A model of the measurement process in quantum theory

H H Diel
Diel Software Entwicklung und Beratung, Seestr.102, 71067 Sindelfingen, Germany
E-mail: diel@netic.de

Abstract. The so-called measurement problem of quantum theory (QT) is still lacking a satisfactory, or at least widely agreed upon, solution. A number of theories, known as interpretations of quantum theory, have been proposed and found differing acceptance among physicists. Most of the proposed theories try to explain what happens during a QT measurement using a modification of the declarative equations that define the possible results of a measurement of QT observables or by making assumptions outside the scope of falsifiable physics. This paper proposes a solution to the QT measurement problem in terms of a model of the process for the evolution of two QT systems that interact in a way that represents a measurement. The model assumes that the interactions between the measured QT object and the measurement apparatus are "normal" interactions which adhere to the laws of quantum field theory.

1. Introduction

QT is a theory on (possible) processes in subatomic physics. It supports the computation of probabilities for a process to evolve from state \( s_i \) toward state \( s_f \). To a limited degree, QT also allows the computation of intermediate states and paths taken to reach the final state \( s_f \). Even less is known about how the multitude of alternative measurement results is converted into a definite result during a measurement. The details on how a measurement performs the transition from possible measurement results to definite measurement results are still in dispute among physicists. Alternative theories, called interpretations of QT (e.g., Copenhagen interpretation, many worlds interpretation (see [4])) have been proposed. Thus far, there does not seem to be general agreement among physicists of the correct, or at least most plausible, interpretation of QT.

The author claims that satisfying answers to the open questions related to QT measurements can only be obtained by considering the process that represents a measurement. The author furthermore assumes that the primary process elements involved in a measurement are interactions between the measured QT object and the measurement apparatus, and interaction processes are therefore the subject to be studied.

The QT area that addresses the interactions between particles and between particles and fields is quantum field theory (QFT). QFT addresses interactions between particles to a great extent (see [6], [8], [9]). QFT, with its Feynman diagrams and description of scattering processes, may also be viewed as containing some elements of a process-based description. The paper shows that the assumption that measurements consist of "normal" interactions that adhere to the laws
of QFT partly explains some of the peculiarities of QT measurements if this is combined with a description of the interaction process.

Within physics the preferred method for the description of temporal relationships and of a physical process is the provision of differential equations. In [3], the author explains that more complicated temporal relationships and processes (which may also occur within physics) cannot be described by purely differential equations. Unfortunately, there does not exist a method (i.e., language) that is equally elegant as differential equations for the specification of more complex processes. Available description methods mainly originated from computer science (e.g., programming languages) and are often more complicated (because they are more powerful) than seems to be necessary for the description of physical processes.

In section 2, the basic aspects of the measurement process are discussed in relation to the measurement problem. Sections 3 and 4 give a summary of the functional model of QT within which the model of the measurement process is embedded.

2. The measurement problem
The measurement problem of QT can be expressed by a set of questions related to the overall question of what exactly happens during a measurement. The set of questions varies depending on selected basic assumptions to start with. A concise description of the measurement problem is given in [7] in the form of a trilemma. In [7], Maudlin shows that the following three claims are mutually inconsistent:

(i) The wave function of a system is complete.

(ii) The wave function always evolves in accord with a linear dynamical equation (e.g., Schrödinger equation).

(iii) Measurements always have a definite outcome.

Maudlin shows variations of these contradicting claims that are contradicting as well.

The proposed model of the QT measurement process has to be built on assumptions that avoid the above-described contradictions. This is the case with the following set of basic assumptions:

(i) The wave function is complete. This means the proposed model of the measurement process acts on the state of the system, and the description of this state of the system is derived purely from the wave function(s) and related parameters of the involved QT entities.

(ii) The wave function (and the state of the system of the process model) does not always evolve in accordance with a linear equation. The linear equations (e.g., Schrödinger equation) describe the evolution of probability amplitudes. The transition from probabilities to facts and the reduction to definite values are not (necessarily) described by linear equations.

(iii) Measurements of, for example, the spin of an electron always have determinate outcomes. A part of the measurement process is the reduction of the set of possible alternative outcomes to a single definite value.

Starting with these basic assumptions, further questions may be asked which have to be answered by a satisfactory model of the measurement process:

• Does measurement determine the state of a QT object?

• Why is it impossible to measure the non-definite state of the system?

• Why can certain observables not be measured simultaneously?

• When (in the sequence of process steps or under which circumstances) does the transition from probabilities to facts occur?

• Is a measurement always coupled with the collapse of a wave function?

• Is the transition from probabilities to facts related exclusively to measurements?

• Is the measurement process random or deterministic?
3. The functional model of Quantum Theory
The model of the measurement process described in this paper is embedded in an overall functional model of QT (see [1]) and is based on the functional model of interactions in QT (see [2]). A functional description of a system describes the dynamical evolution of this system in terms of state changes.

The main characteristics of the functional model of QT described in [1] and [2] are:

- Discreteness of QT attributes
  The functional description of QT assumes discrete and coarse grain attributes not only for three-dimensional space, but for most other entities where standard QFT assumes differentiable attributes. This applies to the spatial extension of particles/waves and to their momentum. Also, the wave function is structured into a discrete set of alternative paths (see section 4.1 System State). This splitting into multiple paths is essential for the functional model of interactions as well as for the model of the measurement process.

- Transition from possibilities to facts
  The functional model of QT demonstrates the evolution of the wave function to generate probability amplitudes in accordance with the predictions of QT/QFT. However, it does not end with the determination of probability amplitudes but includes a model for the realization of the predictions represented by the probability amplitude. This process step is called "the transition from possibilities to facts". With standard QT, the transition from possibilities to facts is a non-deterministic process step that occurs exclusively with measurements.

  One of the key features of the functional description of QT is that the transition from possibilities to facts is not exclusively tied to measurements. The functional description assumes that measurements always imply interactions, more specifically, interactions that lead to a collapse of the wave function. The statement that the transition from possibilities to facts is not exclusively tied to measurements, first of all, means that the collapse of the wave function is not exclusively observed with measurement interactions. The collapse of the wave function also occurs with other ("normal") interactions.

- Particle fluctuations instead of virtual particles
  In the perturbation (Feynman) approach, virtual particles are an essential concept for describing interactions among particles. The functional description reinterprets the role of virtual particles; instead of the original QFT virtual particles, the functional description assumes "particle fluctuations" and "interaction channels". Particle fluctuations initiate the interaction, if the fluctuation location is shared by multiple particles. These particle fluctuations are assumed to actually occur (with a certain probability), whereas virtual particles are constructs which affect only the probability amplitudes of interactions.

- Splitting of a wave function collection into multiple paths
  The splitting of a wave function into multiple paths is a constituent part of the perturbation approach to QFT (see [5]). The overall effect of the wave function progression is then determined by the superposition (via path integrals) of the multiple paths. With the functional model of QT, the splitting into multiple paths is applied to collections of particles (see pw-collection below) which exit an interaction. This allows for the modeling of entanglement.

4. The interaction process
Two types of interactions between particles/waves are distinguished:

(i) "QFT interactions" - interactions that result in a change of the components and/or paths of one or both of the interacting quantum objects. This type of interaction is addressed by QFT in terms of, for example, the scattering matrix and Feynman diagrams.
Table 1. Structure of a q-object consisting of two particle/waves pw1 and pw2.

| paths | pw1-state | pw2-state | amplitude |
|-------|-----------|-----------|-----------|
| path-1 | pw1-state₁ | pw2-state₁ | ampl-1 |
| path-2 | pw1-state₂ | pw2-state₂ | ampl-2 |
| ...   | ...       | ...       | ...       |
| path-N | pw1-stateₙ | pw2-stateₙ | ampl-N |

(ii) "volatile interactions" - interactions which change only the values of attributes (e.g., momenta) of the interacting quantum objects.

For this description of the model of the measurement process, QFT interactions are of primary interest, because (1) QT measurements typically require QFT interactions to achieve observable effects and (2) QFT interactions are the ones which result in the complications associated with the QT measurement problem. In the remaining paper only the QFT interactions are considered.

4.1. System state

Within the state of the system of the functional model, the wave function is represented by the q-object (quantum object). The q-object may consist of a single particle/wave or a collection of (entangled) particles/waves (pw-collection). In a second dimension, the q-object consists of multiple paths with associated probability amplitudes (see Table 1).

q-object := path[1], ...
           path[NPATH];

4.2. Steps in an interaction process

The process steps occurring in the interaction process have to produce results that are compatible with the results predicted by standard QT/QFT, including the generation of result alternatives in terms of the probability amplitudes assigned to the S-matrix. With standard QFT, the treatment of an interaction is based on Feynman diagrams. Although Feynman diagrams already seem to contain certain process-oriented aspects, they are not a suitable basis for a functional (i.e., process-based) description. Typically, many Feynman diagrams are required to compute the result of an interaction. The results of the overall interaction are determined from the superposition of the individual diagrams. There are no reasonable intermediate states or any process structure derivable from the collection of diagrams. As described in section 3, the functional model of QT assumes particle fluctuations and interaction channels instead of Feynman diagrams. The proposed model subdivides the overall interaction process into four process steps:

perform-interaction ::= {
   Step1: Appearance and start of an interaction - particle/wave fluctuation;
   Step2: Generation of the interaction-object;
   Step3: Formation and processing of interaction channels;
   Step4: Generation of the "out"-pw-collection - Information exchange;
}

Step1 (appearance and start of an interaction) and step4 (generation of the "out"-pw-collection) are key for the process model of QT measurement.

1 Nevertheless, typical measurements contain both types of interactions.
4.2.1. Appearance and start of an interaction - particle/wave fluctuation

Concerning the appearance and start of an interaction, this model of the QT measurement process makes two assumptions that are essential for an explanation of the QT measurement process:

(i) The appearance of an interaction is an event that actually happens (with a certain probability). Insofar, the occurrence of an interaction is the first step in the transition from probabilities to facts, which is associated with QT measurements.

(ii) An interaction occurs at a definite position. If a q-object consist of multiple paths, only the path(s) that occupy the interaction position affect the interaction process further. The remaining paths are eliminated. This may be viewed as the collapse of the wave function. The elimination of the unaffected paths represents a reduction of the wave function and of the measurement result to a definite value (with respect to position).

Both assumptions cannot be derived from existing QT/QFT, but they are only in conflict with existing QT/QFT if one believes that the Schrödinger equation and similar equations of motion completely determine the dynamical evolution of a QT system, including the transition from probabilities to facts.

Thus, the appearance of an interaction, including its location, is determined randomly. Various mechanisms are imaginable for the random determination of the interaction position. The functional model assumes that an interaction is a possible consequence of a particle/wave fluctuation, which supports that the interaction occurs at a definite position.

4.2.2. Generation of the interaction-object

At the beginning of the interaction process the information from the interacting particles is merged into the interaction-object. Further details on this process step are not important for the model of QT measurement, but can be obtained from [2].

4.2.3. Formation and processing of interaction channels

The main processing of the interaction consists in the formation and processing of ia-channels (interaction channels). Ia-channels (like virtual particles) guide the possible flow of particle transitions during an interaction. Further details on this process step are not important for the model of QT measurement, but can be obtained from [2].

4.2.4. Generation of the "out"-pw-collection - Information exchange

The processing of the ia-channels ends with a certain "out" particle/wave combination. With some types of interactions, different "out" particle/wave combinations may occur. For example, with Bhabha scattering (i.e., electron-positron scattering) the "out" combinations (electron, positron), (muon, antimuon), and (taun, antitauon) are possible. The process model of QT interactions assumes that, from the possibly multiple alternative "out" particle/wave combinations, only one leads actually to an interaction. This is a further instance of transition from probability to facts.

The detailed mechanism for the selection of the "out" particle/wave combination is beyond the scope of the present paper. Several alternative mechanisms are imaginable.

At the end of the interaction, the ia-channels perform superpositions to produce the "out" pw-collection containing the "out" particle/waves. The "out" pw-collection consists of (a discrete set of) paths to reflect all possible interaction results for which the scattering matrix provides a non-zero probability amplitude.

Thus, the interaction may be said to transform the information from the "in" particles to the information of the "out" pw-collection.

2 Because standard QT does not assume multiple points for the "transition from probability to facts", this possibly represents a deviation from standard QT, which however will be difficult to test.
5. The model of the measurement process

Measurement may be viewed as the mapping of the state of the measured q-object to the state of some measurement device. For this purpose, at least one QFT interaction has to be performed between the measured particle and the measurement apparatus. Depending on the kind of measured state component, further interactions may be required to prepare for the main interaction, and still further interactions to transform the measurement result to usable information. Measurements are realized through normal interactions. Normal interactions are those types of interactions that are used to implement a measurement and may also occur in situations not related to measurements.

To understand the limitations of QT measurement (which result in the QT measurement problem), the understanding is that QFT interactions are not information preserving transformations for two reasons:

(i) Reduction

At the start of the interaction, the multitude of alternative paths is reduced to those paths which occupy the interaction position (see section 4.2.1).

(ii) QFT interactions do not represent a bijective mapping

Although it has been shown that the scattering matrix $S$ is a unitary matrix (i.e. there exists an inverse matrix $S^+$ such that $SS^+ = 1$, see [9]), this does not mean that it is possible to deduce the complete "in" state of the interacting particles from the "out" state of the interaction.

5.1. Answers given by the process model to questions related to the measurement problem

Based on the above described functional model of QFT interactions and the limited information transformation with QFT interactions, the following answers to the questions related to the measurement problem are offered.

- Does measurement always have a definite outcome?

The functional model assumes that measurements are always realized using QFT interactions. QFT interactions reduce the set of alternative paths to a single path as input (parameter) to the interaction process. If the QFT interaction is capable to map this single path to observable facts (e.g., the interaction position) in the "out"-state of the interaction, this may be called a definite outcome. A non-definite outcome is possible (it is even the default case), but is useless if it does not provide information on the complete set of alternative paths.

- Does measurement determine the state of a QT object?

The purpose of a measurement is the determination of specific components of the system state. Unfortunately, a measurement, in general, also changes the state of the measured QT object?

- Why is it impossible to measure the non-definite state of the system?

Measurement of the non-definite state of the system would mean a bijective mapping of the complete set of alternative paths of the q-object (rather than a single path) to an observable "out"-state of a QFT interaction. QFT does not support such interactions.

- Why can certain observables not be measured simultaneously?

Generally, QT observables which do not commute (i.e., $[O_1, O_2] \neq 0$) are said to be non-simultaneously measurable with arbitrary precision. The standard example for QT observables which are not considered to be simultaneously measurable are the position $X$ and the momentum $P$. According to the functional model of QFT interactions, a measurement (i.e., a QFT interaction) which maps the position as well as the momentum of the selected
Table 2. Structure of a q-object $\psi$ consisting of two entangled particle/waves $pw1$ and $pw2$.

| paths | pw1-state | pw2-state | amplitude |
|-------|-----------|-----------|-----------|
| path-1 | pw1-up    | pw2-down  | ampl-1    |
| path-2 | pw1-down  | pw2-up    | ampl-2    |
| ...    | ...       | ...       | ...       |
| path-N | pw1-state$_N$ | pw2-state$_N$ | ampl-N    |

path of the measured q-object, is possible, but useless because the measurement results do not sufficiently reflect the state of the measured QT object.

- Is a measurement always coupled with the collapse of a wave function?
  To deliver observable facts, reasonable measurements have to be realized using QFT interactions. 3 QFT interactions imply a reduction of the set of alternative paths to a single path. This may be called a "collapse of a wave function".

- Is the transition from probabilities to facts related exclusively to measurements?
  In view of the q-objects of the state of the system described in section 3, the phrasing transition from probabilities to facts is misleading. More correctly, we should rather say transition from a set of alternative paths with associated probability amplitudes to a state of the system where one of the alternatives is selected and its properties mapped to observable facts in the "out" state of an interaction.

  As described in sections 3 and 4, this process is not exclusively related to measurements but occurs with each QFT interaction.

- When (in the sequence of process steps or under which circumstances) does the transition from probabilities to facts occur?
  The functional model assumes multiple points within the interaction process where the changes in the state of the system are a function of the probability amplitudes. The most important point is the occurrence of an interaction and the determination of the interaction position.

- Is the measurement process random or deterministic?
  The functional model assumes that the transition from probabilities to facts performed with QFT interactions is random based on probability amplitudes.

6. Discussions

6.1. Handling of entanglement

Entanglement is related to measurement. Two particles/waves $pw1$ and $pw2$ are entangled, if the result of a measurement of $pw1$ influences the possible results of a measurement of $pw2$. The typical example used in QT literature is the wave function

$$\psi = \frac{1}{\sqrt{2}} ( | pw1.\text{up}, pw2.\text{down} > + | pw1.\text{down}, pw2.\text{up} > )$$

referring to a wave function $\psi$ with entangled elements $pw1$ and $pw2$. With the functional model of QT $\psi$ would be represented by a particle/wave-collection consisting of the two elements $pw1$ and $pw2$ and a discrete number of paths which reflect the correlation (see Table 2). 4 As described in sections 3 and 4, a measurement (using a QFT interaction) reduces the set of paths to a single path. This selects not only the definite value for the first measured object (e.g., $pw1$), but also the possible measurement results for the other element, e.g., $pw2$. 5

3 There may be experiments which do not include QFT interactions, but nevertheless deliver useful information. However, such experiments are not considered typical measurements by the author.

4 Differing from eq. (1), the q-object has to state explicitly the whole set of alternative paths.

5 This does not mean that the measurement value for $pw2$ is already uniquely determined.
6.2. Relation to standard QT/QFT

Although the process model aims for maximum compatibility with standard QT/QFT, there are exceptions in the process model. Examples include some small deviations to standard QFT that have been intentionally included, items where it is not clear what the QT/QFT conformal behavior exactly is, and items where there is no equivalent QT/QFT position because the level of detail is below the scope of QT/QFT. For all of these areas, verification by experiments is appropriate. There is one area in which the functional model is designed to deviate from standard QT/QFT: the concept of the transition from probabilities to facts. The process model assumes the transition from probabilities to facts to occur in multiple steps. As indicated in section 4, it will be very difficult to test possible deviations from standard QT in this area.

7. Conclusions

Measurements are realized by interactions between the measured object and parts of the measurement apparatus. With QT measurements, the possibilities for interactions to map the state of the measured QT object to the state of the measurement apparatus are limited. The greatest potential for a useful mapping is given with what in this paper is called QFT interactions. The transformation of the "in"-state of a QFT interaction to the "out"-state is supported by QFT in terms of scattering matrices and Feynman diagrams. However, QFT interactions, too, are severely limited in their capabilities to map the state of the measured QT object to the "out"-state of the interaction, for two reasons:

(i) QFT interactions change the state of the measured object. This reduces the possibilities to determine the state of the measured object through multiple (accumulative) interactions.

(ii) QFT interactions are not information preserving, i.e., it is not possible to deduce completely and exactly the "in"-state of the interaction from the "out"-state (see section 5).

These limitations are the cause of the peculiarities associated with the QT measurement. A more detailed explanation, including answers to questions associated with the QT measurement problem, can be given (and has been given in this this paper) by a model of the QT measurement process.

A key ingredient of the proposed process model of QT measurement is the assumption of a discrete set of alternative wave function paths. The evolution of this set of alternative wave function paths during the process of a QFT-based interaction explains many of the peculiarities of QT measurements.

As described in section 6, there exist a number of points where the functional model of QT interactions (within which the proposed model of QT measurement is embedded) possibly deviates from standard QT/QFT, either intentionally or where the QT/QFT position is unclear, or where the level of detail is below standard QT/QFT. From the list of (possible) deviations and refinements from standard QT/QFT, only a small part is essential for the described process model of QT measurement. The major part of the proposed process model of QT measurement is based on an extended application of existing QT, in particular QT.

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