# A Quantum Theory with Non-collapsing Measurements

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A collapse-free version of quantum theory is introduced to study the role of the projection postulate. We assume "passive" measurements that do not update quantum states while measurement outcomes still occur probabilistically, in accordance with Born's rule. All other defining features of quantum theory, such as the Hilbert space setting, are retained. The resulting quantum-like theory has only one type of dynamics, namely unitary evolution. Passive quantum theory shares many features with standard quantum theory. These include preparational uncertainty relations, the impossibility to dynamically clone unknown quantum states and the absence of signalling. However, striking differences emerge when protocols involve post-measurement states. For example, in the collapse-free setting, no ensemble is needed to reconstruct the state of a system by passively measuring a tomographically complete set of observables – a *single* system will do. Effectively, the state becomes an observable quantity, with implications for both the ontology of the theory and its computational power. At the same time, the theory is not locally tomographic and passive measurements do not create Bell-type correlations in composite systems.

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Experimental evidence for the state change of a quantum system induced by measurements was available since 1925. Using a cloud chamber, Compton and Simon [1] studied the scattering of "x-ray quanta" by electrons. They discovered that the angle characterising the path of the recoiling electron and the angle of the photon scattering direction are strongly correlated. Knowing one of them is sufficient to determine where the particles interacted and these "position measurements" can be carried out in arbitrary temporal order.

According to von Neumann [2], this experiment implements two subsequent measurements of one single observable, namely the spatial coordinate of the interaction locus (which is initially undetermined). The measurements of the angles can happen in quick succession and lead to identical results. The ensuing *deterministic repeatability* is shown by von Neumann to be equivalent to assuming the *projection postulate*: immediately after measuring a non-degenerate observable, a quantum system will reside in the unique eigenstate associated with the observed outcome.

In principle, one could imagine other relations between the outcomes of the same measurement when carried out twice within a short period of time. Von Neumann mentions two options. Either a deterministic mechanism could control the measurement outcomes (this assumption effectively amounts to the existence of hidden variables), or the outcomes of the second measurement could be governed by the same probability distribution as the outcomes of the first.

In this paper, we introduce a quantum-like theory that realizes von Neumann's second option by assuming that measuring an observable causes *no* state update. Then, consecutive measurements of the same observable produce outcomes governed by one and the same probability distribution. All other features of quantum theory, such as its setting in Hilbert space or the Born rule, are retained.

The resulting *passive* quantum theory (pQT) shares many features with standard quantum theory but is manifestly different from it. Passive measurements have far-reaching consequences, both from a conceptual and an applied point of view. Suspending the collapse highlights the subtle ways in which the projection postulate shapes quantum theory.

*Definition of pQT* – Five axioms define a bare-bones version of (non-relativistic) quantum theory. Four of these axioms describe the mathematical framework of the theory: ($\mathcal{S}$) the *states* of a quantum system correspond to rays $|\psi\rangle$ in a separable, complex Hilbert space $\mathcal{H}$, or to their probabilistic mixtures $\rho$; ($\mathcal{O}$) *observables* are represented by Hermitean operators $\hat{A}$ acting on the space $\mathcal{H}$; ($\mathcal{T}$) the *time evolution* of quantum states is governed by Schrödinger's equation; ($\mathcal{C}$) the state space of a *composite system* is obtained by tensoring the Hilbert spaces of its constituent parts.

The fifth axiom $\mathcal{M}$ relates theory to experiment. Its three parts specify ($\mathcal{M}_1$) the *measurement outcomes* (the eigenvalues $a_r$ of the measured observable $\hat{A}$), ($\mathcal{M}_2$) the *probability* with which they will occur (Born's rule: $p_A(a_r) = |\langle a_r|\psi\rangle|^2$ for non-degenerate $\hat{A}$), and ($\mathcal{M}_3$) the *post-measurement states* (the eigenstate $|a_r\rangle$ of $\hat{A}$ when $a_r$ has been observed). Schematically, the projection postulate $\mathcal{M}_3$ states that

$$|\psi\rangle \xrightarrow{a_r} \hat{P}_r|\psi\rangle/\sqrt{\langle\psi|\hat{P}_r|\psi\rangle}\,, \tag{1}$$

where $\hat{P}_r = |a_r\rangle\langle a_r|$ projects on the state $|a_r\rangle$. The quantum states undergo a *non-linear* transformation.

The model pQT is defined by the same set of postulates as quantum theory, except for the state update rule. Denoting states in passive quantum theory – or *p-states*, for short – by $|\widehat{\psi}\rangle$, the modified projection postulate reads

$\widehat{\mathcal{M}}_3$: A system resides in the same state $|\widehat{\psi}\rangle$ *before and after* measuring an observable $\hat{A}$.

Thus, p-states undergo a *linear* transformation when p-measurements are carried out,

$$|\widehat{\psi}\rangle \xrightarrow{a_r} |\widehat{\psi}\rangle\,. \tag{2}$$

Our main goal is to investigate the consequences of replacing the rule (1) by (2).

*Basic properties of pQT* – The predictions of standard quantum theory and pQT agree as long as post-measurement states are not used or referred to. The expectation value of an observable $\hat{A}$ in pQT, for example, can be determined just as in quantum mechanics: the eigenvalue $a_r$ of the observable $\hat{A}$ will occur with probability $p_A(a_r)$ upon measuring it repeatedly on an *ensemble* of systems each of which resides in the p-state $|\widehat{\psi}\rangle$. Hence, preparational uncertainty relations [4, 5] for the variances of non-commuting observables do hold in pQT. It follows that the inequalities exist due to the probabilistic character of measurement outcomes. State changes caused by quantum measurements cannot be their source.

Hence, Heisenberg's original plausibility argument—measuring the position of an electron will cause an uncertainty of its momentum, due to an uncontrollable state change—is invalid for preparational uncertainties. Heisenberg's classically inspired reasoning can only be justified in terms of *measurement* uncertainty [6, 7].

To see where pQT deviates from quantum theory, post-measurement states must play a role. For example, the expectation value of an observable may be obtained in pQT from a *single* copy of a p-state $|\widehat{\psi}\rangle$, in contrast to the ensemble needed in quantum theory. Since a (non-destructive) passive measurement of $\hat{A}$ does not update a p-state, it is possible to repeat it *on one and the same* system as often as is necessary to determine the outcome probabilities $\widehat{p}_A(a_r) = \langle\widehat{\psi}|\hat{P}_r|\widehat{\psi}\rangle$. They follow from the Born rule $\mathcal{M}_2$ and agree with their counterparts in quantum theory, $\widehat{p}_A(a_r) \equiv p_A(a_r)$.

*Single-copy state reconstruction* – Both a quantum state $|\psi\rangle$ and a p-state $|\widehat{\psi}\rangle$ correspond to a unique ray in the Hilbert space of the system but they differ from an operational point of view: the collapse-free theory allows us to reconstruct an unknown p-state $|\widehat{\psi}\rangle$ from a *single* system. To identify the ray in Hilbert space associated with $|\widehat{\psi}\rangle$, one simply repeats p-measurements of an informationally complete set of observables [8–10] on the given system, without the need of an ensemble. *A fortiori*, an experimenter can tell apart any two distinct non-orthogonal p-states $|\widehat{\psi}\rangle$ and $|\widehat{\phi}\rangle$ *with certainty*, even when being presented with a single copy only. Successful state reconstruction and discrimination based on a single copy of the unknown state means that p-states should be thought of as directly observable, *classical*, quantities. From an ontological point of view, this "reality" of p-states removes notorious interpretational issues posed by quantum states.

The absence of a state update after p-measurements means that, effectively, only a *single* dynamical law exists in pQT, described by Axiom $\mathcal{T}$. Hence, the tension between the unitary dynamics of a quantum system and its "stochastic" time evolution caused by measurements is entirely absent in pQT. Attempts to eliminate the non-deterministic evolution from quantum theory have a long history, ranging from models which consider the measurement device as a quantum system [2, 11] to alternative interpretations of the theory [12, 13]. In pQT, this issue does not arise although a measurement problem persists in the sense that Axiom $\mathcal{T}$ appears insufficient to explain the emergence of specific measurement outcomes.

*Density operators in pQT* – Gleason's theorem [14] tells us that mixed states emerge naturally in the Hilbert space setting of quantum theory. The proof of the theorem, based on associating measurement outcomes with projection operators, remains valid in pQT. Thus, non-negative Hermitean operators with unit trace also represent candidates for states in pQT. However, their interpretation as *mixtures* of pure quantum states cannot be upheld in pQT as it is possible to identify an unknown p-state $|\widehat{\psi}\rangle$ by carrying out single-copy state reconstruction, at least in principle. If the ignorance in the classical probability of a p-density operator $\widehat{\rho}$ can always be removed, *proper* (or epistemic) mixtures do not represent a fundamental concept in pQT.

However, *improper* p-density matrices still play a role in pQT. They arise if an observer can access only a part of a larger p-system, just as in quantum theory. To see this, we need to discuss the behaviour of composite systems when p-measurements are carried out. For simplicity, we limit ourselves to bipartite systems.

*Measurements in composite p-systems* – The pure states $|\Phi\rangle$ of a bipartite quantum system are elements of the space $\mathcal{H}_{AB} = \mathcal{H}_A \otimes \mathcal{H}_B$ (cf. Axiom $\mathcal{C}$). The corresponding bipartite p-system has the same state space, i.e. $|\widehat{\Phi}\rangle \in \mathcal{H}_{AB}$. The mathematical distinction between product states and entangled states in the space $\mathcal{H}_{AB}$ applies to both theories.

To measure a "local" observable of the form $\hat{A} \otimes \hat{\mathbb{I}}$ (or $\hat{\mathbb{I}} \otimes \hat{B}$) requires access to one of the subsystems only. Having observed the outcome $a_r$ upon measuring the observable $\hat{A} \otimes \hat{\mathbb{I}}$ by means of a "local" device $\mathcal{D}_A$, the update of the initial *quantum* state $|\Phi\rangle$ can be described as the action of a suitable projection operator,

$$|\Phi\rangle \xrightarrow{a_r} \hat{P}_r \otimes \mathbb{I}|\Phi\rangle / \sqrt{\langle\Phi|\hat{P}_r \otimes \mathbb{I}|\Phi\rangle}\,. \tag{3}$$

In contrast, a p-measurement of the observable $\hat{A} \otimes \hat{\mathbb{I}}$ does *not* cause the p-state $|\widehat{\Phi}\rangle$ to update; effectively, the map in Eq. (2) holds for any state of a bipartite system as well. In quantum theory, the probability to obtain the value $a_r$ is found from repeated measurements on an ensemble of systems in state $|\Phi\rangle$ while in pQT the measurements can be repeated on a single system. Both theories predict the same numerical value,

$$p_A(a_r) = \langle\Phi|\hat{P}_r \otimes \mathbb{I}|\Phi\rangle \equiv \langle\widehat{\Phi}|\hat{P}_r \otimes \mathbb{I}|\widehat{\Phi}\rangle\,. \tag{4}$$

Therefore, local p-measurements on a subsystem can reveal whether the composite system resides in a product state $|\widehat{\phi}_A\rangle \otimes |\widehat{\phi}_B\rangle$ or in an entangled state $|\widehat{\Phi}\rangle$: single-copy state reconstruction will return either the p-state $|\widehat{\phi}_A\rangle$ or the *mixed* state $\widehat{\rho}_A = \mathrm{Tr}_B|\widehat{\Phi}\rangle\langle\widehat{\Phi}|$, respectively. In this case, the use of the p-density matrix $\widehat{\rho}_A$ is justified since it provides the correct description of the subsystem as seen by a local observer.

*Joint probabilities in pQT* – Passive measurements do not create correlations between entangled systems since they do not collapse p-states. Therefore, *local* p-measurements cannot reveal the probabilities of *joint* outcomes which are essential to probe Bell-type inequalities. Only *global* p-measurements can be used to extract joint outcome probabilities which may violate Bell-type inequalities. Interestingly, a violation would not imply the existence of non-classical correlations and hence not rule out the existence of local hidden variables. It is also impossible to reconstruct entangled p-states from local p-measurements which means that pQT is *not* locally tomographic.

*Quantum information in pQT* – The no-cloning theorem [15, 16] states the impossibility to *dynamically* produce copies of unknown quantum states, i.e. through the application of unitary gates. This form of the theorem also holds in pQT but an alternative cloning procedure exists which requires a single system only. Once the state of a p-system has been revealed by single-copy state-reconstruction, another system can be prepared in the observed p-state. In quantum theory, such a measurement-based copying procedure would require an ensemble of identically prepared systems.

The state update induced by quantum measurements is essential for many protocols of quantum information. Teleportation [17] and entanglement swapping [18], for example, rely on system-wide state changes as a result of local measurements. Thus, they will no longer work in pQT. The impossibility to "steer" the state of a distant subsystem means that quantum key distribution protocols based on entangled states are also ruled out. At the same time, single-copy state reconstruction would allow for perfect eavesdropping on p-states, i.e. without leaving a trace.

Collapse-free measurements also modify the computational power of quantum theory. Some p-algorithms turn out to be more powerful than their quantum counterparts. "Quantum parallelism" may be exploited in full since the p-state encoding the result of a quantum computation is "observable" via single-copy state reconstruction, at least in principle. The algorithms by Deutsch and Jozsa, Grover, and Simon [19–21], for example, involve "oracles" which "evaluate" a function $f(x)$ by means of a unitary operator, viz. $\hat{U}_f : |x,0\rangle \to |x, f(x)\rangle$. Letting the linear operator $\hat{U}_f$ act on the symmetric superposition $|s\rangle = 2^{-n/2}\sum_{x=0}^{2^n-1}|x,0\rangle$, the output state carries information about the function $f(x)$ for all its values. A projective measurement on the final state $\hat{U}_f|s\rangle$ will, however, reveal at most one value of $f(x)$, necessitating further calls to the oracle. In the absence of the collapse, however, all values $f(x)$ can be extracted from the final p-state $\hat{U}_f|\widehat{s}\rangle$ by reconstructing it from a single copy. Hence, only a single call to the oracle is necessary within pQT which represents a substantial reduction in computational cost, but a large increase in measurement complexity. In stark contrast, measurement-based quantum computation [22] is evidently impossible in pQT.

Furthermore, p-measurements on their own retain the computational power they possess in quantum theory: it is possible to determine the eigenvalues of Hermitean matrices by p-measurements only since this part of the quantum diagonalization algorithm [23] does not rely on states collapsing.

*Instruments* – The collapse of a quantum state upon measuring an observable $\hat{A} = \sum_r a_r \hat{P}_r$ has a convenient description in terms of a specific quantum instrument. The *Lüders instrument* consists of a collection of maps $\{\omega_1^L, \omega_2^L, \ldots\}$ sending an initial state $\rho$ to the appropriate (un-normalised) post-measurement state

$$\rho \xrightarrow{a_r} \omega_r^L(\rho) = \hat{P}_r \rho \hat{P}_r , \tag{5}$$

conditioned on the outcome $a_r$. The trace of each map equals the outcome probability, $\mathrm{Tr}[\omega_r^L(\rho)] = p_A(a_r)$. Projective measurements act non-linearly on the elements $|\psi\rangle$ of Hilbert space $\mathcal{H}$ (cf. Eqs. (1) and (3)) but linearly at the level of density matrices. More generally, *quantum instruments* consist of linear, completely positive maps [24] of density matrices, all of which can be realised by the Lüders instrument with post-processing [25].

In contrast, pQT is *linear* at the level of p-states, $|\widehat{\psi}\rangle \xrightarrow{a_r} |\widehat{\psi}\rangle$. The maps $\{\omega_1^p, \omega_2^p, \ldots\}$ defining the associated *p-instrument* act *non-linearly* on density matrices,

$$\widehat{\rho} \xrightarrow{a_r} \omega_r^p(\widehat{\rho}) = \mathrm{Tr}[\hat{P}_r \widehat{\rho} \hat{P}_r]\,\widehat{\rho} , \tag{6}$$

so that, generally, $\omega_r^p(\lambda\widehat{\rho}_1 + (1-\lambda)\widehat{\rho}_2) \neq \lambda\omega_r^p(\widehat{\rho}_1) + (1-\lambda)\,\omega_r^p(\widehat{\rho}_2)$ for $\widehat{\rho}_2 \neq \widehat{\rho}_2$ and $\lambda \in (0,1)$. The lack of equality captures the distinguishability between proper and improper mixtures in pQT. Operationally, the left-hand side of this relation corresponds to performing a measurement on the *improper* mixture $\widehat{\rho} = \lambda\widehat{\rho}_1 + (1-\lambda)\,\widehat{\rho}_2$, whereas the right-hand side can be interpreted as the effect of a passive measurement on the *proper* mixture of $\widehat{\rho}_1$ and $\widehat{\rho}_2$ with weights $\lambda$ and $(1-\lambda)$, respectively.

*Linearity and non-signalling* – A non-linear time evolution of quantum states would, in combination with projective measurements on entangled states, enable superluminal communication [26–28]. This result depends on the fact that different convex combinations of quantum states can be used to describe one and the same mixed state. Imagine to remotely prepare a mixed state in one of two distinct convex combinations by local measurements on one part of a bipartite system. If quantum states were to evolve non-linearly, a space-like separated observer could subsequently distinguish these decompositions leading to signalling. However, Gisin's argument does not rule out *all* non-linear time evolutions [29, 30].

The *linearity* of quantum instruments guarantees that the instantaneous and non-local collapse does not lead to violations of special relativity. Alternative state-update rules (rather than alternative time evolutions) may also result in non-linear transformations of joint and reduced states. Any modification leading to signalling would be unphysical. In pQT, measurements have no effect on p-states making them entirely unsuitable for signalling. Thus, both passive measurements and the hypothetical readout devices described by Kent [31] represent examples of measurement-induced transformations *not* dismissed by Gisin-type arguments.

*Simulating QT* – Measurements on a passive quantum system can be made to look as if they were performed on a quantum system, modulo a finite time delay. To see this, let us first consider the measurement of a non-degenerate observable $\hat{A}$ on a single-partite system in an unknown state $|\widehat{\psi}\rangle$. If the outcome $a_r$ is obtained, then the observer simply replaces the original system by another one residing in the p-state $|\widehat{a_r}\rangle$ prepared beforehand. The resulting situation is identical to the one obtained after a standard quantum measurement of the observable $\hat{A}$ with outcome $a_r$ on the state $|\psi\rangle$, although substituting $|\widehat{\psi}\rangle$ by $|\widehat{a_r}\rangle$ will take a finite amount of time. The "replacement" time would be subject to "quantum speed limits" [32] if the set $\{|\widehat{a_r}\rangle\}$ was unavailable and the experimenter had to generate the state $|\widehat{a_r}\rangle$ by unitarily evolving some given state $|\widehat{\chi}\rangle$ into one of the states in $\{|\widehat{a_r}\rangle\}$.

Now consider a bipartite system residing in an unknown entangled p-state $|\widehat{\Phi}\rangle$ and carry out the single-partite measurement $\hat{A}\otimes\hat{\mathbb{I}}$. If the (non-degenerate) outcome $a_r$ occurs, the observer needs to substitute $|\widehat{\Phi}\rangle$ by an appropriate product state $|\widehat{a_r}\rangle\otimes|\widehat{\psi}\rangle$, in line with the quantum mechanical update rule. To identify the factor $|\widehat{\psi}\rangle$, the p-state $|\widehat{\Phi}\rangle$ must be reconstructed by means of bipartite, or "global", measuring devices of the form $\hat{A}\otimes\hat{B}$. Therefore, access to the subsystems of a composite system is required to simulate the quantum collapse of an entangled state.

*Summary and discussion* – We have introduced a collapse-free foil theory of quantum mechanics by assuming that measurements do not cause states to update. Its predictions agree with those of quantum theory as long as post-measurement states are discarded systematically. Any non-quantum feature of pQT can be traced back to states not collapsing when measuring generic observables. Being manifestly different from quantum theory, the model pQT represents a tool to study the role of the collapse rather than suggesting an alternative interpretation aiming to circumvent the projection postulate [12, 13].

The possibility of single-copy state reconstruction turns p-states into observable quantities. As any time-evolved state can be accessed directly in pQT, the cost and computational power of known quantum algorithms must be evaluated anew. Assuming that the measured state has been reconstructed, passive quantum theory can, in principle, simulate quantum theory *including* the collapse if one accepts a time delay in state updates. In contrast, quantum theory cannot simulate pQT.

In standard quantum theory, projective measurements can be used to prepare specific states. In pQT, a desired state can only be prepared by suitably evolving some known state in time, i.e. dynamically.

The comparison with pQT shows that some concepts of quantum theory are equivalent because of the non-trivial state update described by the standard projection postulate. As is well-known, proper and improper mixtures of quantum states are indistinguishable. This is no longer true in pQT where passive measurements can be used to reveal each of the individual states forming a proper mixture. Similarly, in quantum theory the observable $\hat{A}\otimes\hat{B}$ can be measured by either a single global device or by two local devices implementing $\hat{A}\otimes\hat{\mathbb{I}}$ and $\hat{\mathbb{I}}\otimes\hat{B}$ separately, if supplemented by classical communication. In pQT, these two scenarios lead to entirely different outcome statistics.

*Other work* – The idea of being able to "observe" the state of a quantum system, which is one of the essential consequences of assuming passive measurements, was explored occasionally in an *ad hoc* fashion. Busch [33] assumes that there exists a state-determination procedure not based on measurements using an ensemble, with the goal to provide operational evidence for it being incompatible with standard quantum theory. Kent [34] considers a hypothetical read-out device which provides access to the so-called "local state" of a single system. Measurements performed with such a device can, effectively, implement non-linear deterministic maps on states which, however, do not result in superluminal signalling. Therefore, both this "augmented" version of quantum theory and pQT represent examples of measurement-induced non-linear time evolutions not ruled out by Gisin's argument [26].

*Outlook* – A more comprehensive study of pQT and its generalizations [35] will investigate the consequences of passive measurements on other quantum information protocols and concepts such as quantum channels or POVMs. It is also important to understand to what extent pQT is a non-classical theory – what would a description in terms of hidden variables mean? Finally, it is not difficult to see that passive measurements represent just one specific case of possible alternative state-update rules leading to quantum-like theories. However, if consistent modifications of the projection postulate exist, an intriguing question arises: can we identify a physical principle which singles out the quantum mechanical state-update rule among these alternatives?

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