

# Quantum theory without measurement or state reduction problems

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## Abstract

There is a consistent and simple interpretation of the quantum theory of isolated systems. The interpretation suffers no measurement problem and provides a quantum explanation of state reduction, which is usually postulated. Quantum entanglement plays an essential role in the construction of the interpretation.

## 1 Introduction

Quantum theory is the most successful physical theory of our time. Yet the theory is commonly felt to be afflicted with the measurement and state reduction problems. Despite enormous attention [1], the problems remain controversial. My purpose here is to describe a simple way to think about the quantum theory of isolated systems (QTIS) which is free of the problems. Physicists use QTIS every day.

Why *isolated* systems? Because they are exactly the systems whose state evolves according to Schrödinger's equation (SE). The *specified* Hamiltonian  $H(t)$  in SE includes all interactions between the quantum system and the outside world. Thus a system described by SE is isolated, externally acted upon only by the fields incorporated in  $H$  and not acting upon those fields.

According to W. Zurek, "Macroscopic systems are never isolated from their environment. Therefore they should not be expected to follow Schrödinger's equation, which is applicable only to a closed system." [2] Thus a system consisting of a measuring apparatus and the measured quantum system does not evolve according to SE. Therefore, QTIS cannot describe the measurement process. QTIS is not a universal theory.

A universal quantum theory would require a generalization of QTIS. There is a widespread belief that quantum theory *is* universal. In my view, this belief, while perhaps true, is only a prejudice, born of hubris in the 1920's, and certainly not proved today. Recall that Newtonian mechanics was universally thought universal until the late 19th century. So even Maxwell felt it necessary to provide a mechanical model of the electromagnetic field.

“Solve the measurement problem” usually means “Find a quantum description of the measuring apparatus”. My objective here is more modest: to provide a simple and consistent way to think about measurement and state reduction in QTIS. The key word is *consistent*; we do not require, nor shall we provide, a deep understanding of the apparatus. Some say that this sidesteps the real problem of finding a quantum description of a measurement [34]. But we do not today possess such a description [4]. Perhaps there is none [5].

The paper is organized as follows. Sec. 2 reviews QTIS, both its Hilbert space formalism and the physical correlates of its mathematical terms.

Sec. 3 discusses the interpretation of measurement in QTIS. It includes an elaboration of the Zurek quote above, which is the key to showing that QTIS does not suffer a measurement problem. The section is also a prerequisite to an understanding of state reduction in QTIS.

Sec. 4 discusses state reduction in QTIS. I give examples of measurements not accompanied by a state reduction. I then prove that the joint measurement postulate implies that some measurements are accompanied by a state reduction. This shows the inadequacy of most accounts, where a state reduction is postulated always to accompany a measurement [6]. To postulate that a state reduction always occurs is wrong, and to postulate when it occurs is unnecessary.

Sec. 5 summarizes our results.

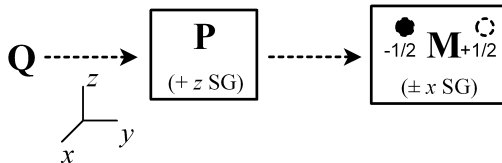
State preparation, measurement, and state reduction are related, but distinct, concepts. They have different meanings for different authors. My meanings are discussed in detail in Sec. 2–4. But a brief preview now will be helpful: A preparation assigns a quantum state to a quantum system. A measurement is an irreversible process which creates a displayed value on a measuring apparatus. A state reduction is a specific kind of preparation which sometimes accompanies a measurement.

## 2 QTIS

The theory is concerned with this physical situation. See Table 1, Col. 1. Let  $\mathbf{Q}$  be a quantum system. Prepare  $\mathbf{Q}$  with apparatus  $\mathbf{P}$ . Then measure  $\mathbf{Q}$  with an apparatus  $\mathbf{M}$ . A value  $\mathbf{m}$  is displayed on  $\mathbf{M}$  with probability  $\text{Pr}(\mathbf{m})$ .

$\mathbf{Q}$  exists independently of any observer. Images of individual atoms moved around on a surface to form a pattern [7] and manipulations of a single ion in a trap [8] reveal atoms to be as “real” as, say, bacteria. The displayed measurement value also exists independently of any observer.

Here is an example. See Table 1, Column 2, and Fig. 1. The quantum system  $\mathbf{Q}$  is a neutron, moving in the  $y$ -direction. The preparing apparatus  $\mathbf{P}$  contains a Stern-Gerlach device oriented in the  $z$ -direction.  $\mathbf{P}$  passes the upper output beam and blocks the lower.



**Fig. 1:** First  $\mathbf{P}$  prepares  $\mathbf{Q}$ . Then  $\mathbf{M}$  measures  $\mathbf{Q}$ , with result  $\frac{1}{2}$ .

The measuring apparatus  $\mathbf{M}$  contains a Stern-Gerlach device oriented in the  $x$ -direction, which accepts  $\mathbf{P}$ ’s output.  $\mathbf{M}$  also contains a detector and display for both output beams. If  $\mathbf{Q}$  enters  $\mathbf{P}$  and a displayed value appears, then  $\mathbf{Q}$  was prepared by  $\mathbf{P}$  and measured by  $\mathbf{M}$ . Experimentally,  $\text{Pr}(\pm\frac{1}{2}) = \frac{1}{2}$ .

QTIS assigns *mathematical* objects to the above *physical* objects: a complex Hilbert space  $Q$  to the quantum system  $\mathbf{Q}$ ; a unit vector  $|p\rangle \in Q$  (up to phase) to the preparing apparatus  $\mathbf{P}$ ; self-adjoint operator  $M$  on  $Q$  to the measuring apparatus  $\mathbf{M}$ ; and the eigenvalue  $m$  of  $M$  to the displayed value  $\mathbf{m}$ . See Table 1, Column 3.  $|p\rangle$  is called a *state*, and  $M$  an *observable* [9].

Physical		Mathematical	
GENERAL	EXAMPLE	GENERAL	EXAMPLE
Quantum system $\mathbf{Q}$	Neutron	Hilbert space $Q$	$C^2$
Preparing apparatus $\mathbf{P}$	$+z$ SG	Vector $ p\rangle$	$ +z\rangle$
Measuring apparatus $\mathbf{M}$	$\pm x$ SG & detectors	Self-adjoint operator $M$	$\frac{1}{2} +x\rangle\langle+x  - \frac{1}{2} -x\rangle\langle-x $
Displayed value $\mathbf{m}$	$\frac{1}{2}, -\frac{1}{2}$	Eigenvalue $m$ of $M$	$\frac{1}{2}, -\frac{1}{2}$

**Table 1:** Some physical and mathematical parts of QTIS.

In the example of Table 1, QTIS assigns the Hilbert space  $Q = C^2$  to the neutron (considering only the spin degree of freedom); state  $|p\rangle = |+z\rangle = \sqrt{\frac{1}{2}}|+x\rangle - \sqrt{\frac{1}{2}}|-x\rangle$  to the preparing apparatus  $\mathbf{P}$ ; observable  $\sigma_x = \frac{1}{2}|+x\rangle\langle+x| - \frac{1}{2}|-x\rangle\langle-x|$  to the measuring apparatus  $\mathbf{M}$ ; and the eigenvalues  $m = \pm\frac{1}{2}$  of  $\sigma_x$  to the displayed values  $\mathbf{m} = \pm\frac{1}{2}$ . See Table 1, Col. 4. QTIS predicts  $\Pr(\pm\frac{1}{2}) = (\pm\sqrt{\frac{1}{2}})^2 = \frac{1}{2}$  by the

### Measurement Postulate

Prepare  $\mathbf{Q}$  in state  $|p\rangle$ . Then measure observable  $M$  of  $\mathbf{Q}$ .

Let  $M = \sum m_i|m_i\rangle\langle m_i|$  and  $|p\rangle = \sum p_i|m_i\rangle$ .

If  $|m_j\rangle$  is nondegenerate, then  $\Pr(\mathbf{m}_j) = |p_j|^2$ .

We also need a special case of the joint measurement postulate:

### Joint Measurement Postulate

Prepare  $\mathbf{Q} + \mathbf{R}$  in state  $|p\rangle$ . Then measure observables  $M$  of  $\mathbf{Q}$  and  $N$  of  $\mathbf{R}$ .

Let  $M = \sum m_i|m_i\rangle\langle m_i|$ ,  $N = \sum n_j|n_j\rangle\langle n_j|$ , and  $|p\rangle = \sum p_{ij}|m_i\rangle|n_j\rangle$ .

If  $|m_k\rangle$  and  $|n_l\rangle$  are nondegenerate, then  $\Pr(\mathbf{m}_k \& \mathbf{n}_l) = |p_{kl}|^2$ . [10]

### 3 Measurement

Preparations and measurements are different: a preparation associates to  $\mathbf{Q}$  a *state* (a mathematical object); a measurement creates a *displayed value*  $\mathbf{m}$  (a physical object) [11]. A preparation need not be a measurement: a Stern-Gerlach device with its lower output blocked prepares neutrons in the  $|+\frac{1}{2}\rangle$  state, but no displayed value appears. A measurement need not be a preparation: a photon polarization measurement which destroys the photon in a photographic plate does not prepare the photon.

The measurement postulates are the only physical assertions of QTIS. They give probabilities of displayed  $\mathbf{m}$ 's on  $\mathbf{M}$  after a preparation of  $\mathbf{Q}$  by  $\mathbf{P}$ . QTIS is, *and is only*, a theory of such probabilities [12]. A measurement need only display results  $\mathbf{m}$  in accord with the measurement postulate; a measurement does not necessarily determine the state of  $\mathbf{Q}$  before or after the measurement. We accept, as do standard interpretations of quantum theory, that

$$\text{Displayed measurement values } \mathbf{m} \text{ are } \textit{created} \text{ by a measurement.} \quad (1)$$

According to (1), a quantum measurement, unlike a classical measurement, does not *reveal* a pre-existing value. Instead,  $\mathbf{m}$  is something *new* in the universe.

The remarkable thought experiment of Greenberger, Horne, and Zeilinger [13] (GHZ), later realized [14], illuminates (1). We use the formulation of Mermin [15]. The experiment involves perfect correlations between spin measurements on a single set of three particles. It is an important improvement over John Bell's famous experiment, which involves partial correlations and many sets of two particles.

GHZ consider a system of three spin- $\frac{1}{2}$ 's in a certain specified state, separating from a point toward three observers. After the particles separate, the observers choose, independently, randomly, and in spacelike separated regions, to measure  $\sigma_x$  or  $\sigma_y$  on their particle. For example, they might measure the triple of observables  $\sigma_x^1, \sigma_y^2$ , and  $\sigma_y^3$ . In this case the results of the measurements are correlated: the results of any two of the measurements determines that of the third.

It seems that the measured values of  $\sigma_x^1, \sigma_y^2$ , and  $\sigma_y^3$  must be "in" the spin- $\frac{1}{2}$ 's as they separate: how else could the particles "know" how to behave in this correlated manner in spacelike separated regions? Similar considerations of three other triples of observables makes it seem that that all six spin values  $\sigma_x^1, \sigma_y^1, \sigma_x^2, \sigma_y^2, \sigma_x^3, \sigma_y^3$  must be "in" the particles as they separate, and that there are several correlations between these values. But this is not the case: An examination of the  $2^6$  possible assignments of the six spin values shows that none has all of the required correlations!

Thus, despite the correlations between the spacelike separated measurements, the measured spin values are not "in" the individual spin- $\frac{1}{2}$ 's as they separate; instead, they are established later, nonlocally, when the spins are measured. *Nature exhibits nonlocal behavior.* We accept this. This eliminates

the most plausible alternative to (1): that a measurement reveals a preexisting local value [16].

We can reexpress the nonlocality shown by the GHZ experiment using (1):

Measurement values *created in spacelike separated regions can be correlated.* (2)

From (1),  $\mathbf{Q} + \mathbf{M}$ 's evolution during a measurement is nondeterministic. SE's evolution is deterministic. Thus  $\mathbf{Q} + \mathbf{M}$  does not evolve according to SE during a measurement. We arrived at the same conclusion in Sec. 1, based on the fact that  $\mathbf{Q} + \mathbf{M}$  is not isolated. If we were to insist that  $\mathbf{Q} + \mathbf{M}$  evolves according to SE during a measurement, then we would have a contradiction, which is the notorious measurement problem. QTIS avoids the problem by recognizing that in principle SE cannot describe the evolution of  $\mathbf{Q} + \mathbf{M}$ . Since this is essential to the consistency of our interpretation of measurement in QTIS, we elaborate.

Macroscopic systems are not, under ordinary circumstances, isolated. They cannot be isolated if we can *see* them. They interact with their own radiation field and that of other objects. They absorb cosmic background radiation photons. Due to their extremely dense energy spectra, they are coupled with even astronomically distant matter [17]. This is true even classically: a calculation of Borel [18] shows that the gravitational field of a gram of matter at Sirius moving one centimeter completely changes the classical microscopic state of a container of gas at Earth in  $10^{-6}$  sec!

Macroscopic systems *can* evolve according to SE, as both calculations [19] and experiment [20] show. But only if the system is sufficiently isolated. The literature on macroscopic quantum coherence in general [21], and on quantum computers in particular [22], recognizes that isolation of the relevant degrees of freedom is necessary to obtain quantum behavior.

Experiments with SQUIDs provide vivid examples of macroscopic quantum behavior. If environmental interactions are sufficiently suppressed, then the magnetic flux of a SQUID exhibits *quantum tunneling* as predicted by SE between *macroscopically* different flux states [23]. If environmental interactions are not suppressed, then the flux remains fixed.

Another experiment provides strong evidence for a *quantum superposition* of oppositely flowing macroscopic currents of 2-3  $\mu\text{A}$ , causing a local magnetic moment of  $10^{10}\mu\text{B}$  in a SQUID [24, 25]. The experimental apparatus "is carefully filtered and shielded and cooled to 40 mK" to achieve isolation.

Several experiments have demonstrated a loss of quantum behavior when a previously isolated system interacts with its environment or emits photons [26].

Of course quantum theory is widely used in modeling nonisolated objects. But more must be put into the model than QTIS. This is true even at the molecular level. Consider, for example, molecular structure, essential to chemistry and molecular biology. The structure is *not* in QTIS: it is "put in by hand" using the Born-Oppenheimer approximation, which is not part of QTIS [27].

Even after molecular structure is "put in", QTIS cannot always explain the stability of the structure. For example, sugar is found only in stable left and

right hand states, without the tunneling between them predicted by SE. Joos and Zeh find, even after taking into account the long tunneling time, that this “must have reasons which lie outside the molecule.” [28] According to Cina and Harris, “the presence of the surrounding medium is believed to stabilize the handed states.” [29]

The fixed reading of a measuring apparatus is the fixed magnetic flux in a nonisolated SQUID and the fixed handedness of a sugar molecule writ large.

We have seen that “**Q** is microscopic” is neither necessary (SQUID examples) nor sufficient (sugar example) that “**Q** is isolated”. QTIS is a theory of the *isolated*, which is not the same as a theory of the *small*. In particular, QTIS is not a universal theory. Perhaps there is a quantum extension of QTIS which is universal. Perhaps there is not [30].

We simply accept here (1) and (2) as fundamental facts about quantum phenomena, and then construct a simple and consistent understanding of QTIS with their help [31]. Thus the measurement postulate of QTIS postulates, but does not explain, the created measurement values of (1). And the joint measurement postulate postulates, but does not explain, the nonlocal correlations in (2). If an extension of QTIS which describes the measurement process is found someday, then the approach taken here will still provide a simple and consistent way to think about measurement and state reduction in QTIS.

(Similarly, special relativity *postulates*, but does not *explain*, a universal light speed. Perhaps some future theory will explain a universal light speed in terms of deeper principles. But today we happily use special relativity and no one complains of a “universal light speed problem”. And a deeper theory would not invalidate special relativity. Note also a striking similarity: relativity does not explain the *flow* of time, just as QTIS does not explain the *creation* of measurement values.)

Our interpretation of QTIS and the Copenhagen interpretation [32] of Bohr and others share a feature: neither provides a quantum description of the measuring apparatus. But there is an important difference: Bohr offers an unexplained quantum/classical duality as a reason, whereas we offer an explained isolated/nonisolated duality.

## 4 State Reduction

The previous section discussed the creation of displayed measurement values  $\mathbf{m}$  on  $\mathbf{M}$  in a measurement of  $Q$ . This section discusses the state of  $\mathbf{Q}$  after a measurement. Many authors [33] adopt the

### State Reduction Postulate

A measurement of  $M$  with result  $\mathbf{m}_j$  prepares  $\mathbf{Q}$  in state  $|m_j\rangle$ .

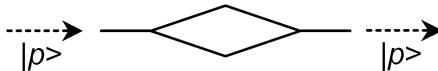
However, a photon polarization measurement which destroys the photon in a photographic plate does not prepare the photon in *any* state, much less the one specified by the reduction postulate. Consider another example, due to John Bell [34]. A momentum measurement on a neutron is made by observing a recoil proton. Unlike the photon measurement, this is a preparation: the measurement leaves the neutron in some state. But a reduction need not occur: a measurement with value  $\mathbf{k}$  need not prepare the neutron in state  $|\mathbf{k}\rangle$ . Indeed, the neutron can be brought nearly to rest by the measurement. Also, measurements of some nonlocal observables necessarily violate the reduction postulate [35]. These examples show that Nature does not always obey the reduction postulate. Thus we reject it.

The difficulty with the postulate has been recognized. Pauli called a measurement which is accompanied by a reduction a measurement of the *first kind*, otherwise it is a measurement of the *second kind*. But this is just a naming of possibilities, which does not tell us when a measurement is accompanied by a reduction.

We now present a measurement example in which QTIS, with no reduction postulate, *predicts* a state reduction. We consider a thought experiment of Scully, Shea, and McCullen (SSM) [36]. The thought experiment vividly illustrates state reduction, but it is not certain that it can be realized [37]. However, similar, though less pedagogically attractive, experiments *have* been realized [38, 39].

The SSM thought experiment is an elaboration of a thought experiment of Wigner [40]. In Wigner's experiment, two Stern-Gerlach devices oriented in the  $z$ -direction are placed back-to-back with auxiliary magnetic fields so that a neutron  $\mathbf{Q}$  entering the first device leaves the second with its original direction. See Fig. 2. A  $\mathbf{Q}$  prepared in state  $|-\frac{1}{2}\rangle$  traverses the lower path and emerges reprepared in the same state:  $|-\frac{1}{2}\rangle \rightarrow |-\frac{1}{2}\rangle$ . (We ignore the irrelevant spatial degree of freedom of  $\mathbf{Q}$ .) Similarly,  $|+\frac{1}{2}\rangle \rightarrow |+\frac{1}{2}\rangle$ . By the linearity of Schrödinger evolution,

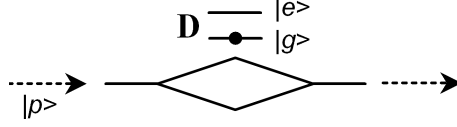
$$|p\rangle \equiv \alpha_- |-\frac{1}{2}\rangle + \alpha_+ |+\frac{1}{2}\rangle \rightarrow |p\rangle. \quad (3)$$



**Fig. 2:** Wigner's experiment: Back-to-back Stern-Gerlach devices.  $\mathbf{Q}$  enters and exits in state  $|p\rangle$ .



SSM modified Wigner's experiment by placing a two state quantum system  $\mathbf{D}$  near the upper path. See Fig. 3.  $\mathbf{D}$  is prepared in its ground state  $|g\rangle$ . It is excited to  $|e\rangle$  by an upper path  $\mathbf{Q}$ . Now



**Fig. 3:** SSM's experiment: The quantum system  $\mathbf{D}$  is added to Fig. 2.

$$|-\frac{1}{2}\rangle|g\rangle \rightarrow |-\frac{1}{2}\rangle|g\rangle \text{ and } |+\frac{1}{2}\rangle|g\rangle \rightarrow |+\frac{1}{2}\rangle|e\rangle. \quad (4)$$

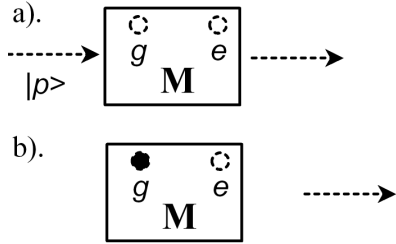
(See [41].) Again by linearity,

$$\begin{aligned} |p\rangle|g\rangle &= \{\alpha_-|-\frac{1}{2}\rangle + \alpha_+|+\frac{1}{2}\rangle\}|g\rangle \\ &\rightarrow \alpha_-|-\frac{1}{2}\rangle|g\rangle + \alpha_+|+\frac{1}{2}\rangle|e\rangle \equiv |P\rangle. \end{aligned} \quad (5)$$

(The state of  $\mathbf{Q}$ , obtained by taking the partial trace over  $\mathbf{D}$  of  $|P\rangle$ , is now mixed; this is *not* state reduction.)

This reversible evolution to  $|P\rangle$  is governed by SE and no displayed value appears; it is not a measurement. The evolution is called a *premeasurement*.

Let  $\sigma_z$  be the z-component of  $\mathbf{Q}$ 's spin. Let  $D$  be an observable of  $\mathbf{D}$  with eigenvectors  $|g\rangle$  and  $|e\rangle$ . From Eq. 5 and the joint measurement postulate, a measurement on state  $|P\rangle$  of the observables  $\sigma_z$  and  $D$  has  $\Pr(-\frac{1}{2} \& e) = \Pr(+\frac{1}{2} \& g) = 0$ . Thus the results would be *correlated*:  $-\frac{1}{2} \& g$ , or  $+\frac{1}{2} \& e$ . The systems  $\mathbf{Q}$  and  $\mathbf{D}$  are *entangled*.



**Fig. 4:** a).  $\mathbf{Q}$  enters  $\mathbf{M}$  in state  $|p\rangle$  and then exits. b). A displayed value  $g$  is created.

Now measure  $D$ . We assume nothing about the measuring apparatus or  $\mathbf{D}$ 's postmeasurement state. Let  $\mathbf{M}$  be the combined apparatus of the premeasurement and the  $D$ -measurement. In the premeasurement,  $\mathbf{Q}$  enters  $\mathbf{M}$  in state  $|p\rangle$ , and then exits, preparing  $\mathbf{Q} + \mathbf{D}$  in state  $|P\rangle$ . See Fig. 4a. Then in the  $D$ -measurement, a displayed value  $g$  or  $e$  is created. See Fig. 4b. I claim that  $\mathbf{M}$  also measures  $\sigma_z$  on  $\mathbf{Q}$  and that the measurement is accompanied by a state reduction.

$\mathbf{M}$  prepares  $\mathbf{Q}$ , as  $\mathbf{Q}$  has *some* state after the  $D$ -measurement. What is this state? Suppose  $\mathbf{M}$  displays  $g$ . From the correlations just discussed, a  $\sigma_z$ -measurement on  $\mathbf{Q}$  would now give the result  $-\frac{1}{2}$ . The only state which would certainly give  $-\frac{1}{2}$  is  $|\frac{1}{2}\rangle$ . Thus  $\mathbf{Q}$ 's state is  $|\frac{1}{2}\rangle$ . See Fig. 5b. Similarly, if  $\mathbf{M}$  displays  $e$ , then  $\mathbf{Q}$  is prepared in state  $|\frac{1}{2}\rangle$ . The measurement of  $\mathbf{D}$  inside  $\mathbf{M}$  can prepare  $\mathbf{Q}$  outside  $\mathbf{M}$  because, according to (2), Nature can create separated, random, and correlated events.

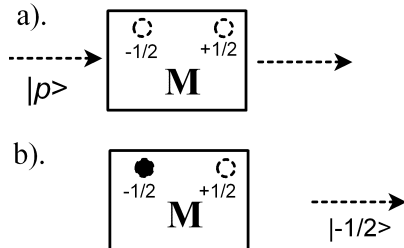
$\mathbf{M}$  also performs a  $\sigma_z$ -measurement on state  $|p\rangle$  of  $\mathbf{Q}$ . To see this, first note that from Eq. 5,  $\Pr(g) = |\alpha_-|^2$  and  $\Pr(e) = |\alpha_+|^2$  for a measurement of  $M$  on state  $|P\rangle$ . Fig. 5 replaces  $g$  with  $-\frac{1}{2}$  and  $e$  with  $+\frac{1}{2}$  on  $\mathbf{M}$ 's display in Fig. 4. Then  $\Pr(-\frac{1}{2}) = |\alpha_-|^2$  and  $\Pr(+\frac{1}{2}) = |\alpha_+|^2$ . From Eq. 3, these are the probabilities of  $\sigma_z$  for  $|p\rangle$ . Thus  $\mathbf{M}$  with the changed display performs a  $\sigma_z$ -measurement. From the last paragraph, a measured result  $\pm\frac{1}{2}$  is accompanied by a preparation of  $\mathbf{Q}$  in state  $|\pm\frac{1}{2}\rangle$ . This is exactly state reduction. The claim is proved.

*State reduction is simply a way to express the joint measurement postulate after one measurement has been made, and its result known.* State reduction is not a *dynamical* consequence of Schrödinger's equation; it is a *logical* consequence of entanglement. We have proved this only for the special case above. But the argument here can be generalized to measurements of all POVM observables on all density operator states [42].

We have attributed  $\mathbf{Q}$ 's state reduction to the creation of an  $\mathbf{m}$  on  $\mathbf{M}$ . It is *essential* to the consistency of our interpretation that  $\mathbf{Q} + \mathbf{M}$  is not isolated. For if it were, then it would obey SE. Then our explanation of  $\mathbf{Q}$ 's state reduction would be in terms of  $\mathbf{Q} + \mathbf{M}$ 's unexplained deviation from SE's deterministic evolution in the creation of  $\mathbf{m}$ , which is no explanation at all.

Two points further illustrate the nature of measurements and state reduction. First, when  $\mathbf{Q}$  traverses the lower path it does not interact directly with the detector  $\mathbf{D}$ . Nevertheless, a measured value  $-\frac{1}{2}$  appears on  $\mathbf{M}$  and  $\mathbf{Q}$ 's state is reduced to  $|\frac{1}{2}\rangle$ . (This is called a *negative result* measurement [43]).

Second, if the interaction between  $\mathbf{Q}$  and  $\mathbf{D}$  is changed so that Eq. 4 has instead  $|\frac{1}{2}\rangle|g\rangle \rightarrow |\frac{1}{2}\rangle|e\rangle$  (retaining  $|\frac{1}{2}\rangle|g\rangle \rightarrow |\frac{1}{2}\rangle|g\rangle$ ), then  $\mathbf{M}$  still performs a  $\sigma_z$  measurement. But when the measured value is  $+\frac{1}{2}$ , there is no state reduction to  $|\frac{1}{2}\rangle$ . For  $\mathbf{Q}$  is always prepared in state  $|\frac{1}{2}\rangle$  by the measurement. This is another example where the state reduction postulate fails. A measurement is only the creation of a measurement value on a measuring apparatus; a quantum system need not possess this value before the measurement (according to GHZ) or after the measurement (according to this example).



**Fig. 5:** State reduction. a).  $\mathbf{Q}$  enters  $\mathbf{M}$  in state  $|p\rangle$  and then exits. b). A displayed value  $-\frac{1}{2}$  is created. Therefore  $\mathbf{Q}$ 's state is reduced to  $|\frac{1}{2}\rangle$ .

## 5 Summary

We have provided a simple and consistent way to think about measurement and state reduction in QTIS:

**MEASUREMENT.** The macroscopic system  $\mathbf{Q} + \mathbf{M}$  is not isolated, and so cannot be described by QTIS. Thus QTIS cannot be a universal theory and has no measurement problem. In QTIS the role of  $\mathbf{M}$  is to create and display measurement values according to the probabilities in the measurement postulate.

**STATE REDUCTION.** Examples show that a state reduction need not accompany a measurement. But another example shows that a state reduction can occur. QTIS explains the reduction as a consequence of the joint measurement postulate. Not insisting on a quantum explanation of measurement makes possible a quantum explanation of state reduction.

## References

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- [2] Wojciech Zurek, “Decoherence and the transition from quantum to classical,” *Physics Today* **44** (10), 36-44 (1991).
- [3] “The apparatus should not be separated off from the rest of the world into black boxes, as if it were not made of atoms and ruled by quantum mechanics.” (J.S. Bell, “Against ‘measurement’,” *Physics World* **3** (8) 33-40 (1990)) I would reply: *Why* must the *nonisolated* apparatus (which is, I agree, made of atoms) be ruled by quantum mechanics?
- [4] For example, Zurek [2], has attempted to give a quantum description of a measurement. The results so far are incomplete, provisional, complicated, and controversial: see the letters to the editor in response to Zurek’s paper (*Physics Today* **46** (4), 13 (1993).)
- [5] “What is required is to explain how one particular macrostate can be forced by the quantum formalism to be realized – a feature of the world which is so direct and basic part of our experience that we cannot even imagine what life would be without it. In the opinion of the present author (which is shared by a small but growing minority of physicists) no solution to this problem is possible within the framework of conventional quantum mechanics.” (A. J. Leggett, “On the Nature of Research in Condensed-State Physics,” *Foundations of Physics* **22**, 221-233 (1992).)
- “The quantum theory of measurement is motivated by the idea of the universal validity of quantum mechanics, according to which this theory should be applicable, in particular, to the measuring process. Hence one would expect, and most researchers in the foundations of quantum mechanics have done so, that the problem of measurement should be solvable *within* quantum mechanics. The long history of this problem shows that, in spite of many important partial results, there seems to be no straightforward route towards its solution.” (P. Busch, P. Lahti, P. Mittelstaedt, *The Quantum Theory of Measurement* (Springer-Verlag, Berlin, 1991), p. 138.)
- “There are good reasons to doubt that quantum mechanics in its present form is the appropriate theory of macroscopic systems.” (K. Kraus, *States, Effects, and Operations* (Springer-Verlag, Berlin Heidelberg, 1983), p. 99.)
- “There is no dynamical explanation for the definite occurrence of a particular measurement outcome, as opposed to other possible measurement outcomes in a quantum measurement process – the occurrence is constrained by the kinematic probabilistic correlations encoded in the projective geometry of Hilbert space, and only by these correlations.” (J. Bub and I. Pitowsky, *Two Dogmas About Quantum Mechanics*, arXiv 0712.4258.)
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- p. 220; Arno Böhm, *Quantum mechanics: foundations and applications* (Springer-Verlag, New York, 1986), 2nd ed., p. 72; F. Schwabl, *Advanced quantum mechanics* (Springer, Berlin, 1999), p. 40.
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- [9] More generally, states are represented by density operators and observables by positive operator valued measures (POVMs). See K. Kraus [5].
- [10] This is a special case of a more general postulate concerning joint measurements of commuting observables.
- [11] This distinction between measurements and preparations, made as early as 1937 (H. Margenau, “Critical Points In Modern Physical Theory,” *Phil. Sci.* **4**, 337 - 370 (1937) and “Philosophical problems of measurement in physics,” *Phil. Sci.* **25**, 23-33 (1958)), is not universally appreciated even today.
- [12] It is often said that because SE is time reversal invariant, so is QTIS. But the measurement postulate incorporates an irreversibility in QTIS: *first* prepare, *then* measure. Thus QTIS is not time reversal invariant, nor can an arrow of time be deduced from the theory.
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- [16] Still, the GHZ experiment does not force us to accept (1), as there are other interpretations, for example, Everett’s relative state interpretation (Hugh Everett, “Relative state’ formulation of quantum mechanics,” *Rev. Mod. Phys.* **29**, 454-462 (1957), footnote p. 459.) and Bohm’s causal interpretation (C. Dewdney, et al., “Spin and non-locality in quantum mechanics,” *Nature* **336**, 536-544 (1988), Figs. 5 and 6. See also C. Dewdney, et al., “A causal account of non-local Einstein-Podolsky-Rosen spin correlations,” *J. Phys. A* **20**, 4717-4732 (1987) and C. Dewdney, et al., “What happens in a spin measurement?,” *Phys. Lett. A* **119**, 259-267 (1986)).
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