambiguously and with certainty, that is, if S is in an eigenstate of E (call it $|\psi_k\rangle$) then the state of A after the interaction between the two is an eigenstate of a “pointer” observable Z (with eigenbasis $\{|\phi_i\rangle\}$ associated with a pointer reading z_k), which serves to indicate that the value of E was a specific value e_k. (The free-Hamiltonian function contribution to the evolution of the system is considered negligable relative to effect of the measurement interaction contribution.) Measurements in which this takes place are sometimes referred to as “perfect measurements” and all other measurements “imperfect.” Accordingly, for measurable properties represented by Hermitian operators, the calibration condition can be considered in the form of a probability reproducibility condition, namely, that a probability measure E_T for a property be “transcribed” onto that of the corresponding apparatus pointer property, thereby “objectifying” it. In addition to the above process of *registration* of the measured property by apparatus A, measurement is taken to include the reading of registered value.

The question of how pointer objectification is achieved, in view of the non-objectivity of the measured operator, is the first part of the “objectification problem,” formed together with the achievement of "value objectification" [18], its second part. A pointer reading refers to the property value of the object system prior to measurement only if the measured observable was objective *before* the measurement.

The traditional quantum measurement problem arises because if the initial state of the joint system S + A is $|\psi_k\rangle|\phi_k\rangle$ and the measurement interaction were to be described by a time evolution described by a unitary operator U (corresponding to Process II), then the final state of the joint system would be $U|\psi_k\rangle|\phi_k\rangle$, which is an eigenstate of the observable $\mathbb{I}\otimes Z$ and the linearity of the unitary time-evolution operator then leads to the joint state being a superposition eigenstate of that observable.

$$|\psi_k\rangle|\phi_0\rangle \rightarrow U|\psi_k\rangle|\phi_0\rangle\ . \tag{1}$$

The result is a lack of objectification of the pointer observable in general, for example, when this superposition is non-trivial, i.e. has more than one summand, rather than being simply $|\psi_k\rangle|\phi_k\rangle$. When the measurement value is "non-objective" like this, the question arises as to what happens to the system in the course of the measurement. In general, some sudden state change so as to arrive at a joint state accurately reflecting the measurement outcome $|\psi_k\rangle|\phi_k\rangle$ is unavoidable. Attempts to minimize the irreducible state disturbance naturally lead to the concept of *ideality* of a measurement. Ideality requires another characteristic, that of repeatability: a *repeatable* measurement will put the system in a state in which the pointer reading X refers to an objective value of the measured observable. The notion of disturbance is sometimes defined by the requirement that the if S is in an eigenstate $|\psi_k\rangle$ before measurement it will be in that same state after measurement. If this is not the case, the measurement is considered *disturbing*.

Schwinger argued in particular that, due to the inevitability of the sorts of uncontrollable discrete particle interactions, which are due specifically quantum participants in the measurement process, namely, the intermediary particles involved in any actual interaction, one "must acknowledge that every time we make a measurement we introduce a new physical situation that is essentially different from the situation before the measurement" explaining such disturbance [4]. The resulting change, leading to the failure of repeatability due to this "new physical situation" arising from the interaction of elementary components of the measuring apparatus with the measured system. This is seen by Schwinger as underwriting the non-unitary nature of the result of measurement interaction as formalized in terms of S and A alone, although he does not view this as arising from separate sort *quantum mechanical process* from what otherwise takes place. In Sect. 4 below, we explain how this insight can be formulated as an argument in support of the view that the quantum mechanical measurement problem results from an *inappropriate idealization of the measurement process in quantum mechanics*.

However, before developing this argument, it is valuable first to sketch the main line of investigation of the quantum measurement problem by others which represents a partial retreat from the idealizations of von Neumann. Significantly, Huzihiro Araki and Mutsuo Yanase [19], following Eugene Wigner [20], produced a theorem within von Neumann's general approach to measurement theory demonstrating the availability of approximate measurements in the theory. Asssuming, as usual, that the measured object was prepared in an eigenstate $|\psi_m\rangle$ of the quantity E to be measured, while the measuring apparatus was prepared in an initially uncorollated state $|\xi\rangle$, they first find that

$$U(t)[|\psi_m\rangle|\xi\rangle] = |\psi_m\rangle|\phi_m\rangle\ , \tag{2}$$

with the corresponding unique state of the apparatus obtains only if the operator E commutes with all additively considered quantities and t is a time sufficiently long for the apparatus to reach $|\psi\rangle_m|\phi_m\rangle$ in the process, cf. [21]. They then define approximate measurements via a notion of *malfunctioning* for the apparatus. In particular, this will happen when, instead of the above precise measurement evolution of the joint system, one has an additional state-vector component, so that

$$U(t)[|\psi_m\rangle|\xi\rangle] = |\psi_m\rangle|\phi_m\rangle + |\chi\rangle|\theta_m\rangle\ , \tag{3}$$

where $\langle\phi_m|\theta_m\rangle = 0$ and $||\chi\rangle|\phi_m\rangle|^2 < \epsilon$, and the correspondence between the reading and object value occurs with probability $1 - \epsilon < 1$. Araki and Yanase provided an illustrative situation in which the malfunction probability ϵ could be made as small as desired and from this demonstration claimed that such an approximate measurement could always be made, which might be viewed as removing the ideal requirement that measurements always result in perfectly correlated pointer readings; their idea was to address the imperfections of actual measurements by weakening the correlation between object observables and pointer observables. However, a number of works have reduced the prospect of such a solution to the measurement problem, in particular, those of Bernard d'Espagnat [22,23] and Arthur Fine [24], culminating in the proof by Shimony [25] showing that this particular solution will not do when assuming the object observable of interest is a sharp, that is, self-adjoint operator (or represented by a spectral measure) as above, cf. [21]. Moreover, another way of taking into account imperfection, namely taking the object observables themselves to be unsharp, was taken up by Paul Busch and Shimony to extended Shimony's 1974 result to the case of unsharp observables represented as a positive operator valued measure [26]. Thus, it is seen that even approximate measurements cannot generally be achieved via Process II alone.

Another means that has been used to illustrate the inappropriateness of the idealizations made in the quantum theory of measurement is Schrödinger's cat example. In this example, an unstable atom S is prepared the decay of which would release a hammer H that, when released, would break a vial containing poison and allow the cat C, which is taken as otherwise isolated from the rest of the universe, to be exposed to the poison [27]. The results is the "absurd" (as Schrödinger calls it) appearance of two equiprobable distinct states of the cat's 'health' at a particular moment in the corresponding state of the joint system,

$$|\Psi\rangle = 1\sqrt{2}(|\text{undecayed}\rangle_{\text{S}}|\text{unreleased}\rangle_{\text{H}}|\text{alive}\rangle_{\text{C}} + |\text{decayed}\rangle_{\text{S}}|\text{released}\rangle_{\text{H}}|\text{dead}\rangle_{\text{C}}). \tag{4}$$

This situation illustrates the use, decried by Bohr, of quantum theory in the classical realm, cf. [14]. One can equally well, as a position like Bell's would relatively favor, view this as a situation involving complex physical circumstances. Schwinger would later point, in particular, to the role of fundamental force quanta in producing such decays, which is not taken into account in this treatment.

4 Schwinger's View of Disturbance

Schwinger took a different tack in his consideration of limitations on the measurement process from that of the formal theory of measurement, by improving upon the "old" idea of measurement disturbance first introduced by Bohr in 1927 (in lectures published in 1928) as mentioned in Sect. 2 above, namely, that the quantum of action is responsible for inherent limitations on quantum measurement as enshrined in the quantum postulate. Schwinger's improvement is to provide a characterization of this responsibility by reference to a feature which, given the structure of the world at the subatomic scale, any measurement must involve: the interaction of particles of non-negligible force charge. It is the appearance of these particles which is uncontrollable; Schwinger argues that the corresponding interaction will always be sufficiently strong at the atomic scale that it cannot be neglected. In classical theory, the interactions between the physical systems involved can always be taken to be arbitrarily weak. The inability to neglect the influence of atomic level interactions, according to him, is what renders quantum measurements classically inexplicable.

> The measurement act involves a strong interaction—I repeat: on the microscopic scale it is necessarily strong because we cannot cut the strengths of the charges…; we cannot change the properties of these fundamental particles…so the measurement unavoidably produces a large disturbance, which we cannot correct for in each individual event in any detail. ([4])

Furthermore, the states of quanta, including those of interaction-mediating particles, cannot be controlled and so cannot be prepared. This lack of control will lie at the bottom of any chain of measurement from the subatomic scale upward to that of any human beings considered. Thus, because one "can only predict or control what happens on the average, never in any individual instance…the program of computing what the effect of the disturbance was and correcting for it is, in general, impossible" [4].

Models of imperfect measurements, such as those mentioned above, have been developed but strong arguments have been given showing that there will always be measurements that cannot be modeled by them, cf. [28]. The picture of the quantum measurement of Schwinger is different from those in those various models. On Schwinger's view, quantum mechanics is to be seen as a theory of processes which is in his words "statistically deterministic," just as is that of von Neumann. For example, Schwinger writes that quantum mechanics "is a causal, but [only] statistically deterministic theory", [4], p. 15. But for Schwinger, the discontinuous change of state connected with the measurement process is intimately connected with the *structure of the world*, which involves at its most basic level, indistinguishable elementary quanta whose individual identity cannot even generally be established. It is his view that, in general, it is not legitimate to talk, for example, about a distinct electron and photon when the two are interacting, as in the Heisenberg microscope example. Thus, the measurement process when treated in detail, cannot even be accurately represented as above in Eq. 1. In fact, considering this picture further, one sees that the relevant interaction mediating particles will not even exist when the measurement apparatus is prepared.

Notably, this runs contrary to the often expressed opinion that the essential character of the measurement problem is preserved in the transition from the quantum mechanical description to the quantum field theoretical description, cf. e.g. [29]—the essential nature of the problem being the presence of a unitary temporal evolution of state for quantum systems, making it apparently impossible for the systems quantum mechanics describes ever to exhibit a non-unitary change of state. Because of the consideration of the role of the quantum fields in any measurement interaction, one might imagine that the shortcomings of Eq. 1 could be compensated for through the inclusion of the relevant quantum fields as an environment, say one appearing as a third subsystem to be included in the description of the measurement process. However, the latter is not available in the case of the description of an individual instance of any measurement. The inclusion of an environment as a third subsystem has been attempted in quantum mechanics in what is known as the "decoherence approach" but this approach differs from the inclusion of a precise specification of the field in the description of the process.

The decoherence approach makes at least two assumptions about the subsystems involved. First, the object of measurement should have a relatively small number of degrees of freedom relative to the measuring apparatus which is considered to include a very much larger number of degrees of freedom. In the decoherence treatment the total system considered is thus

$$\mathcal{H} = \mathcal{H}_{\rm A} \otimes \mathcal{H}_{\rm e}\ , \tag{5}$$

where $\mathcal{H}_{\rm e}$ could itself be analyzed as a tensor product of sub-sub-environments, each described by its own Hilbert space. Second, it is assumed that the degrees of freedom of the apparatus are affected by the macro-variables (in the statistical sense) of the environment which are treated as distinguished states of the apparatus, while the object of measurement is assumed *not* to be disturbed by the environment, cf. e.g., [28] Sec. 4:

> Consider an object with a discrete set of macroscopically distinguishable states (an example could be a chiral molecule), interacting with some unspecified particles in the environment. The particles are scattered off the object, after which they essentially cease to interact with it, and move away in different directions. Suppose for simplicity that the environment is initially in a product state $|\epsilon_0^1(t)\rangle \otimes |\epsilon_0^2(t)\rangle \otimes \ldots$ At any time t, a certain number $n(t)$ of particles has been scattered off the object, and each of these is in a state, say $|\epsilon_i^k(t)\rangle$, that depends on the state $|\psi_i\rangle$ of the object, and that asymptotically approaches a plane wave $|\epsilon_i^k\rangle$.

In the process, the apparatus state evolves into the state ρ, a "decohered" density matrix which is nearly diagonal in pointer variable of interest. As seen above, Schwinger's picture differ significantly from this picture because of its emphasis on the uncontrollability of field quanta precluding the specification of the "environmental" initial state of this description.

Rather than constructing a theory of measurement according with any of the above models, Schwinger [4] induces a formalism for calculating the results of quantum measurements by considering situations involving the measurement of one of three relevant properties A, B, and C on a set of identically prepared systems, the selective measurement, non-measurement, and non-selective measurement of B, and points of the significance of the difference between the non-selective measurement of B and the non-measurement of B for the notion of disturbance in quantum measurement, namely, that (even the) non-selective measurement discontinuously disturbs the object system. To illustrate the pertinence of the structure of the world here, he considers the example of measuring the electric field at a point, which is standardly done by placing a test charge at that point ("itself an idealization") and measuring the force on the test charge. The character of actual test charges is that they differ from those considered in the classical theory of measurement which takes their magnitude to be arbitrarily small: the classical assumption is all very well "until one reaches the atom and the electron within it and discovers that (current speculations aside) there are no smaller charges," showing that the structure of the world "sets a fundamental limit to the basic idealization that is implicit in classical physics. And that's what quantum mechanics is all about" [4], p. 46.

For Schwinger, quantum mechanics was a symbolic expression of laws of measurement at the microscopic level. He induces his formalism by first considering (echoing Bohr) the "symbol" M_b of the non-selective measurement of a property B to be such that the condition that the process leading from measured system state a to state c have the probability

$$p(c, b, a) = \sum_{i=1}^{m} |\langle c|b_i\rangle\langle b_i|a\rangle|^2 = |\langle c|P_b|a\rangle|^2 \,. \tag{6}$$

One can then write M_b in the form

$$M_b = \sum_{i=1}^{m} |b_i\rangle e^{i\phi(b_i)}\langle b_i| \,, \tag{7}$$

where the $e^{i\phi(b_i)}$ are real phases. The notion of uncontrolled disturbance is then brought into play (closely following the mathematics of Heisenberg's treatement in [8], Ch. 4, Sect. 1): it is noted then that if the events of measurement are uncontrolled, the $e^{i\phi(b_i)}$ phases are randomly distributed, so that off-diagonal elements of the density matrix of the ensemble of measurements are all zero upon the measurement of the property B, the symbol corresponding to B being $B = \sum_{i=1}^{m} b_i|b_i\rangle\langle b_i|$.

Schwinger simply viewed the measurement problem as "a non-existent problem, one the flows from a false premise, namely the von Neumann dichotomization of quantum mechanics…Perhaps what has been lacking is a detailed analysis of the dynamics involved in some realistic measurements" [31], p. 369. Thus, rather than arguing that there is a different physical process, for example, decoherence responsible which is to be modeled in quantum mechanics, inspired by Bohr's early emphasis on quantum mechanics' accounting for the finite and uncontrollable nature of interactions on the atomic scale, Schwinger holds the position that the quantum formalism already takes the discrete, uncontrolled nature of interactions mediated by field quanta into account through its statistical and vectorial state character, making any such attempt to explain Process I *within quantum mechanics* superfluous and misguided.

It should be noted, finally, that Schwinger objected to the standard treatment of quantum fields, and introduced source theory as alternative approach (for example to that which had been introduced by Feynman and Dyson) that avoids the use of operator-valued functions of space-time and allows quantum field theory to be defined non-perturbatively in terms of Green's functions [32], which he hoped would avoid various significant difficulties faced by the standard approach itself; Schwinger's is a phenomenological treatment specifically intended to connect physically observable quantities and their correlations.

5 Beyond Schwinger's Measurement Algebra

Bohr claimed that the "impossibility of neglecting the interaction with the agency of measurement means that every observation introduces a new uncontrollable element," which he rendered a principle. Later, Schwinger suggested an underlying physical basis for this "element," as one lying beyond basic quantum mechanics: measurements essentially involve uncontrolled disturbance because physical interaction involves *fundamental particles*, which bear discrete properties and whose behavior during measurement interactions is beyond control. Indeed, because the interactions essential to any quantum measurement are mediated by quanta—which, unlike the systems typically considered in basic quantum mechanics, are indistinguishable entities that are excitations of an underlying field—measurements in basic quantum mechanics are processes which exhibit behavior that reflects the disturbance arising from the uncontrollability of these quanta, which is not a feature of classical processes.

A further exploration of the notion that quantum field excitations play a role in quantum measurement, because they are ineliminable entities serving as the mediators of the forces responsible both for the stability of the material components of any measurement apparatus used by human beings (or in some cases, such as the direct persception of light, our own sensory organs and nervous system) and the internal mechanical interactions and signals of which are essential in providing experimental data to us regarding the entities we measure, is called for: it is worthwhile enquiring as to whether this insight of Schwinger can lead to further progress in understanding quantum measurement.

Let us now, briefly and finally assume a realist perspective distinct from Schwinger's philosophical inclinations. Schwinger's suggestion that disturbance originating in quantum fields can be seen as grounding quantum measurement theory *within* quantum mechanics can be taken in relation to the notion of the objective indefiniteness of those dynamical physical properties of quantum mechanics systems. These are those which have *not* been become definite by previous, preparatory interactions but, instead, become actual only through measurement-like interactions. This can be done by viewing the presence of the pertinent field quanta as a *manifestation of such actualization*. In interactions such as successful measurements, field quanta can then be viewed as having irreversible effects because they come into existence and persist long enough to give rise to a chain of effects resulting in the production of experimental data.

6 Conclusion

In its standard formulation, quantum mechanics takes measurements as fundamental: the quantum state of a measured system is taken to change discontinuously when a measurement is made of a property of the system. Bell's judgment was that it is problematic for a fundamental theory (as opposed to practical purposes of laboratory use) and must be due to a lack of conceptual imprecision because the notion of measurement is self-evidently non-fundamental. An important example of the contrary idea that measurement *is* fundamental is Bohr's position that quantum mechanics must and does involve an essential wholeness that is evident in the consideration of atomic processes, the realm for which the theory was first designed and in which it is unavoidable, where the indivisible quantum of action differentiates quantum processes from the continuous processes of classical mechanics; this wholeness was emphasized by Bohr through his use of the term "phenomenon" to refer to observations as obtained under specified circumstances, including the specification of the entire experimental arrangement.

It is natural, however, following Bell's critique of quantum measurement theory, to wonder whether there is not another, more basic reason for this. Here, Schwinger's more specific picture of quantum discontinuity as due to ineliminable, uncontrollable disturbance was contrasted with various versions of accouting for measurements within quantum measurement theory. It was seen that Schwinger's explanation for the discontinuous nature of state evolution during quantum measurements has a fundamentally different character from other approaches to the resolution of the difficulties surrounding measurement as a quantum mechanical process, one more in line with Bell's critique of the theory of measurement *within* quantum mechanics, by noting the presence of elements beyond basic quantum mechanics, namely *field quanta*.

Serious consideration of this picture of measurement suggests that any detailed treatment of measurement must go beyond basic quantum mechanics to a more detailed picture explicitly including the role of quantum fields in actual measurements and other large-scale natural processes encountered in the physical sciences.

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