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## Can the two-time interpretation of quantum mechanics solve the measurement problem?



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## ABSTRACT

Over many years, Aharonov and co-authors have proposed a new interpretation of quantum mechanics: the two-time interpretation. This interpretation assigns two wavefunctions to a system, one of which propagates forwards in time and the other backwards. In this paper, I argue that this interpretation does not solve the measurement problem. In addition, I argue that it is neither necessary nor sufficient to attribute causal power to the backwards-evolving wavefunction  $\langle\phi|$  and thus its existence should be denied, *contra* the two-time interpretation. Finally, I follow Vaidman in giving an epistemological reading of  $\langle\phi|$ .

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### 1. Introduction

It is uncontroversial to say that there is no (global) consensus as to which interpretation of quantum mechanics should be adopted. In this paper, I will evaluate a new interpretation proposed by Aharonov and Gruss (2005), Aharonov, Cohen, Gruss, and Landsberger (2014) called the Two-Time Interpretation (TTI),<sup>1</sup> which claims to be local, deterministic and to predict and explain novel phenomena. I will concentrate on whether this interpretation solves the measurement problem: since a prerequisite for joining the panoply of interpretations of quantum mechanics (QM) is to solve the measurement problem. I will argue that it does not.

The measurement problem arises as follows. When a measuring device<sup>2</sup> measures a system initially in the state

<sup>1</sup> The two papers cited explicitly expound the TTI, but other papers such as Aharonov and Rohrlich (2005) and Aharonov and Vaidman (2008) hint at it, since — as will become apparent shortly — the TTI naturally arises out of a wider research programme.

<sup>2</sup> As usual, we model a measurement by a composite unitary operator  $U$  that takes the measuring device to one of several distinguishable (orthogonal) states depending on the system's state. Thus, a measuring apparatus that measures spin- $x$  behaves as follows:

$$U| \uparrow_x \rangle_S | \text{ready} \rangle_A \rightarrow | \uparrow_x \rangle_S | \text{up} \rangle_A$$

$$U| \downarrow_x \rangle_S | \text{ready} \rangle_A \rightarrow | \downarrow_x \rangle_S | \text{down} \rangle_A.$$

$| \Psi_S \rangle = \alpha | \uparrow_x \rangle + \beta | \downarrow_x \rangle$ , the joint state of the system and apparatus evolves, by linearity, to

$$| \Phi_{S+A} \rangle = \alpha | \uparrow_x \rangle_S | \text{up} \rangle_A + \beta | \downarrow_x \rangle_S | \text{down} \rangle_A. \quad (1)$$

The macroscopic measuring device is now entangled with the system and the composite system is in a superposition with respect to the product state basis. However, we never experience macroscopic superpositions, such as measuring devices pointing at both 'up' and 'down'. Rather, the measuring device will appear to display a single *definite outcome*.

In practice, in order to get empirical content from the formalism we apply a set of rules for measurement (sometimes called 'the measurement algorithm' (Wallace, 2012)): write the state in the basis of the measured quantity/observable, and the pointer,  $\alpha_i | a_i \rangle | A_i \rangle$ , and then interpret  $|\alpha_i|^2$  as the probability ( $Pr$ ) of finding state  $| a_i \rangle$ . In the case above, the measuring device is either found in the state  $| \text{up} \rangle$  with  $Pr = |\alpha|^2$  or  $| \text{down} \rangle$  with  $Pr = |\beta|^2$ . Thus one way of describing the measurement problem is to say that this algorithm lacks a justification and 'to solve the measurement problem we need to give a well-formulated theory which explains the success of the measurement algorithm' (Wallace, 2008).

In this paper I evaluate whether the TTI can solve this measurement problem. As the TTI arises from a particular reading of the two-state vector formalism (TSVF), I will first, in Section 2, discuss the TSVF. In Section 3, I outline the key tenets of the TTI as well as its proposed solution to the measurement problem. Section

4 first investigates whether the TTI explains the success of the measurement algorithm, and then whether it is well-formulated. In Section 5, I argue that there are further problems facing this interpretation, and in Section 6 I advocate an alternative reading of the situation.

## 2. What is the two-state vector formalism?

The two-state vector formalism (TSVF) (Aharonov & Vaidman, 2008; Aharonov, Bergmann, & Lebowitz, 1964) alters the traditional formalism of QM by assigning an additional state vector  $\langle\phi|$  to a system, as well as the usual state vector,  $|\psi\rangle$ . The latter state vector  $|\psi(t_0)\rangle$  unitarily evolves according to the Schrödinger equation, under  $U$ . However, the state  $\langle\phi(t_1)|$  evolves unitarily backwards in time under  $U^\dagger$  and thus is called the ‘backwards-evolving state vector’.<sup>3</sup> Combined they form the two-state vector,

$$\langle\phi||\psi\rangle \quad (2)$$

which also evolves unitarily. The philosophical motivation behind TSVF is to remove the time asymmetry implicit in the standard QM formalism, which Aharonov and Reznik (2002) see as originating in the usual conception of state, rather than being inherent in QM. Using final and initial conditions is more time-symmetric than just initial conditions.

The TSVF is not an interpretation of QM: rather it is a mathematical formalism that applies to pre- and postselected (PPS) ensembles. A preselected ensemble is a *prepared* ensemble: all the systems gave the same outcome of a particular measurement at  $t_0$ . For example, it might be specified that the electrons in a Stern-Gerlach experiment are all initially  $|\uparrow_z\rangle$ . A postselected ensemble is defined analogously: e.g. those systems that gave the value  $a_i$  for observable  $A$  at time  $t_1$  ( $> t_0$ ).

Postselection can be viewed as specifying a final condition for the system just as preparation/preselection specifies an initial condition. A PPS system (a member of a PPS ensemble) therefore has two boundary conditions: a final as well as an initial condition.<sup>4</sup> These boundary conditions (and therefore the two-state vector) are defined by measurement outcomes, as shown in Fig. 1. We envisage that measurements are made on the system in the period  $t_0 < t < t_1$ , as shown in Figs. 2 and 3. Note how the situation differs from classical mechanics: classically, if we know the initial condition and the dynamics (the Hamiltonian) then the information contained in the final condition is redundant. However, in QM there is, for some measurements, no way even in principle to predict the result. Thus, specifying a final condition gives us more information about the system than just an initial condition.

Next, a method of determining the probabilities of outcomes of different measurements on PPS systems is needed. This is given by the Aharonov, Bergmann and Lebowitz (ABL) rule (Aharonov et al., 1964) which tells us, given an initial state  $|a\rangle$  and a final state  $|b\rangle$ , the probability that an intermediate projective measurement of the non-degenerate operator  $C$  yields eigenvalue  $c_i$ . We begin with the formula

$$\mathcal{P}(c_i|a, b) = \frac{\mathcal{P}(b|c_i)\mathcal{P}(c_i|a)}{\sum_j \mathcal{P}(b|c_j)\mathcal{P}(c_j|a)} \quad (3)$$

Note that this expression is derived from the probability calculus: the Hamiltonian is set to zero and the only physical assumption is

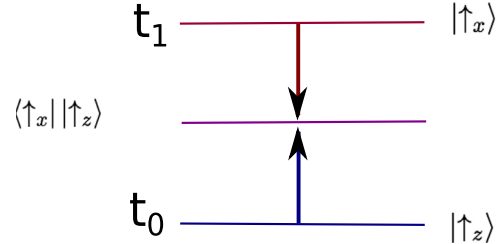


Fig. 1. Preselection at  $t_0: S_z=+\frac{1}{2}$ . Postselection at  $t_1: S_x=+\frac{1}{2}$ .

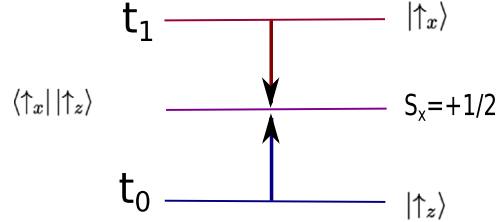


Fig. 2. An intermediate measurement of  $S_x$  in the period  $t_0 < t < t_1$  finds the eigenvalue  $+\frac{1}{2}$  with  $Pr=1$ .

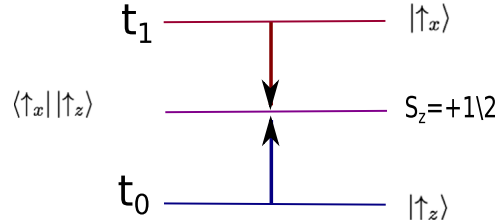


Fig. 3. An intermediate measurement of  $S_z$  in the period  $t_0 < t < t_1$  finds the eigenvalue  $+\frac{1}{2}$  with  $Pr=1$ .

that  $c_i$  screens off  $b$  from  $a$ , i.e. the intermediate measurement is projective. Using  $Pr(g|f) = |\langle gf|f\rangle|^2$ , we find:

$$\mathcal{P}(c_i|a, b) = \frac{|\langle b|c_i\rangle\langle c_i|a\rangle|^2}{\sum_j |\langle b|c_j\rangle\langle c_j|a\rangle|^2} \quad (4)$$

In the case of non-trivial time evolution, the ABL rule becomes:

$$\mathcal{P}(c_i|a, b) = \frac{|\langle b|U(t_b, t)|c_i\rangle\langle c_i|U(t, t_a)|a\rangle|^2}{\sum_j |\langle b|U(t_b, t)|c_j\rangle\langle c_j|U(t, t_a)|a\rangle|^2} \quad (5)$$

For the PPS system shown in Figs. 1–3, the ABL rule gives  $Pr=1$  for an intermediate result of  $S_z=+\frac{1}{2}$  and likewise for  $S_x=+\frac{1}{2}$ . For  $S_y=+\frac{1}{2}$ ,  $Pr = \frac{1}{2}$ . The ABL rule is time-symmetric in the sense that, if the initial and final states are exchanged, then provided the Hamiltonian is time-reversal invariant, the probabilities do not change. Note that for convenience the self-Hamiltonian (i.e. the Hamiltonian of the measured system) is often set to zero by advocates of this programme (for example, (Aharonov et al., 2014, p. 138)), a practice which I follow in this paper. Gell-Mann and Hartle refer to the ABL rule as a “time-neutral formulation of quantum mechanics” (Gell-Mann & Hartle, 1994, p. 7).

Does TSVF have any advantage over the standard formalism? According to proponents of the TSVF, certain features of QM that would otherwise be opaque, are brought to light through the prism of the TSVF. For instance, discussing the path of a quantum particle through an interferometer is a fraught task: did the particle pass through both slits? Can we, or should we, assign a trajectory? In this connection, Vaidman suggests that the TSVF is illuminating: in particular, it is the right formalism for describing the past of a quantum particle (Vaidman, 2013; Danan, Farfurnik, Bar-Ad, & Vaidman, 2013). Additionally, the proponents of TSVF

<sup>3</sup> In what follows, for brevity  $\langle\phi|$  denotes the generic backwards-evolving state.

<sup>4</sup> In practice, measurements on postselected ensembles involve doing a measurement on the whole preselected ensemble, then performing a selective measurement and discarding the results for systems that do not pass the postselection.

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