Research Article

Local Everettianism and Asymmetric Relative Statehood

Conor Husbands[1]

1. Independent researcher

This article disputes the consistency of Everettian quantum mechanics with locality in the context of certain entangled measurements of spin. It considers the ontological conception of locality provided by Timpson and Brown, whose prominent explanatory framework aims to show that the conditions of this definition are met by their Everettian reading of a canonical EPR-style setup. It then argues that this reading fails to generalise to more complex entangled spin-measurements. It presents by way of a counter-example a thought-experiment in which the definiteness of the relative state of a given subsystem is influenced by measurements performed at space-like separation. These measurements qualify the theory as nonlocal, except at exorbitant conceptual costs, such as the repudiation of realism. Four arguments are provided by way of justification. This result undermines the claim that Everettian quantum mechanics is compatible with a substantive notion of locality provided by Timpson, Brown, Wallace and other authors.

Correspondence: papers@team.qeios.com — Qeios will forward to the authors

Introduction

The vaunted preservation of locality within Everettian approaches to quantum mechanics (EQM) remains no less controversial to detractors than compelling to adherents. This attribute of the interpretation was extolled from its conception by Everett in *Theory of the Universal Wavefunction,*[1] but called into repeated question in subsequent decades, especially following the studies and theorems of Bell. Recent years have seen an intensification of this debate. Deutsch and Hayden in their[1] "Information Flow in Entangled Quantum Systems" advocate stridently for locality within EQM and claim that interactions between quantum systems exert "no effect on distant systems" from which they are dynamically isolated, even if the two are entangled.[2] Waegell and McQueen use a reformulated version of Bell's arguments as a means

 doi.org/10.32388/IHMHPN

to prise different interpretations of locality and argue that prominent expressions of EQM fail to extrude causal relations between distant (space-like separated) events from the theory. Faglia, in his[2] "Non-separability, Locality and Criteria of Reality," responds critically to the Waegell-McQueen analysis, arguing that their assumption of a disputable "Criterion of Reality" principle constitutes a significant weakness. Drezet advances a similar thesis, drawing upon the GHZ theorem.[3] Saunders, in a recent paper, argues by means of an analysis of physical (cf. epistemic) probability that violations of the common postulate of outcome independence underpin rather than refute the many-worlds asserted by EQM.[4] Perhaps the most prominent litigators of this (non-)property of EQM are Timpson and Brown, in their[3] "Entanglement and Relativity"[5] and[4] "Bell on Bell's Theorem" defending this interpretation against accusations of nonlocality made in the context of the entangled measurements involved in EPR and Bell-style thought-experiments.

This article puts forward a counter-example to the claim that certain existing formulations of EQM provide local explanations of entangled measurements. It does this by means of a variation of the EPR-style experiments examined in the Timpson-Brown papers. In the counter-example, the definiteness of the relative state of a given subsystem is influenced by measurements performed at space-like separation. This undermines the claim that EQM is compatible with a substantive notion of locality provided by Timpson, Brown, Wallace[6] and other Everettians.

I.

Timpson and Brown[7] provide an authoritative reconciliation of Everettianism with locality in the context of entangled measurements of spin. This reconciliation occurs in the context of a familiar family of experiments: measurements of spin-$\frac{1}{2}$ particles, projected from a source in opposite directions, are made by two observers at space-like separation, and accordingly in the putative absence of possible causal influence between the measurements. The correlations which nonetheless arise between outcomes of these measurements call into question whether influences do not propagate between them. The urgency of this question was redoubled with the work of Bell in the 1960s which demonstrated the inconsistency of local hidden variable theory with the predictions of quantum mechanics, the latter being validated by numerous series of tests. Against this backdrop, EQM has been held out as an attractive interpretative framework, consistent with the predictions and results of quantum theory whilst preserving locality. Whilst Everett himself acknowledged this merit without sounding trumpets,[8] recent scholars have been far more strident: as well as the commentators cited above, the likes of Bacciagaluppi and Ney go as far as to extol locality-preservation as the chief attraction of EQM.[9]

The argumentative thrust of locality-preserving EQM is multi-faceted, if not altogether rhizomatic. For some, the assertion of the continuous reality of all components of the universal wavefunction evolving in accordance with the Schrödinger equation forestalls the abrupt global ontological changes which distinguish nonlocal effects. For others, the inability to transmit information between space-like separated entangled measurements, as expressed in e.g. the Deutsch-Hayden theorem, cements its consistency with locality.[10] In the case of Timpson and Brown, the justification goes back to the provenance of Everettianism itself: Everett's assertion of a "fundamental relativity of states"[11] is weaponised by these authors as a means to elude the implication that spatio-temporally distant states are altered by measurements outcomes at a given subsystem. Although a spin-measurement outcome at the station of a given observer yields information about the state of a distant system, only the coupling of the vector corresponding to this state has reality, and therefore only the relative state of this system to the observer shifts as a result of the intervention.

This article endeavours to demonstrate that the reconciliation of EQM with locality does not generalise beyond the more straightforward examples of entangled spin-measurements considered by Timpson, Brown et. al. to the full spectrum of experiments which harbour semblances of nonlocality. It is instructive to begin with a synopsis of the argumentation provided by these authors before proceeding to the examination of counter-examples. This argumentation has two components, corresponding to cases in which measurements are performed along one as well as along distinct axes of spin angular momentum. These components nonetheless have in common the motive to prove that these "qualifying measurements" do not exert nonlocal effects on the distant subsystem. The first argument offered by Timpson and Brown could be represented as follows:

1. Following a qualifying measurement of an observer on a subsystem the distant subsystem possesses a determinate-definite state relative to this observer if and only if in an eigenstate rather than a superposition with respect to this observer (depending on the angle of spin measurement) – *Determinacy-Definiteness Criterion*
2. A qualifying measurement M_Q on a subsystem S_1 exerts a nonlocal effect on a distant subsystem S_2 if and only if S_2 is rendered determinate-definite by virtue of M_Q –*Nonlocality Definition*
3. The experiment EPR-TB features a qualifying measurement M_Q on S_1 by an observer O_1 such that S_2 remains in a superposition with respect to O_1 – *EPR Interpretation*

 doi.org/10.32388/IHMHPN

4. Following M_Q, S_2 does not possess a determinate-definite state relative to O_1 by virtue of M_Q – *Indeterminacy Thesis*
5. M_Q does not exert a nonlocal effect on S_2 – *Locality-preservation*

This argument envisages a pair of observers O_1, O_2 of entangled subsystems S_1, S_2 who perform qualifying measurements of spin at space-like separation. Of these measurements the first, made by the observer O_1, is labelled M_Q, and both are made along axes which are at an angle θ to one-another. In the formalism of Timpson and Brown, the letters A, B are used to describe the apparatus used by the observers to measure S_1, S_2 with A being used by O_1. The abbreviation EPRTB denotes the evolved version of the Einstein-Podolsky-Rosen experiment analysed by Timpson and Brown. Following these lexical clarifications it is worth addressing the meaning and purpose of premises 1)-4) and the conclusion 5).

The first premise sets out a criterion according to which a measurement performed at one subsystem does or does not induce the distant system to adopt a determinate or definite relative state. In this account, the notion of a relative state is indispensable in forestalling such inducements, as well as being a core element of the ontology of EQM:

> In the Everett approach...what claim importance are the states relative to other states in an expansion of the wavefunction. A given sub-system might not, then, be in any definite state on its own, but relative to some arbitrarily chosen state of another sub-system, it will be in an eigenstate of an observable. That is, it possesses a definite value of the observable relative to the chosen state of the other system.[12]

The second premise posits a set of necessary and sufficient conditions for a qualifying measurement to be deemed nonlocal. That this premise is decidedly nontrivial is evident from the fact that little or no accord among commentators exists as respects definitions of this term, one to which the brief précis of above paragraphs attests. Since a more detailed discussion of the span of the debate remains outside of the scope of this article, the definition provided by Timpson and Brown will not be interrogated at length and the second premise will be granted provisionally. Since 4) is entailed by the conjunction of 1) and 3), and 5) by the conjunction of 2) with 4), the third premise is the remaining *analysandum* in order to assess the plausibility of the argument's conclusion which, if veridical, enables EQM to account for a class of spin-measurement experiments in a way which is conceptually consistent with the brand of locality identified in the second premise.[13]

doi.org/10.32388/IHMHPN

The justification for the third premise is Timpson and Brown's analysis of the EPR-TB experiment. They represent the initial state of the system in the following form:[14]

$$|\uparrow\rangle_{A_1}\frac{1}{\sqrt{2}}(|\uparrow\rangle_{O_1}\left(\alpha|\uparrow_\theta\rangle_{O_2}+\beta|\downarrow_\theta\rangle_{O_2}\right)-|\downarrow\rangle_{O_1}(\alpha'|\uparrow_\theta\rangle_{O_2}+\beta'|\downarrow_\theta\rangle_{O_2}))|\uparrow_\theta\rangle_{A_2}$$

Here, $|\uparrow\rangle_{A_1}$ is the initial state of the measuring apparatus applied by O_1 to their subsystem (a device for the detection of spin) and $|\uparrow\rangle_{O_1}, |\downarrow\rangle_{O_1}$ are the states of spin of the particle in this subsystem. The relevant equivalents in the case of the subsystem of O_2 are $|\uparrow_\theta\rangle_{A_2}$, $|\uparrow_\theta\rangle_{O_2}$ and $|\downarrow_\theta\rangle_{O_2}$. The amplitudes whose mod-squares yield the probabilities of the up (↑) or down (↓) outcomes for the spin of the two particles are represented by $\alpha, \beta, \alpha', \beta'$. Finally, it should be noted that the action of $|\uparrow\rangle_{A_1}$ on $|\uparrow\rangle_{O_1}, |\downarrow\rangle_{O_1}$ and of $|\uparrow_\theta\rangle_{A_2}$ on $|\uparrow_\theta\rangle_{O_2}, |\downarrow_\theta\rangle_{O_2}$ is given by:

$$|\uparrow\rangle_{A_1}|\uparrow\rangle_{O_1}\rightarrow|\uparrow\rangle_{A_1}|\uparrow\rangle_{O_1}$$

$$|\uparrow\rangle_{A_1}|\downarrow\rangle_{O_1}\rightarrow|\downarrow\rangle_{A_1}|\downarrow\rangle_{O_1}$$

$$|\uparrow_\theta\rangle_{A_2}|\uparrow_\theta\rangle_{O_2}\rightarrow|\uparrow_\theta\rangle_{A_2}|\uparrow_\theta\rangle_{O_2}$$

$$|\uparrow_\theta\rangle_{A_2}|\downarrow_\theta\rangle_{O_2}\rightarrow|\downarrow_\theta\rangle_{A_2}|\downarrow_\theta\rangle_{O_2}$$

The equation which describes the post-measurement state is, therefore, the following:

$$\frac{1}{\sqrt{2}}(|\uparrow\rangle_{A_1}|\uparrow\rangle_{O_1}\left(\alpha|\uparrow_\theta\rangle_{O_2}|\uparrow_\theta\rangle_{A_2}+\beta|\downarrow_\theta\rangle_{O_2}|\downarrow_\theta\rangle_{A_2}\right) \\ -|\downarrow\rangle_{A_1}|\downarrow\rangle_{O_1}(\alpha'|\uparrow_\theta\rangle_{O_2}|\uparrow_\theta\rangle_{A_2}+\beta'|\downarrow_\theta\rangle_{O_2}|\downarrow_\theta\rangle_{A_2})$$

The most relevant feature of this representation for the Timpson-Brown argument is the fact that, relative to determinate states of the subsystem in the propinquity of O_1, being $|\uparrow\rangle_{O_1}, |\downarrow\rangle_{O_1}$, the distant subsystem lies in superposition. No one state from the pair $|\uparrow_\theta\rangle_{O_2}, |\downarrow_\theta\rangle_{O_2}$ or indeed from the pair $|\uparrow_\theta\rangle_{A_2}, |\downarrow_\theta\rangle_{A_2}$ factorises corresponding states of the distant subsystem exclusively. However, the distant observer is at liberty to employ a different representation which involves rearranging the above post-measurement state so that O_1's states are in superposition. This yields the following expression:

$$\frac{1}{\sqrt{2}}(|\uparrow_\theta\rangle_{A_2}|\uparrow_\theta\rangle_{O_2}\left(\alpha|\uparrow\rangle_{O_1}|\uparrow\rangle_{A_1}-\alpha'|\downarrow\rangle_{O_1}|\downarrow\rangle_{A_1}\right) \\ +|\downarrow_\theta\rangle_{A_2}|\downarrow_\theta\rangle_{O_2}(\beta|\uparrow\rangle_{O_1}|\uparrow\rangle_{A_1}-\beta'|\downarrow\rangle_{O_1}|\downarrow\rangle_{A_1})$$

The relevance of this symmetry and its associated freedom for each observer to express the pre- and post-measurement states such that eigenstates of A_1 factorise linear combinations of states of A_2 or such that eigenstates of A_2 factorise linear combinations of states of A_1 is, for Timpson and Brown, the support it provides for their analysis of EPRTB in terms of the notion of a relative state. Eigenstates of A_2 are in superposition relative to A_1 and eigenstates of A_1 are in superposition relative to A_2 by virtue of this symmetry. Thus, the measurement performed by O_1 satisfies the conditions within premise 3) above: S_2 remains in a superposition with respect to O_1. Given the criterion for determinacy-definiteness submitted in 1) and subsequent premises' description of the EPRTB scenario, the authors' fifth premise follows logically. The conclusion follows from the conjunction of this with the second premise and, as adumbrated previously, this completes the argument of Timpson and Brown that local Everettian explanations of EPRTB succeed.

In parenthesis, and for the purposes of laying groundwork for the next section, it should be noted that this configuration is not the sole focus of the EPRTB paper. They also provide an analysis of an EPR experiment in which parallel spin measurements are made by the two observers – that is, measurements of spin angular momentum along axes which are aligned. The differences between their account of this scenario and the non-parallel case have implications for the ontology of their theory. Crucially, in the parallel case, measurements of spin confer knowledge of the state of distant as well as the local subsystem. Since the quantum state is given by

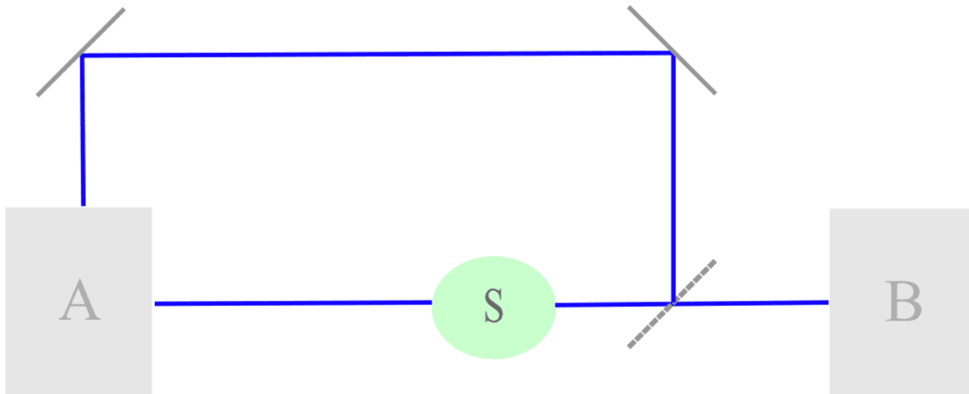
$$\frac{1}{\sqrt{2}}(| \uparrow\rangle_{A_1}| \uparrow\rangle_{O_1}| \downarrow\rangle_{A_2}| \downarrow\rangle_{O_2} - | \downarrow\rangle_{A_1}| \downarrow\rangle_{O_1}| \uparrow\rangle_{A_2}| \uparrow\rangle_{O_2})$$

there is no uncertainty for either observer as to the spin of the distant particle following their measurement. Of the two possible measurement outcomes for this particle, only $| \downarrow\rangle_{A_2}, | \downarrow\rangle_{O_2}$ are compatible with $| \uparrow\rangle_{A_1}, | \uparrow\rangle_{O_1}$ and only $| \uparrow\rangle_{A_2}| \uparrow\rangle_{O_2}$ are compatible with $| \downarrow\rangle_{A_1}| \downarrow\rangle_{O_1}$. Thus, whichever of the two is regarded as the distant subsystem, such a subsystem takes on a determinate-definite state relative to the intervening observer immediately upon measurement, according to Timpson and Brown. The distinction between these authors' treatment of the parallel and non-parallel cases will prove decisive in the variation on the EPRTB experiment assessed in the remainder of this article.

II.

This section attempts to demonstrate that the relevant characteristics of EPRTB – namely, those which soundness of the argument of the authors cited above – fail to generalise to variations of this experiment. This militates against the inference that the forgoing apologia support a more general local Everettian account of entangled spin-measurements. Subsequently, it attempts to show that, given the first and second premises of Timpson and Brown, these variations qualify the Everettian account as *nonlocal*.

The variation to EPRTB involves a beam-splitting device such as a half-silvered mirror being inserted in the channel transporting the spin-$\frac{1}{2}$ particle to O_2's apparatus. Fully silvered mirrors are then utilised to direct the reflected component of the particle's state towards the apparatus of O_1. The path lengths can be varied so that the arrival times of the particles at each station are arbitrarily close or far apart in the laboratory rest frame.



The above diagram illustrates this configuration (where S represents the source, A and B the stations of O_1 and O_2, and the dashed and solid lines the half and fully silvered mirrors respectively). The evolution of the spin-$\frac{1}{2}$ particle of S_2 is given by the following:

$$|\uparrow\theta\rangle_{O_2^0} \rightarrow \frac{1}{\sqrt{2}}\left(|\uparrow\theta\rangle_{O_2} + i|\uparrow\theta\rangle_{O_2^2}\right) \rightarrow \frac{1}{\sqrt{2}}\left(|\uparrow\theta\rangle_{O_2} - |\uparrow\theta\rangle_{O_2^3}\right) \rightarrow \frac{1}{\sqrt{2}}\left(|\uparrow\theta\rangle_{O_2} - i|\uparrow\theta\rangle_{O_2^4}\right)$$

$$|\downarrow\theta\rangle_{O_2^0} \rightarrow \frac{1}{\sqrt{2}}(|\downarrow\theta\rangle_{O_2} + i|\downarrow\theta\rangle_{O_2^2}) \rightarrow \frac{1}{\sqrt{2}}(|\downarrow\theta\rangle_{O_2} - |\downarrow\theta\rangle_{O_2^3}) \rightarrow \frac{1}{\sqrt{2}}(|\downarrow\theta\rangle_{O_2} - i|\downarrow\theta\rangle_{O_2^4})$$

This evolution follows the interaction-free measurement framework proposed by Vaidman and Elitzur.[15] From the perspective of O_1, whose spin-$\frac{1}{2}$ particle's dynamics are unaffected by the presence of the beam-splitter, the evolution of the pre-measurement state is therefore given by:

$$\frac{1}{\sqrt{2}}|\uparrow\rangle_{A_1}(|\uparrow\rangle_{O_1}(\alpha|\uparrow\theta\rangle_{O_2^0} + \beta|\downarrow\theta\rangle_{O_2^0}) - |\downarrow\rangle_{O_1}(\alpha'|\uparrow\theta\rangle_{O_2^0} + \beta'|\downarrow\theta\rangle_{O_2^0})|\uparrow\theta\rangle_{A_2}$$

$$\rightarrow \frac{1}{\sqrt{2}}|\uparrow\rangle_{A_1}\left(\frac{1}{\sqrt{2}}|\uparrow\rangle_{O_1}\left(\alpha(|\uparrow\theta\rangle_{O_2} - i|\uparrow\theta\rangle_{O_2^4}\right) + \beta\left(|\downarrow\theta\rangle_{O_2} - i|\downarrow\theta\rangle_{O_2^4}\right)\right)$$
$$- \frac{1}{\sqrt{2}}|\downarrow\rangle_{O_1}\left(\left(\alpha'(|\uparrow\theta\rangle_{O_2} - i|\uparrow\theta\rangle_{O_2^4}\right) + \beta'\left(|\downarrow\theta\rangle_{O_2} - i|\downarrow\theta\rangle_{O_2^4}\right)\right))|\uparrow\theta\rangle_{A_2}$$

doi.org/10.32388/IHMHPN

On the assumption that the apparatus of O_1 is not utilised to measure the spin state of S_2, the post-measurement state is analogous to that of EPRTB:

$$\frac{1}{2}\Big(|\ \uparrow\rangle_{A_1}|\ \uparrow\rangle_{O_1}\Big(\alpha(|\ \uparrow_\theta\rangle_{O_2}-i|\ \uparrow_\theta\rangle_{O_2^4}\Big)+\beta\Big(|\ \downarrow_\theta\rangle_{O_2}-i|\ \downarrow_\theta\rangle_{O_2^4}\Big)\Big)-|\ \downarrow\rangle_{A_1}$$
$$|\ \downarrow\rangle_{O_1}(\alpha^{'}\Big(|\ \uparrow_\theta\rangle_{O_2}-i|\ \uparrow_\theta\rangle_{O_2^4}\Big)+\beta'(|\ \downarrow_\theta\rangle_{O_2}-i|\ \downarrow_\theta\rangle_{O_2^4})))\ |\ \uparrow_\theta\rangle_{A_2}$$

However, a somewhat decisive respect in which this variation is distinct from EPRTB is the respect in which it is possible for O_1 to make measurements which pertain to the state of S_2 using its very own apparatus A_1 owing to the effect of the beam-splitter and intervening channels. These measurements will confer information as to the spin of the distinct particle previously only accessible to O_2. One can therefore define an operator whose application represents the measurement of spin (belonging to S_2) by O_1:

$$|\ \uparrow_\theta\rangle_{A_1}|\ \uparrow_\theta\rangle_{O_2^4}\to|\ \uparrow_\theta\rangle_{A_1}|\ \uparrow_\theta\rangle_{O_2^4}$$

$$|\ \uparrow_\theta\rangle_{A_1}|\ \downarrow_\theta\rangle_{O_2^4}\to|\ \downarrow_\theta\rangle_{A_1}|\ \downarrow_\theta\rangle_{O_2^4}$$

$|\ \uparrow_\theta\rangle_{A_1}$ and its eigenstates $|\ \uparrow_\theta\rangle_{A_1},|\ \downarrow_\theta\rangle_{A_1}$ are distinct from $|\ \uparrow\rangle_{A_1}$ and its eigenstates $|\ \uparrow\rangle_{A_1},|\ \downarrow\rangle_{A_1}$ as the measurements at stake are distinct (although possibly simultaneous). The state after measurement can be written thus:

$$\frac{1}{2}(|\ \uparrow_\theta\rangle_{A_1}|\ \uparrow\rangle_{A_1}|\ \uparrow\rangle_{O_1}\Big(\alpha\Big(|\ \uparrow_\theta\rangle_{O_2}-i|\ \uparrow_\theta\rangle_{O_2^4}\Big)+\beta\Big(|\ \downarrow_\theta\rangle_{O_2}-i|\ \downarrow_\theta\rangle_{O_2^4}\Big)\Big)$$
$$-|\ \uparrow_\theta\rangle_{A_1}|\ \downarrow\rangle_{A_1}|\ \downarrow\rangle_{O_1}\Big(\alpha'\Big(|\ \uparrow_\theta\rangle_{O_2}-i|\ \uparrow_\theta\rangle_{O_2^4}\Big)+\beta'\Big(|\ \downarrow_\theta\rangle_{O_2}-i|\ \downarrow_\theta\rangle_{O_2^4}\Big)\Big))|\ \uparrow_\theta\rangle_{A_2}$$

Evidently, O_1 has a probability $\frac{1}{4}(\alpha^2+\alpha'^2)$ of obtaining a spin-up result for S_2 and a probability $\frac{1}{4}(\beta^2+\beta'^2)$ of obtaining a spin-down result for this subsystem (omitting any normalisation constraints on combinations of $\alpha,\alpha^{'},\beta,\beta'$), just as for S_1 were they to apply $|\ \uparrow\rangle_{A_1}$ rather than $|\ \uparrow_\theta\rangle_{A_1}$. Now, one may proceed to evaluate the implications of these findings for the EPRTB analysis. Above, it was contended in outline that this analysis fails to generalise to variants such as those exhibited in this section. This contention is grounded on the conclusion that, despite S_2 being in superposition, it is possible for O_1 to measure the state of spin occupied by S_2 by application of $|\ \uparrow_\theta\rangle_{A_1}$.

With the groundwork laid, it is possible to proceed to test the Timpson-Brown perspective against this variation. Prior to this measurement, two facts are unequivocal: (i) S_2 occupies a determinate-definite state of spin relative to neither O_1 nor O_2 and (ii) S_2 is in superposition. Following the measurement, a question arises as to whether S_2 possesses a definite such state relative to these observers. This ambiguity is discernible from the fact that whilst the distant particle belonging to this subsystem would be considered by them to be in an eigenstate of the operator $|\uparrow_\theta\rangle_{A_1}$ it remains in superposition from the perspective of the application operator $|\uparrow_\theta\rangle_{A_2}$ which remains to be deployed by O_2. Since the first premise of the Brown-Timpson argument uses the contrast between these two statuses as a criterion for the determinacy-definiteness of the subsystem in question, a decision made either way impacts whether it occupies a determinate-definite state by dint of the action of O_1. These authors are categorical that a given subsystem need not occupy a determinate-definite state relative to a given observer simply because it does so relative to another. In what follows, both of these eventualities are considered.

First, consider O_1. Consider further the implications of an affirmative response to this question: S_2 possesses a determinate-definite such state relative to O_1. According to the Brown-Timpson argument, this affirmation qualifies the theory as nonlocal. This follows from premise 2). The relative state of a distant system becomes definite by virtue of the application of $|\uparrow_\theta\rangle_{A_1}$ by O_1. Correlatively, the conditions of premise 3) are violated insofar as this observer's qualifying measurement reveals that subsystem S_2 occupies an eigenstate with respect to this observer. Under this set of assumptions, this argument not only fails to constitute a valid locality-preserving Everettian account of this EPR configuration; it is nonlocal on its own terms, with a proper subset of its axioms being sufficient to establish this conclusion. Naturally, this generates a contradiction with 5).

Second, consider the implications of a negative response to this question as respects O_1: S_2 possesses no definite state relative to O_1. This might be thought to follow from the fact that this subsystem remains in superposition as respects the basis vectors $|\uparrow_\theta\rangle_{O_2}$, $|\downarrow_\theta\rangle_{O_2}$: based on the determinacy-definiteness criterion espoused by Timpson and Brown in their first premise, the distant particle has no definite spin. However, this interpretation violates a rudimentary axiom of quantum measurement: it implies that a spin-state can be measured for the particle despite that it occupies no determinate eigenstate. This contradicts the sufficient relation between determinacy of measurement outcome and eigenstatehood as given, for instance, by Dirac:[16]

> If the system is in a state such that a measurement of a real dynamical variable ξ is certain to give one particular result (instead of giving one or other of several possible results according to a probability law, as is in general the case), then the state is an eigenstate of ξ and the result of the measurement is the eigenvalue of ξ to which this eigenstate belongs.

This inconsistency establishes that the distant subsystem S_2 does indeed possess a determinate-definite state of spin relative to O_1. Indeed, such a subsystem is in as much of an eigenstate relative to this observer as was its counterpart in the case of parallel spin measurement, in which only one state of spin of S_2 is compatible with a given state of spin of S_1 (provided O_1 is able to make the requisite observation). Further, more heuristically, such a line of interpretation unwittingly enshrouds the measurement process in mysticism: how could the spin-state of the distant particle, measured directly by virtue of its local duplicate, *not* possess a determinate-definite state following measurement by the apparatus of O_1?

Having concluded the evaluation of the S_2 particle's state relative to O_1, one is led to ask: what of its post-measurement state relative to O_2? Again, two alternatives can be considered.

First, consider the line of interpretation according to which the particle in S_2 does *not* occupy a determinate-definite state relative to O_2. This entails a fundamental asymmetry in the relative statehood of the subsystem when considered with respect to each observer. If this asymmetry be admitted, an ostensible pathway remains for a defence of the Everettian claim to locality-preservation: if, in spite of the measurement by O_1, the relative state of the distant subsystem remains unperturbed, one might naturally think that the overall system stands unimbued by the tincture of nonlocal effects. On the face of it, this intuition is buttressed by the reasoning of Timpson-Brown in the case of non-parallel spin measurements, insofar it is the determinacy-definiteness of the distant subsystem *relative to* O_1 which hinges on whether or not S_2 occupies an eigenstate or superposition from the perspective of this observer. The subsystem need not, therefore, be determinate-definite for one by virtue of being so for the other. However, this interpretation carries an absurd implication. Assume that the application of $|\uparrow_\theta\rangle_{A_1}$ by O_1 establishes that the system is in $|\uparrow_\theta\rangle_{O_2^4}$ or $|\downarrow_\theta\rangle_{O_2^4}$ relative to O_1, but fails to establish that it is in $|\uparrow_\theta\rangle_{O_2}$ or $|\downarrow_\theta\rangle_{O_2}$ relative to O_2. The system will possess a determinate *value* of spin, being $\pm\frac{1}{2}$, relative to the former but not relative to the latter. From the perspective of O_1, then, it is certain that O_2's measurement of spin will yield $\pm\frac{1}{2}$. Nonetheless, *ex hypothesi*, there is no determinate-definite state relative to O_2.

This section lists four objections to this denial of a determinate-definite state of S_2 relative to O_2 in the setup.

1.

On the basis of this denial, it is possible to predict with certainty the outcomes of measurement performed by observers yet for them to fail to occupy the determinate-definite states they measure.[17]

doi.org/10.32388/IHMHPN

This is a thoroughly counter-intuitive upshot of this line of interpretation whose consistency with any meaningful commitment to realism is dubious.[18] To see this clearly, it is fruitful to introduce the following intuitive "localized element of reality" principle conceived by Waegell and McQueen:

> If an intervention and response happen in a finite region of space-time, and the response can be predicted with certainty, then there is an element of reality located only in that region that determines that response.[19]

This principle expresses a species of realism inspired by the Einstein-Podolsky-Rosen engagement with the controversy as to the completeness of quantum theory. Allow the "response" in question to be either of the following interactions of O_2 with S_2:

$$|\uparrow_\theta\rangle_{A_2}|\uparrow_\theta\rangle_{O_2} \rightarrow |\uparrow_\theta\rangle_{A_2}|\uparrow_\theta\rangle_{O_2}$$

$$|\uparrow_\theta\rangle_{A_2}|\downarrow_\theta\rangle_{O_2} \rightarrow |\downarrow_\theta\rangle_{A_2}|\downarrow_\theta\rangle_{O_2}$$

If, in the reference frame of O_1, this interaction takes place after O_1's application of $|\uparrow_\theta\rangle_{A_1}$ to S_1, the response was determined by an extant element of reality in the neighbourhood of S_2. This follows from the "localized element of reality" principle. Nonetheless, it can be arranged so that O_1's application of $|\uparrow_\theta\rangle_{A_1}$ takes place at such a time that no non-superluminal signal could communicate between the members of each of the following two pairs of events:

$$|\uparrow_\theta\rangle_{A_1}|\uparrow_\theta\rangle_{O_2^4} \rightarrow |\uparrow_\theta\rangle_{A_1}|\uparrow_\theta\rangle_{O_2^4}, |\uparrow_\theta\rangle_{A_2}|\uparrow_\theta\rangle_{O_2} \rightarrow |\uparrow_\theta\rangle_{A_2}|\uparrow_\theta\rangle_{O_2}$$

$$|\uparrow_\theta\rangle_{A_1}|\downarrow_\theta\rangle_{O_2^4} \rightarrow |\downarrow_\theta\rangle_{A_1}|\downarrow_\theta\rangle_{O_2^4}, |\uparrow_\theta\rangle_{A_2}|\downarrow_\theta\rangle_{O_2} \rightarrow |\downarrow_\theta\rangle_{A_2}|\downarrow_\theta\rangle_{O_2}$$

O_1's prediction of O_2's measurement outcome (being one of $|\uparrow_\theta\rangle_{A_2}, |\downarrow_\theta\rangle_{A_2}$) occurs immediately in their reference frame as a result of their own measurement outcome (being one of $|\uparrow_\theta\rangle_{O_2^4}, |\downarrow_\theta\rangle_{O_2^4}$). Therefore, a space-like separated element of reality exists following O_1's measurement. Call this element λ. This constitutes a nonlocal effect in the sense of the second EPRTB premise, viz. that a qualifying measurement M_Q on a subsystem S_1 exerts a nonlocal effect on a distant subsystem S_2 if and only if S_2 is rendered determinate-definite by virtue of M_Q. Here, the element λ created by O_1's measurement (assimilable to M_Q) constitutes a subsystem as does S_2 in the original EPRTB framing. However, the existence of nonlocal effects such as these is precisely what EQM seeks to deny. The Everettian therefore is obliged to reject the "localized element of reality" principle to avoid inconsistency (a strategy which has been deployed in e.g. Faglia, P.[2]). This principle is, however, minimalistic. Without it, EQM would be committed to denying the reality of the quantum state – more precisely, the existence of any real elements of the physical state in question which determine measurement outcomes – until the point at which the measurement of O_2 is performed. In this case, EQM takes on a decidedly instrumentalist tenor. The denial of a determinate-definite state of S_2 relative to O_2 in the variation on the EPRTB experiment therefore leads to at least one of the two following rebarbative outcomes: (i) a denial of the realist doctrine expressed in the "localized element of reality" principle or (ii) an admission that nonlocal effects nonetheless persist within this variation.

2.

It follows from this denial that the correlation between the spin-measurement outcome at S_1 and the unrealised spin-measurement outcome at S_2 is not reflected in the physical or ontic state of S_2.[20] The quantum state of O_2's subsystem is thus underdetermined by its ontic state, the latter being identified with solely the physical content of O_2's light cone (which, by stipulation, does not overlap with that of O_1), as it fails to reflect the correlations between the measurement outcomes of the two observers which must exist in the light cone to guarantee the fulfilment of such correlations. This quantum state – which may be identified with, *inter alia*, the reduced density matrix which encodes the measurement predictions available to O_2 – is unchanged as a result of the space-like separated measurement. It is accordingly consistent with both measurement outcomes at S_1 and does not reflect the outcome which must now be obtained following O_1's measurement: after this measurement, it is determined (regardless of the reference frame) that O_2's measurement will yield the opposite spin-value. After both measurements are complete and once a signal is allowed to propagate between the two systems, there will be a constant conjunction between spin-up results at O_1 and spin-down results at O_2 as between spin-up results at O_2 and spin-down results at O_1. The quantum state identified by EQM is therefore underdetermined by the ontic state. Accordingly, it cannot be considered to be physically real, furnishing another sense in which this line of defence induces Everettianism to jettison realism.

3.

The denial that S_2 has any relative state *until measured* by O_2 is a negation of realism. This denial is the price of the asymmetry drawn between the determinacy-definiteness of the two subsystems' relative states in order to expunge the risk of locality violation due to O_1's intervention. Ascribing to S_1 a relatively determinate-definite post-measurement state but denying such a status to S_2 is grounded in the following criterion: All and only those states measured by O_i possess determinate-definite relative states relative to O_i. It is this manoeuvre which commits EQM to a further denomination of instrumentalism and qualifies the theory as anti-realist. If relative states are the elements of the Everettian ontology then, prior to measurement, S_2 is denied a real state in the complement of the spatio-temporal region of O_1 and, thus, the immediate propinquity of O_2. Otherwise, the definition of which of the elements in the Everettian ontology qualify as determinate-definite would be subject to inconsistent standards: were the determinate-definite relative state of S_2 to O_1 qualify as such on the basis that the spin-state of O_2's particle had decohered together with this observer into a correlated pair of states, but the distant subsystem, pre-measurement from the perspective of the distant observer, remain real, the criteria used to assign distinct statuses to the two would fail to reconcile. The two states differ *in principle* on the basis of this distinction, rather than by dint of the contrivances of the experimental setup.

4.

A further and final deficiency with the denial that the particle in S_2 occupies a determinate-definite state after the intervention of O_1 occurs due to inconsistencies generated within EQM itself as a consequence. The very premises employed by advocates of this framework in the context of EPR measurements imply the negation of the claim denied. Timpson and Brown themselves indicate that the state of the distant subsystem can transition to a determinate-definite state as a result of O_1's measurement: in the case of entangled measurements of spin along parallel axes – in contradistinction to those at a general angle θ to one another – the fact that only one vector corresponding to the distant measurement outcome factorises the local measurement outcome functions as a basis to infer the definiteness of the distant state. Indeed, this is the implication of the first premise of their argument formalised above, positing as it does not only necessary but also sufficient conditions for the determinacy-definiteness of distant states (albeit this is a premise which is deployed in their analysis of non-parallel rather than parallel measurements of spin). The following passage is decisive in illustrating this commitment:

> Following the measurements at A and B, not only does each measured system have a definite spin state relative to the indicator state of the device that has measured it, but the systems and measuring apparatuses in each region (e.g. system 1 and apparatus m_A in A) have definite spin and indicator states relative to definite spin and indicator states of the system and apparatus in the other region (e.g. m_B in B). That is, following the two local

measurements, from the point of view of the systems in one region, the states of the systems in the far region correspond to a definite, in fact perfectly anti-correlated, measurement outcome. This is in contrast to the general case of non-parallel spin measurements at A and B.

A and B in the EPRTB experiment map to S_1 and S_2 in the notation of this section, as do m_A and m_B to A_1 and A_2. It is implicit in the article of these authors that the basis for the denial of determinate-definite relative states of distant subsystems and observers in the case of non-parallel measurements of spin – despite the affirmation of such states in the case of parallel such measurements – is the lack of a determinate measurement outcome relative to the *local* observer. This fact does not obtain in the case of the modified EPRTB set-up analysed in this section, nor in the original EPRTB case. Were the distant system in the original case in a determinate-definite state of spin but the distant system in the modified case in no determinate-definite such state, a fundamental difference would have to exist between the two to warrant their distinct ontological statuses. Whilst by no means a guarantee, this provides reasonable grounds to assume that, by virtue of the logic of the EPRTB demonstration and subsequent to the application of $|\uparrow_\theta\rangle_{O_2^4}$ by O_1, S_2 possesses a determinate-definite state of spin relative to both observers.

The concluding postulate of this section is, then, that the distant system S_2 does indeed possess a determinate-definite state relative to both of O_1, O_2. The asymmetry posited by EQM between the relative state of this subsystem with respect to O_1 over against O_2 cannot be accommodated. The justification for this concluding postulate is that its negation entails unpalatable consequences in the context of EPRTB in four respects. This entails that O_1's measurement induces a transition of the distant subsystem into a determinate-definite relative state at space-like separation. Recall that the second premise of the Timpson-Brown argument holds that a qualifying measurement M_Q on a subsystem S_1 exerts a nonlocal effect on a distant subsystem S_2 if and only if S_2 is rendered determinate-definite by virtue of M_Q. By this definition, the effect of this measurement is a nonlocal effect. Accordingly, the Everettian framework fails to qualify as local in this scenario, according to the definition provided by EQM advocates.

Conclusion

Locality has been subjected by recent interlocutors in the foundations of quantum mechanics to contrasting definitions of a number perhaps as great as that of the differing interpretative schools of the theory. The heterogeneity of these definitions has been such as to lead aspects of the debate to reduce to clashes of semantic intuitions, with opposing parties agreeing on the presence or absence of certain physical effects but disagreeing over the merits and demerits of the ascription of the term "nonlocal." Some advocates of the Everettian picture have, for instance, conceded that the theory violates Bell-style inequalities whilst denying that this poses any problem for their attempts to reconcile the same with a substantive notion of locality. Others have represented the absence of action-at-a-distance in the sense of dynamical nonlocality or superluminal signalling, possibilities which have been dismissed[21] on relativistic grounds, as being sufficient to accommodate locality within EQM. In one notable case, the impossibility of information transmission across space-like separated entangled systems is considered a mark of this characteristic.[22] The difference these conceptions of locality pose in relation to the historic thinking of e.g. Einstein and Bell, the latter couched in terms of the probabilistic independence of space-like separated systems, is a stark demonstration of the diverse constellation of perspectives on the meaning of this term.

This article disputes the plausibility of ontologically local Everettianism. The main exposition of EQM which is utilised as an argumentative foil in this study is the authoritative 2002 article "Entanglement and Relativity" of Timpson and Brown. The opening section of the article reconstructs in propositional form their argument, relating as it does to parallel and non-parallel entangled spin measurements. It also defines the notion of locality operative in their analysis, which is set out in ontological terms: A qualifying measurement M_Q on a subsystem S_1 exerts a nonlocal effect on a distant subsystem S_2 if and only if S_2 is rendered determinate-definite by virtue of M_Q. The second section of the article attempts to present a variation on the Timpson-Brown rendition of the EPR experiment. Subsequently, it argues for two conclusions. First of all, the strategy which figures in this rendition with a view to preserve locality within EQM does not generalise to more complex cases of entangled spin-measurements such as this variation. Secondly, the Everettian framework qualifies as nonlocal in this variation, by dint of the fact that determinate-definite relative states of space-like separated subsystems can be induced by local measurements. Four objections are mustered against the opposing view: (i) this view entails that it is possible to predict with certainty the outcomes of measurement performed by observers yet for them to fail to occupy the determinate-definite states they measure; (ii) this view leads to the quantum state of the subsystem in question being underdetermined by its ontic state; (iii) this view entails that no relative state exists until measured, which entails in turn instrumentalism; (iv) this view is internally inconsistent, given the Timpson-Brown presentation. In the *gedankenexperiment* explored in this discussion, therefore, EQM does indeed qualify as nonlocal in the ontological sense circumscribed by exponents such as Timpson and Brown.

Footnotes

1. [5]

2. [1]

3. [6]

4. [7]

5. [3]

6. [8]

7. [3]

8. [5]

9. [9][10]

10. [1]

11. [5]

12. [3]

13. This, it must be noted, takes for granted the notion of locality featured in the second premise. If this premise is denied, the option remains open to the reader to deny the consistency of EQM with locality too. In particular, many commentators have taken locality to entail, among other things, outcome independence, viz. the probabilistic independence of space-like separated measurement outcomes, which is violated even within the EQM reformulation of the entangled measurements discussed in this article.

14. Substitutions of subscripts and other variables have been made vis-à-vis the authors' original presentation in order to preserve the consistency of this presentation with this article's earlier contents without any (deliberate) adulteration of the logic or structure of their argument.

15. [11]

16. [12] It is worth noting that some commentators such as Wallace have objected to the fundamental link between eigenvector and eigenvalue posited in conventional delineations of QM: [13]

doi.org/10.32388/IHMHPN

[17] One might also be led to question whether it could be upheld that EQM remains a ψ-ontic QM model in the terms of the influential taxonomy of Harrigan and Spekkens. If the most fundamental entities which populate reality according to the Everettian ontology are the reduced, local, relative states rather than a global universal state, then one might well suspect that this ontology entails multiple quantum states for a given ontic state and therefore fails to clear the bar set by the authors, namely that these quantum states are non-overlapping over the space of ontic states. If so, they would be classified as ψ-epistemic. A more detailed assessment of this possibility goes beyond the scope of this paper, but for further background see Harrigan, N. and Spekkens, R.[14].

[18] A similar point has been emphasised in Waegell, M. and McQueen, K.[15] in which it is proposed that the Everettian explanation of EPR-style measurements is inconsistent with an Einsteinian principle of completeness (couched in terms of the existence of localised elements of reality) given a set of assumptions common to most of these explanations.

19. [15]

[20] The classification of the state as "ontic" follows the definitions of Harrigan, N. and Spekkens, R.[14] and subsequent commentators.

[21] See e.g. [16]

22. [1]

References

1. a, b, c, d *Deutsch D, Hayden P (2000). "Information Flow in Entangled Quantum Systems." Proc Math Phys Eng Sci.* ***456****(1999):1759–1774.*
2. a, b *Faglia P (2024). "Non-separability, locality and criteria of reality: a reply to Waegell and McQueen." Stud Hist Philos Sci.* ***106****:43–53.*
3. a, b, c, d *Brown H, Timpson C (2002). "Entanglement and Relativity." In: Fano V, Lupacchini R, editors. Understanding Physical Knowledge. University of Bologna. https://arxiv.org/pdf/quant-ph/0212140.*
4. ^ *Brown H, Timpson C (2016). "Bell on Bell's Theorem: The Changing Face of Nonlocality." In: Bell M, Gao S, editors. Quantum Nonlocality and Reality: 50 Years of Bell's Theorem. Cambridge: Cambridge University Press; p. 91–123.*

doi.org/10.32388/IHMHPN

5. [a, b, c] *Everett H (1973). "The Theory of the Universal Wave Function." In: Dewitt B, Graham N, editors. The Many-Worlds Interpretation of Quantum Mechanics. p. 3-140.*
6. [^] *Drezet A (2023). "An Elementary Proof That Everett's Quantum Multiverse Is Nonlocal: Bell-Locality and Branch-Symmetry in the Many-Worlds Interpretation." Symmetry.* ***15****(6):1250. https://arxiv.org/abs/2306.07794.*
7. [^] *Saunders S (2025). "Physical Probability and Locality in No-Collapse Quantum Theory." https://arxiv.org/pdf/2505.06983.*
8. [^] *Wallace D (2012). The Emergent Multiverse: Quantum Theory According to the Everett Interpretation. Oxford: Oxford University Press.*
9. [^] *Bacciagaluppi G (2002). "Remarks on Space-time and Locality in Everett's Interpretation." In: Placek T, Butterfield J, editors. Non-locality and Modality. Dordrecht and Boston: Kluwer Academic Publishers; p. 105-122.*
10. [^] *Ney A (forthcoming). "The Argument from Locality for Many Worlds Quantum Mechanics." J Philos. https://philpapers.org/archive/NEYTAF-2.pdf.*
11. [^] *Elitzur A, Vaidman L (1993). "Quantum Mechanical Interaction-Free Measurements." Found Phys.* ***23****:987–997.*
12. [^] *Dirac P (1947). The Principles of Quantum Mechanics. 3rd ed. London: Oxford University Press.*
13. [^] *Wallace D (2019). "What is Orthodox Quantum Mechanics?" In: Cordero A, editor. Philosophers Look at Quantum Mechanics. Cham: Springer Verlag; p. 285-312.*
14. [a, b] *Harrigan N, Spekkens R (2010). "Einstein, incompleteness and the epistemic view of quantum states." Found Phys.* ***40****:125–157. https://arxiv.org/pdf/0706.2661.*
15. [a, b] *Waegell M, McQueen K (2020). "Reformulating Bell's Theorem: The Search for a Truly Local Quantum Theory." Stud Hist Philos Sci Part B.* ***70****:39–50. https://arxiv.org/pdf/2003.03395.*
16. [^] *Eberhard P (1978). "Bell's Theorem and the Different Concepts of Locality." Il Nuovo Cimento B.* ***46****:392–419.*

Declarations

Funding: No specific funding was received for this work.

Potential competing interests: No potential competing interests to declare.