Bohr-Heisenberg Reality and System-Free Quantum Mechanics

George Jaroszkiewicz* and Jon Eakins
*School of Mathematical Sciences, University of Nottingham
University Park, Nottingham NG7 2RD, UK

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Abstract

Motivated by Heisenberg’s assertion that electron trajectories do not exist until they are observed, we present a new approach to quantum mechanics in which the concept of observer independent system under observation is eliminated. Instead, the focus is only on observers and apparatus, the former describing the latter in terms of labstates. These are quantum states over time-dependent Heisenberg nets, which are quantum registers of qubits representing information gateways accessible to the observers. We discuss the motivation for this approach and lay down the basic principles and mathematical notation.

1 Introduction

System-free quantum mechanics (SFQM) is an alternative and powerful way of thinking about and describing quantum processes. In principle it should do everything that standard quantum mechanics (SQM) can do and more; it should allow a discussion of situations involving more than one observer and provide a framework for describing dynamically coupled sequences of experiments, such as networks of Mach-Zender interferometers coupled in parallel, series, or both. Although our approach is novel, it was motivated by and is the logical consequence of Heisenberg’s view of reality, which led to matrix mechanics in 1925 [1]. Paradoxically, Heisenberg’s approach to quantum mechanics (QM) appeared too metaphysical and mathematically challenging for many theorists, and quickly lost ground to the more intuitive wave-mechanical formalism introduced by Schrödinger the following year. Although these radically different formulations were soon shown to be mathematically equivalent by Schrödinger himself [2], deep differences remained between the views of Heisenberg and Schrödinger on the nature of physical reality. The former wished to focus only on what could be observed, whilst the latter believed in an underlying classical reality generating those observations.

Heisenberg restated his views in his uncertainty paper of 1927 [3]. In the context of the correspondence principle [4] he wrote: “I believe that the existence of the classical ‘path’ can be pregnantly formulated as follows: The ‘path’ comes into existence only when we observe it.” This statement is the foundation of the system-free approach to QM.

We shall call the principle that “if we have not observed something then it does not exist” quantum counterfactuality, or Heisenberg’s reality principle. In SFQM we take quantum counterfactuality to its logical conclusion and assume that systems under observation themselves do not exist independently of any contextual observation. Because Bohr’s views
on QM were allied to those of Heisenberg, we shall also refer to this idea as Bohr-Heisenberg reality.

In the next section we discuss the properties of observers and apparatus, which are central to our approach. Then we introduce the notion of a Heisenberg net, which provides the mathematical basis for our description. A Heisenberg net is a representation of all the information gateways accessible to an observer at a given time. This leads naturally to a discussion of the preferred basis and signal states. This puts us in a position to introduce the central concept of the labstate, which encodes the potential outcomes of an experiment in terms of the signals which the apparatus may emit. Dynamics is discussed in terms of how the labstate changes in time, requiring us to bring in the novel concepts of Born maps, semi-unitary operators and Schrödinger evolution. Finally, we discuss how signal operators evolve and give an expression for path summations, which are the SFQM analogues of Feynman path integrals in SQM. Nowhere do we deal with a state of a system under observation.

2 Observers

Following Heisenberg, the objective of SFQM is to focus as much as possible on those aspects of quantum physics which are physically meaningful, so what can we be sure of? When we describe a physics experiment, we can always be sure of two things: first, that there is an observer and second, that they use some apparatus. In SFQM, observers and apparatus are primary concepts which have to be taken as given. However, we can say some things about their properties.

In SFQM, an observer is always a physically real, classically autonomous subset of the universe with a sense of time, which can manipulate or interact with another physically real subset of the universe called the apparatus. Each observer has a time-dependent information/memory content and a set of rules for processing this information and manipulating their apparatus accordingly. There is no necessity to regard an observer as conscious, or alive in a biological sense.

The time associated with any observer is always discrete, but this discreteness is not necessarily defined in terms of equal standard intervals of time. Temporal discreteness arises because information is gained or lost by an observer only in stages, such as during state preparation or quantum outcome detection. Now from the point of view of decoherence theory or quantum field theory, it could be argued that we cannot always be absolutely certain when information has been extracted. In practice however, experimentalists really have no such problem, and it is this fact which we rely on here. Everything that experimentalists ever do amounts to the collection of answers to elementary yes/no questions. Moreover, although ordinary experience leads us to imagine that time is continuous, there is actually no hard evidence for that view. On the contrary, all of quantum physics is based on a comparison between initial and final states, which necessarily introduces a discrete view of time.

In SFQM, it is possible to discuss as many different observers as we want. Each observer will have their own sense of time, relative to which both their associated apparatus and information content may change. An important rule which is an essential and established feature of quantum counterfactuality is that different observers never share apparatus or information content at the same time. If they did, they would have to be regarded as a single observer with a single apparatus. This has significant implications for relativistic physics, which we do not have space to comment on here.
3 Heisenberg nets

Although SFQM is a consistent quantum theory fully backwards compatible with SQM, it is sufficiently different in its core values to warrant a modified notation for state vectors and operators. Recall that in SQM, states are often described by Dirac kets with angular brackets, such as $|\psi\rangle$. In SFQM we replace the angular brackets by round brackets, such as $|\psi\rangle$. Then it will always be clear which formalism is being used. This is very important, because conceptually quite different Hilbert spaces are involved in describing what looks superficially like the same thing. As for operators, we shall always denote SFQM operators acting over Heisenberg nets in blackboard bold font, such as $\mathbb{A}^+$. We provide an explicit mathematical representation of SFQM using the concept of a Heisenberg net, defined as follows.

First, we use the fact that an observer comes provided with a sense of time. This means that for a given observer, there is a notion of simultaneity. Different parts of a laboratory will be described at the same instants of the observer’s time, very much as if there was some sort of absolute time. Different observers need not have a sense of a common time or rate of time, however. That is consistent with relativity, which emphasizes the physical significance of non-integrable proper time compared to the purely formal integrable coordinate time used to discuss points in the spacetime manifold. Whenever we discuss a Heisenberg net, we will be thinking about it at a given instant of time in some local laboratory frame of reference. This frame need not be regarded an inertial frame, or even a freely-falling laboratory, so in this respect we anticipate the eventual construction of a SFQM approach to general relativity.

Second, at a given instant $n$ of an observer’s time, the observer assigns one quantum bit (qubit) to each information gateway, i.e., each piece of their apparatus where information could in principle be inserted into, or extracted from, the current state of their apparatus by them at that time. What such a qubit means will be further explained below.

The Heisenberg net $\mathcal{H}_n$ associated with a given observer at time $n$ is just the Hilbert space of all those qubits associated with their apparatus at that time. In SFQM, we shall assume that apparatus may change dynamically, so the associated Heisenberg net changes in consequence. At any given time we shall always suppose that there is a finite number, $r_n$, of such qubits. This is the only assumption that makes sense in the context of our description, because there are no real quantum experiments which can extract an infinite amount of information from any source. We note here a comment by Marvin Minsky on Feynman’s ideas on the representation of physics as a computational process [5]. Minsky wrote that Feynman did not like the concept of continuous space, because he could not see how a finite volume of space could contain an infinite amount of information [6].

We label the qubits in the Heisenberg net at time $n$ by $Q^1_n, Q^2_n, \ldots, Q^{r_n}_n$. How the upper index is assigned is arbitrary, there being no requirement at this stage to think of some of the qubits as nearest neighbours, or even ancestors of earlier qubits with the same indices. These qubits form a quantum register, or Heisenberg net $\mathcal{H}_n$, which is the tensor product $\mathcal{H}_n \equiv Q^1_n \otimes Q^2_n \otimes \ldots \otimes Q^{r_n}_n$. This is a Hilbert space of dimension $d_n \equiv 2^{r_n}$. The number $r_n$ of qubits will be referred to as the rank of the Heisenberg net at time $n$.

Before we discuss what states in a Heisenberg net register represent, let us clarify what the qubits making up the register represent. Most importantly and contrary to what might be expected, a given SFQM qubit does not represent the two distinct physical outcomes, such as spin up or spin down, of experiments such as the Stern-Gerlach experiment. Rather, each qubit represents a separate outcome detector, or detector site, or whatever constitutes a signal detector, associated with a single outcome. The two possible outcomes of an idealized Stern-Gerlach apparatus therefore require two SFQM qubits: one for the spin-up outcome and another for the spin-down outcome. Likewise, any apparatus described according to
SQM with $k$ possible outcomes would require $k$ qubits. This applies to situations where the PVM (projection valued measure) or the POVM (positive operator valued measure) formulations in SQM are used. The rule is simply to look at the laboratory, determine all those part of the apparatus where information could be obtained in elementary yes/no terms, and assign a qubit to each one.

Each Heisenberg net qubit has two possible physically observable states, but only one of these represents a positive physical signal in the associated detector. One of these states, denoted by $|0\rangle$, represents the detector in the void state. If the observer looked at the detector when it was in that state, it would register nothing, i.e., no signal. The other possible state of the detector is denoted by $|1\rangle$ and represents the fact that, if the observer looked at that detector when it was in that state, it would register a signal.

We emphasize several points. First, these detectors are not necessarily localized in space. For example, some of them could be associated with momentum, and as such, would not necessarily have a spatially localized physical realization. Each Heisenberg net qubit represents an elementary information gateway for the potential modification of the information content held by the observer, and this is rather general. This information is an essential ingredient in SFQM in another way; it is used by the observer to interpret what each qubit means. Without such information, apparatus is meaningless.

Second, SFQM is a universal theory, in that in principle its formalism should be applicable to any quantum experiment. We do not need to think only in terms of electrons and photons. What distinguishes one type of experiment from another, even in those case where the Heisenberg nets appear identical, will be the information content and the subsequent dynamical evolution.

Third, quantum counterfactuality is used throughout. We are dealing with a quantum theory, and therefore, the possible states of a Heisenberg net, referred to as labstates, represent a form of potentiality for observation in the future. This means that, if the observer chooses not to look at their detectors at time $n$ but "passes the labstate on to new apparatus", then the labstate at that time becomes the initial labstate for the next jump forwards in time. The formalism requires us in practice to restrict the discussion of all quantum processes to the forwards direction of time only.

For a given detector/information gateway $P$, the associated qubit $Q_P$ has all of the structure of a two dimensional Hilbert space. Given the natural basis states $\{ |0\rangle_P, |1\rangle_P \}$ for $Q_P$, we define the signal excitation operator $a^+_P \equiv |1\rangle_P \langle 0|$ and its dual, $a_P \equiv |0\rangle_P \langle 1|$. Apart from the identity operator $I_P$, these are the only qubit operators we shall use.

### 4 The preferred basis

SFQM avoids the well-known preferred basis problem which haunts SQM because there is a natural mechanism for selecting such a basis. This is the information content $I_n$ held by the observer at time $n$. Given any piece of detecting equipment, the observer will always know what amounts to a lack of a signal and what represents a signal. Given this knowledge, it is a trivial matter to associate the corresponding basis vectors $|0\rangle$ and $|1\rangle$ with this information for each qubit. Extending this to all the qubits in the current Heisenberg net gives $B_n$, the natural, preferred basis for $\mathcal{H}_n$.

There are various equivalent representations of $B_n$ which we shall use as circumstances dictate. The product representation describes the $d_n \equiv 2^{rn}$ elements of $B_n$ in terms of tensor products of individual qubit states, i.e.,

\[
B_n = \{ |0, n\rangle_1 |0, n\rangle_2 \ldots |0, n\rangle_{r_n}, |1, n\rangle_1 |0, n\rangle_2 \ldots |0, n\rangle_{r_n}, \ldots \\
\ldots, |1, n\rangle_1 |1, n\rangle_2 \ldots |1, n\rangle_{r_n} \},
\]

(1)
where for example $|i, n\rangle$ represents state $i$ of the $j^{th}$ qubit in the Heisenberg net at time $n$. Here we have suppressed the tensor product symbol.

The occupation representation is a more compact version of the above. Now we label the $d_n$ elements of $B_n$ in terms of the associated finite binary sequences, i.e.,

$$B_n = \{|00 \ldots 0, n\rangle, |10 \ldots 0, n\rangle, \ldots, |11 \ldots 1, n\rangle\}. \quad (2)$$

The signal representation is based on excitations of the void state $|0, n\rangle \equiv |00 \ldots 0, n\rangle$. First, we define the signal operators $\{A_{i,n}^+: i = 1, 2, \ldots, r_n\}$ by

$$A_{i,n}^+ \equiv I_{1,n}I_{2,n} \cdots I_{i-1,n}A_{i,n}^+I_{i+1,n} \cdots I_{r_n,n}, \quad 1 \leq i \leq r_n, \quad (3)$$

where again we have suppressed the tensor product symbol, and then we may write

$$B_n = \{|0, n\rangle, A_{1,n}^+|0, n\rangle, A_{2,n}^+|0, n\rangle, \ldots, A_{1,n}^+A_{2,n}^+ \cdots A_{r_n,n}^+|0, n\rangle\}. \quad (4)$$

The signal representation is particularly well-suited for SFQM. The basis set can be partitioned into disjoint signal classes, defined by the number of signal operators involved. The zero-signal class consists of just one element, the void state. The one-signal class consists of basis states of the form $A_{i,n}^+|0, n\rangle$, and there will be $r_n$ such states, and so on. More generally, the $k$-signal class consists of states of the form $A_{i_1,n}^+A_{i_2,n}^+ \cdots A_{i_k,n}^+|0, n\rangle$ and there are $\binom{r_n}{k}$ such elements in $B_n$. Counting up all the elements in all the signal classes gives us a total of $2^{r_n}$, as expected.

An arbitrary one-signal labstate will be a superposition of one-signal basis states, i.e.,

$$|\psi, n\rangle = \sum_{i=1}^{r_n} \psi_i^i A_{i,n}^+|0, n\rangle, \quad \psi_i^i \in \mathbb{C}, \quad (5)$$

suitably normalized to unity. For such a labstate, any actual outcome would involve a signal from only one detector site, with all the others remaining void. Quantum uncertainty means that, before the observer looked, they would not in general know for sure which one of the detectors would fire. Non-locality occurs here in terms of the apparatus detectors, not in terms of any system under observation. This effectively eliminates the wave-particle duality issue.

One-signal labstates model those situations when we know we are dealing with a one-particle system, such as a single electron or single photon, for example. Many traditional scenarios in SQM can be discussed solely in terms of such states, but we note that SFQM goes beyond one-signal labstates. For example, experiments involving pairs of photons in the initial state would be described by two-signal labstates in SFQM. Experiments such as those discussed by Einstein, Podolsky and Rosen (EPR), which involve two separated detectors firing simultaneously, would also require the use of two-signal labstates. There is nothing in the formalism which forbids superposition of different signal class elements, or dynamical changes of signal class. In this respect, SFQM is more like quantum field theory rather than Schrödinger wave mechanics.

The computation representation is based on the fact that any finite binary sequence $\{\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_r\}, \varepsilon_i = 0 \text{ or } 1$, can be mapped into a unique integer $i$ in the range $0 \leq i < 2^r$ via the computational map $i = \varepsilon_12^0 + \varepsilon_22^1 + \ldots + \varepsilon_r2^{r-1}$. Then we may write

$$B_n = \{|i, n\rangle : i = 0, 1, 2, \ldots, 2^{r_n} - 1\}. \quad (6)$$

Orthonormality is best described in terms of this representation, because now we can write $(i, n|j, n) = \delta_{ij}$, $0 \leq i, j < 2^{r_n}$. Completeness and the resolution of the identity $I_n$ are also best described in this representation.
5 Labstates

The labstate $|\psi, n\rangle$ is the current quantum state of an observer’s Heisenberg net at time $n$. We shall restrict our attention in this paper to pure labstates, which means that Heisenberg nets are regarded as certain and labstates are single elements in them. We have no space here to discuss mixed labstates, which will occur in situations where the observer’s information about the current labstate or the Heisenberg net itself is incomplete.

In general, labstates will always be normalized to unity, because the standard Born probability rules are assumed and there is no concept here of leakage of probability. If for example a signal corresponding to a particle “disappears”, the probability associated with it is transferred to the void state. For a given labstate, the probability that the apparatus is void added to the sum of the probabilities that one or more detectors have fired always sums up to unity. Using the computation representation of the basis $B_n$, a labstate can always be written in the form

$$|\psi, n\rangle = \sum_{i=0}^{d_n-1} \psi_i| i, n\rangle,$$

The coefficients $\{\psi_i\}$ in this expansion have the usual Born probability interpretation: $|\psi_i|^2$ is the probability that, given that particular labstate at time $n$, all of the detectors associated with the preferred basis vector $| i, n\rangle$ would each be in their signal state. For a given integer $i$ in the range $[1, d_n - 1]$, we can determine which qubits are in their signal state by inverting the computational map and decomposing $i$ as a unique sum of terms in the form $i = 2^{j_1-1} + 2^{j_2-1} + \ldots + 2^{j_k-1}$, where $j_1 < j_2 < \ldots < j_k$ are non-negative integers, for some non-zero $k$. Then we can write

$$|i, n\rangle = A_{j_1, n}^+A_{j_2, n}^+\ldots A_{j_k, n}^+|0, n\rangle,$$

for $0 < i < d_n$, which means that the detectors corresponding to qubits $Q_{j_1, n}^+, Q_{j_2, n}^+, \ldots, Q_{j_k, n}^+$ will fire whilst all the others remain void. To illustrate the point, suppose we have a rank-two Heisenberg net at time $n$. Then the most general labstate is of the form

$$|\psi, n\rangle = \{\alpha + \beta A_{1, n}^+, \gamma A_{2, n}^+, \delta A_{1, n}^+A_{2, n}^+\} |0, n\rangle,$$

with $|\alpha|^2 + |\beta|^2 + |\gamma|^2 + |\delta|^2 = 1$. Then the probability that no signal would fire is $|\alpha|^2$, the probability that only detector one would fire is $|\beta|^2$, the probability that only detector two would fire is $|\gamma|^2$, and the probability that detectors one and two would fire simultaneously is $|\delta|^2$, if the observer looked.

6 Dynamics

SFQM is designed to encode quantum dynamics in as realistic a way as possible, which means that there is no concept here of inconsistent histories or many worlds. An important characteristic of SFQM is that there is no scope for unphysical quantum states to occur. The only states considered are labstates, and these are always physically meaningful.

The information content held by an observer at time $n$ is regarded as classically certain and objective, relative to that observer, but it is not constant in time. As the observer’s time progresses, several things change with it, including the information content, the labstate, and the Heisenberg net itself.
6.1 Born maps

Given two finite dimensional Hilbert spaces $\mathcal{H}$, $\mathcal{H}'$, we define a Born map $\mathcal{B}$ to be a norm-preserving map from $\mathcal{H}$ into $\mathcal{H}'$, i.e., for any state $\psi \in \mathcal{H}$, the image $\psi' \equiv \mathcal{B}\psi$ of $\psi$ is an element of $\mathcal{H}'$ such that $(\psi', \psi') = (\psi, \psi)$. Born maps are not necessarily linear and the two Hilbert spaces involved need not have the same dimension.

In SFQM, Born maps may be used to discuss state preparation and outcome detection. These represent processes involving non-trivial changes in an observer’s information content. In SQM, such actions are described by non-unitary evolution and are normally associated with state reduction, or wave-function collapse. These are commonly regarded as a blemish on an otherwise beautiful theory. There should not be the same stigma attached to non-linear Born evolution in SFQM, because the collapse does not refer to any supposed changes in a system under observation, but to changes in the information content held by an observer.

6.2 Semi-unitary operators

In SQM, the observer’s information content does not change between state preparation and outcome detection. This is most obvious in the Heisenberg picture. In the formally equivalent Schrödinger picture, evolution of the wavefunction is unitary, which involves a linear operator. In SFQM, therefore, we shall assume that evolution between state preparation and outcome detection involves linear Born maps. It turns out that linearity imposes important restrictions on the evolution operators which have far-reaching consequences.

We define a semi-unitary operator as a linear Born map. It is easy to prove that if $U$ is a semi-unitary operator from $\mathcal{H}$ to $\mathcal{H}'$, then $\dim \mathcal{H} \leq \dim \mathcal{H}'$ and $U^+U = I$, the identity operator over $\mathcal{H}$. If $\dim \mathcal{H} < \dim \mathcal{H}'$, then it is easy to see that $UU^+ \neq I'$, the identity operator over $\mathcal{H}'$. Moreover, if $U$ is semi-unitary, then inner products, and not just norms, are preserved, i.e., if $\psi' \equiv U\psi$, $\phi' \equiv U\phi$, then $(\psi', \phi') = (\psi, \phi)$ for any vectors $\psi$, $\phi$ in $\mathcal{H}$.

We now apply these ideas to SFQM. If the dynamical evolution operator $U_{n+1,n}$ carrying the labstate from $\mathcal{H}_n$ to $\mathcal{H}_{n+1}$ is semi-unitary then for evolution given by

$$\ket{\psi, n} \rightarrow \ket{\psi', n + 1} \equiv U_{n+1,n}\ket{\psi, n},$$

we know inner products are preserved, i.e.,

$$(\psi', n + 1|\phi', n + 1) = (\psi, n|\phi, n),$$

for all $\ket{\psi, n}, \ket{\phi, n}$ in $\mathcal{H}_n$, and from this we can prove that total probability will be conserved.

We may express semi-unitary evolution of the preferred basis $B_n$ in terms of the preferred basis $B_{n+1}$ at time $n + 1$, i.e., writing

$$U_{n+1,n}|i, n\rangle = \sum_{j=0}^{d_{n+1}-1} U_{n+1,n}^{j,i}|j, n + 1\rangle,$$

where the coefficients $\{U_{n+1,n}^{j,i}\}$ satisfy the semi-unitarity equations

$$\sum_{k=0}^{d_{n+1}-1} (U_{n+1,n}^{k,j})^* U_{n+1,n}^{k,i} = \delta_{ij}.$$
Typical quantum experiments are, by construction, closed, which means that, as far as physically possible, all external processes are excluded from interaction with the apparatus in the time between state preparation and outcome detection. In SFQM, an important rule characterizing semi-unitary evolution for such situations which distinguishes it from state preparation and outcome detection is its action on the void state. Closed semi-unitary evolution describes the behavior of laboratory equipment in the absence of any active intervention by the observer or any external agency. In such circumstances, it would be bizarre if the void labstate spontaneously changed into a non-zero signal labstate during a closed experiment. Likewise, a non-zero signal labstate would normally evolve into some other non-zero signal labstate in the absence of any active intervention during a closed experiment.

This leads us to formulate the following rule: closed semi-unitary evolution in SFQM, corresponding to Schrödinger (unitary) evolution in SQM, will generally evolve a void labstate into a labstate, whilst non-zero signal labstates evolve into non-zero signal labstates. That would correspond to an experiment detecting particle decay products.

We shall call any evolution satisfying (14) and (15) Schrödinger evolution.

Expressed mathematically, this means

$$U_{n+1,n} |0, n\rangle = |0, n+1\rangle$$

for any closed experiment and

$$(0, n + 1 | U_{n+1,n} | \psi, n\rangle = 0$$

for any non-zero signal labstate $|\psi, n\rangle$, which by definition satisfies the rule $(0, n | \psi, n\rangle = 0$.

We shall call any evolution satisfying (14) and (15) Schrödinger evolution.

For Schrödinger evolution in SFQM, the corresponding matrix $[U_{n+1,n}^{i,j}]$ takes the form

$$[U_{n+1,n}^{i,j}] = \begin{bmatrix} 1 & 0 & \ldots & 0 \\ 0 & U_{n+1,n} & \ldots & U_{n+1,n}^{d_n,1} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & U_{n+1,n}^{d_n,1} & \ldots & U_{n+1,n}^{d_n,d_n} \end{bmatrix}, \quad d_{n+1} \geq d_n,$$

which guarantees that the void state remains isolated during the time between state preparation and outcome detection.

In general, a non-zero signal labstate $|\psi, n\rangle$ will be a linear combination of terms of the form $A_{i_1,n}^+ \ldots A_{i_k,n}^+ |0, n\rangle$, for some integer $k > 0$ and with $i_1 < i_2 \ldots < i_k$. Consider Schrödinger evolution from time $n$ to time $n + 1$. If we write

$$A_{i_1,n}^+ \ldots A_{i_k,n}^+ |0, n\rangle \rightarrow U_{n+1,n} A_{i_1,n}^+ \ldots A_{i_k,n}^+ |0, n\rangle$$

then using closed semi-unitarity we find

$$U_{n+1,n} A_{i_1,n}^+ \ldots A_{i_k,n}^+ |0, n\rangle = \left\{ U_{n+1,n} A_{i_1,n}^+ U_{n+1,n}^+ \right\} \left\{ U_{n+1,n} A_{i_2,n}^+ U_{n+1,n}^+ \right\} \ldots \left\{ U_{n+1,n} A_{i_k,n}^+ U_{n+1,n}^+ \right\} |0, n + 1\rangle,$$

which means that, in principle, a knowledge of the transitions

$$A_{i,n}^+ \rightarrow U_{n+1,n} A_{i,n}^+ U_{n+1,n}^+$$

of the individual signal operators should give us complete knowledge about the dynamics.

In general, a given signal operator may evolve to a multiple-signal operator. Such a scenario may occur when experiments are performed on bound states, for example. An initially prepared bound state would be described by a one-signal labstate which could then evolve into a two or more-signal labstates. That would correspond to an experiment detecting particle decay products.
7 Path summation

Given a normalized initial labstate

$$|\psi, M\rangle \equiv \sum_{i=0}^{d_M-1} \psi^i |i, M\rangle$$

(20)

at time $M$, then semi-unitary evolution gives

$$|\psi, M\rangle \rightarrow U_{M+1,M} |\psi, M\rangle \equiv \sum_{j=0}^{d_{M+1}-1} \sum_{i=0}^{d_M-1} U_{j,i}^{i,j} |j, M+1\rangle,$$

(21)

where the coefficients $\{U_{j,i}^{i,j}\}$ satisfy semi-unitarity, provided $r_{n+1} \geq r_n$. Then the amplitude $A(j, M+1|\psi, M)$ to go to $|j, M+1\rangle$ from the initial labstate $|\psi, M\rangle$ is given by

$$A(j, M+1|\psi, M) = \sum_{i=0}^{d_M-1} U_{j,i}^{i,j}.$$

(22)

Semi-unitarity then leads to total probability conservation, i.e.,

$$\sum_{j=0}^{d_{M+1}-1} |A(j, M+1|\psi, M)|^2 = 1.$$

(23)

Suppose however that at time $M+1$, the observer does not attempt to determine any outcome but in effect channels the labstate into new apparatus (to use the language of SQM). Then $|\psi, M+1\rangle$ serves as an initial state for the next jump, and so on. After a sequence of successive semi-unitary jumps, ending at time $N$, the amplitude $A(j, N|\psi, M)$ to go to $|j, N\rangle$ for $N > M$ is given by

$$A(j, N|\psi, M) = \sum_{i=0}^{d_N-1} U_{j,i}^{i,j}.$$

(24)

It is easy to see that total probability is conserved in this case. We note that semi-unitarity requires $r_M \leq r_{M+1} \leq \ldots \leq r_N$. The particular scenario where strict equality occurs corresponds to what happens in SQM, where it is usual to identify successive Hilbert spaces with each other. In such a case, semi-unitarity can be replaced by unitarity, so that the dynamics appears reversible.

Expression (24) can be written out in the form of a path-summation, i.e.,

$$A(j, N|\psi, M) = \sum_{i=0}^{d_{N-1}} \sum_{i=0}^{d_{N-2}} \ldots \sum_{i=0}^{d_M} U_{N,N-1}^{i,j} U_{N-1,N-2}^{i,j} \ldots U_{M+1,M}^{i,j},$$

(25)

which is the SFQM version of the Feynman path integral. We note that in the Feynman path integral, as it is conventionally formulated over physical space, there is an implicit assumption that the particle could be observed in principle anywhere in physical space. Since space is regarded as a continuum in SQM, the formalism naturally leads to integration rather than summation. Additionally, the time parameter is taken to a continuum limit, which is a source of severe technical problems in SQM. Neither of these continuity assumptions are made in the SFQM approach.
7.1 Time reversal experiments

It is possible, under carefully controlled circumstances, to violate the semi-unitarity inequality, i.e., to have an experiment where \( r_{n+2} < r_{n+1} > r_n \) whilst maintaining total probability conservation and a good physical interpretation. Such a possibility occurs in time reversal experiments, for instance, where the observer would carefully arrange their apparatus in such a way so as to ensure \( U^{i,j}_{n+2,n+1} = (U^{i,j}_{n+1,n})^* \). Magnetic resonance experiments are specifically designed to test the degree to which this relationship holds in the presence of temperature-dependent (irreversible) processes.

8 Concluding remarks

We have presented a general framework for encoding quantum principles in instrumentalist terms, consistent with Bohr-Heisenberg reality. By focusing on what is physically meaningful, i.e., the apparatus, and not on any supposed system under investigation, we find a formalism which deals with quantum physics in a realistic way. The focus now is on information acquisition and loss, which is all that experimentalists ever deal with.

We do not have the space here to discuss a number of important and related issues, such as the role of null experiments in creating a “multi-fingered” view of time, and the dynamical generation of spacelike and timelike causal structures in quantum processes. Neither do we have room to discuss various specific applications to quantum physics, such as quantum optics networks [7], which generally confirm the validity and usefulness of SFQM.

References

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