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Original Paper

Relational blockworld: Providing a realist psi-epistemic account of quantum mechanics

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Abstract: We update our Relational Blockworld (RBW) explanation of quantum physics and argue that it provides a realist psi-epistemic account of quantum mechanics as called for by Leifer. RBW accomplishes this by employing discrete graphical amalgams of space, time and sources ("spacetimesource elements") and an adynamical global constraint as 'hidden variables' that avoid the need for counterfactual definiteness in a realist account. Instead of an equation of motion governing time-evolved entities, the adynamical global constraint is used for computing the graphical transition amplitude whence a probability amplitude for our fundamental spacetimesource element. We begin with a largely conceptual and philosophical introduction to RBW's most prominent features, i.e., adynamism, relationalism/contextualism, and the unmediated exchange of energy. This conceptual introduction includes a simple interferometer computation of the relative intensities found in a weak measurement that we compare with the authors' computation per weak values. We use this to contrast our adynamical explanation of the experiment with the apparently dynamical, retro-time-evolved explanation of the authors' Two State Vector Formalism. Next we use spacetimesource elements instead of paths in Dowker's GHZ set-up to contrast RBW with Sorkin's Many Histories account. We argue that rather than multiple paths per Many Histories, what is called for is no paths per RBW. The adynamical interpretation of these two quantum experiments, afforded by the global perspective, suggests that quantum mechanics might be underwritten adynamically. Thus, in the second part of the paper, we motivate an adynamical global constraint using coupled harmonic oscillators and then apply it to an analysis of the twin-slit experiment. This illustrates how the adynamical global constraint of our "modified lattice gauge theory" underwrites quantum field theory whence quantum mechanics. We conclude with a brief dismissal of the measurement problem and an RBW explanation of entanglement, environmental decoherence, quantum non-commutivity, quantum versus classical behavior, and the Born rule.

Keywords: block universe; ontic structural realism; adynamical global constraint; weak values; retrocausal; realist psi-epistemic

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1. Introduction

Herein, we provide an update of our foundations-driven account of quantum physics called *Relational Blockworld*[(1)] (RBW) that began its life as a presentation at the *2005 New Directions in the Foundations of Physics* conference held at the American Institute of Physics. Since that time, RBW has matured into more than an interpretation of quantum mechanics (QM), e.g., we have recently provided an associated relational, adynamical, background independent approach to quantum gravity and the unification of physics[(2)].As we acknowledged in our *2005 New Directions* presentation, RBW as an interpretation of QM actually requires a formalism underneath the quantum (a hidden variable), so we have been developing said formalism since. With the completion of that formalism and its commensurate account of quantum gravity and unification, we realized it was now time to go back and deliver on our 2005 promissory note. Thus, herein we offer a fully developed RBW interpretation of QM.

In terms of a QM interpretation, RBW is providing a realist psi-epistemic account exactly as Leifer[(3)]suggests: “If we are to maintain psi-epistemic explanations, then we instead need to look for retrocausal ontological models that posit a deeper reality underlying quantum theory that does not include the quantum state.” However, we will argue that the most fundamental underlying explanation is not so much retrocausal in the sense of information *traveling* from the future to the past, but adynamical per a global 4D perspective, what we call an adynamical global constraint (AGC). That is what we hope to make clear in this paper. The AGC constrains the probability amplitude for our beables, i.e., spacetimesource elements, which are spatiotemporal 4D ontological entities. For example in the twin-slit experiment, the spatiotemporal distribution of detector clicks is in accord with the distribution of spacetimesource elements per the probability amplitude obtained in accord with the AGC. To be clear, a spacetimesource element is not *in* spacetime, it is *of* spacetime, even while a distribution of detector clicks is viewed in the spacetime context of the experimental equipment and process from initiation to termination.

While our account takes the block universe seriously and uses future boundary conditions to explain experimental outcomes, it differs from some retrocausal accounts in many respects. First and foremost among the differences, we do not provide an account that fits within the dynamical paradigm (dynamism) whereby the past determines the future, yet information somehow *travels* from the future to the past and fundamental explanations are still in terms of dynamical equations of motion. For example, there are no waves coming from the future in our view. We believe that taken together, quantum theory and relativity are really telling us that dynamism, the notion of fundamental entities being evolved in time by dynamical laws, is not the way to think about fundamental physics. Rather, we think it is worth pursuing the idea that an AGC might be fundamental to both quantum theory and relativity. One can find the roots of this sort of thinking in the development of Lagrangian mechanics and the path integral formalism. As Feynman put it[(4)]:

> In the customary view, things are discussed as a function of time in very great detail. For example, you have the field at this moment, a different equation gives you the field at a later moment and so on; a method, which I shall call the Hamiltonian method. We have, instead [the action] a thing that describes the character of the path throughout all of space and time. … From the overall space-time point of view of the least action principle, the field disappears as nothing but bookkeeping variables insisted on by the Hamiltonian method.

In previous publications[(5)], we spent a great deal of time trying to motivate our reasons for going in this direction. We will only briefly revisit the main reason here. That is, we believe that once you accept the block universe, it seems possible that dynamical explanation is not fundamental because 'it's all just there'. In any case, whatever dynamical laws are in a block universe, they are not event factories bringing new events into being that were never real before[1].

Second, we also think it is worth pursuing the idea that entities emerge from a fundamentally relational basis, i.e., relations are fundamental, not entities with intrinsic properties and 'primitive thisness'. There is much in quantum theory that leads one in that direction including entanglement, indistinguishability of quantum particles, etc. According to some theorists, if we move to quantum field theory (QFT) and quantum cosmology things get worse for dynamism in this regard. For example, the "Unruh effect" named after Bill Unruh is a well-known but counter-intuitive prediction of QFT that with respect to the reference frame of an accelerating observer (in the relativistic sense of the word), empty space contains a gas of particles at a temperature proportional to the acceleration[(6)]. While not yet experimentally confirmed, it is claimed that an analog under centripetal acceleration is observed in the spin polarization of electrons in circular accelerators. It is also claimed the Unruh effect is necessary for consistency of the respective descriptions of observed phenomena, such as particle decay, in inertial and in accelerated reference frames. Perhaps this should not be so counter-intuitive given

[1]We believe certain quantum phenomena, such as delayed choice, potentially reinforce this idea.

that in the Standard Model of particle physics generally, single-particle states for inertial reference frames in Minkowski spacetime are superpositions of eigenstates of the number operator for an accelerated class of reference frame. Therefore presumably single-particle states for an inertial reference frame are non-particle states for an accelerated reference frame. QFT characterizes a particle not simply as a property of an underlying quantum field unto itself, but as an inherently relational manifestation between a quantum field and a class of reference frame. Thus, the number of particles present is dependent upon the observer's state of motion and is therefore a relationship between the observer and the quantum field. In short, because the state of a free-field is reference frame dependent, the number of particles is also reference frame dependent. Therefore in section 2 we will characterize RBW as a unique form of ontological structural realism (OSR).

Third, because of our hunch about an AGC being fundamental, we based our account on the path integral formalism (PI) and seek a realist account with a single history. More specifically, our AGC is constructed in a modified version of lattice gauge theory. Lattice gauge theory is then assumed fundamental to QFT whence QM. That's how our AGC ultimately underwrites QM. The twin-slit analysis in section 3 will make this explicit. Fourth, we wanted not merely another *interpretation* of non-relativistic quantum mechanics, but a physical model that would also cover relativistic QFT and provide the grounds for quantum gravity and unification. Fifth, we sought a *realist* psi-epistemic account of the quantum in a 4D setting without the need for realism about configuration space. Sixth, in order to construct an account that was *realist* psi-epistemic, without configuration space but only spacetime, consistent with special relativity, with none of the problems associated with invoking paths, particle or field histories, waves, etc., we sought a characterization of the quantum in terms of unmediated interaction, i.e., no "quantum worldlines." While retrocausal accounts are proliferating[7], PI is proliferating among foundationalists[8][9][10], belief in the fundamentality of relations is proliferating[11], and psi-epistemic accounts are proliferating (though not realist ones)[12], we know of no account that embodies all six of the aforementioned features and weaves them into a seamless package. The reasons for these six choices will become clear as we proceed, but suffice it to say they each have an important role to play.

While no account embodies all six of our desiderata, we are certainly not alone in thinking in terms of adynamical global constraints, as Price & Wharton[13] make clear:

> In putting future and past on an equal footing, this kind of approach is different in spirit from (and quite possibly formally incompatible with) a more familiar style of physics: one in which the past continually generates the future, like a computer running through the steps in an algorithm. However, our usual preference for the computer-like model may simply reflect an anthropocentric bias. It is a good model for creatures like us, who acquire knowledge sequentially, past to future, and hence find it useful to update their predictions in the same way. But there is no guarantee that the principles on which the universe is constructed are of the sort that happens to be useful to creatures in our

particular situation.

> Physics has certainly overcome such biases before – the Earth isn't the center of the universe, our sun is just one of many, there is no preferred frame of reference. Now, perhaps there's one further anthropocentric attitude that needs to go: the idea that the universe is as "in the dark" about the future as we are ourselves.

The interpretations of QM that sail under the retrocausal banner are quite diverse, obviously. And it only takes a quick perusal of the retrocausal literature to see that there is no universal agreement on what counts as retrocausal. For example, are any of the following necessary or sufficient: 1) the use of definite future boundary conditions, 2) the posit of a block universe, 3) employing novel retro-time evolved mechanisms such as waves from the future, 4) explicitly rejecting Bell's statistical independence assumption, 5) acknowledgement of time-symmetric dynamical laws, or 6) some truly robust or non-deflationary account of agent intervention or the future causing the past. There are retrocausal accounts such as Kastner's Possibilist Transactional Interpretation(14)(PTI) that violate 1 and 2, so these are not necessary. Nor are they sufficient, since neither the least action principle nor the block universe entails retrocausation. There are retrocausal accounts that violate 3 such as RBW, so it is not necessary. 4 is not sufficient because Bell's "superdeterminism" (SD) exploits this loophole but is not retrocausal. A superdeterministic world is one in which independence is violated via a *past* common cause – a common cause of one's choice of measurements and say the particle spin properties, in the case of Bell correlations. In short, SD is a conspiratorial theory with only past-to-future causation. Many acknowledge the time-symmetric nature of most dynamical laws and yet do not espouse retrocausation, so 5 is not sufficient. And there are retrocausal accounts such as Wharton's "Lagrangian-only" approach(15) that defend only relatively deflationary accounts of agent intervention and causation, so 6 is not necessary. It seems that the only claim we can pin down as the necessary and sufficient condition for being a retrocausal interpretation of QM is that the account must in some ontological and not merely formal sense have the future determining the past or present as much as the past or present determines the future in some situations.

Evans tries to provide the basic package of necessary beliefs that combine to give retrocausality per the school of Price & Wharton(16):

> This then is the package of metaphysical ideas that combine to give a picture that is consistent with the possibility of retrocausality. We begin with two established meta-physical foundations in the block universe model of time and the interventionist account of causation. We then remove two potential obstacles originating in our ordinary temporal intuitions: we realise that we have no evidence to suggest our macroscopic asymmetric causal intuitions can be extrapolated to the microscopic realm and we realise that we do not necessarily have epistemic access to the past independent of our own future actions. With these obstacles gone, the emerging picture of a temporally and causally symmetric reality viewed from an epistemically limited vantage point concords

> well with the possibility of retrocausality. A significant aspect of this assembly of ideas is that none of the included elements are precluded by the known physical structure of our reality. Indeed, if anything, these elements are supported by the structure of at least one of our best physical theories: quantum mechanics.

But, again, conditions 2 (block universe) and 6 (robust interventionalism) are apparently not necessary for a retrocausal account in general.

So, looking at retrocausal accounts more generally it seems that there are two basic ways to go, one we call "time-evolved" or "retro-time-evolved" and the other we call global (4D). The former focus on positing (relatively) new dynamical mechanisms to underwrite retrocausation and the latter take a more global, adynamical approach[2]. As will become clear, RBW is an attempt to do physics from a global (4D) point of view in the sense that we underwrite dynamical laws and causal patterns with an adynamical global constraint. That is, rather than trying to add some new mechanism within the block universe (such as waves from the future or possible futures) to account for how information from the future got to the emission event in the past, we step back and note that in a block universe the experimental process from initiation to termination, with everything in between, is all just 'there'.

These two approaches are largely mutually exclusive at least with respect to fundamental physical models of retrocausation. However, there is some room for compromise. Take for example the Price & Wharton school. In Price's Helsinki toy model paper(17) he "shows how something that 'looks like' retrocausality can emerge from global constraints on a very simple system of 'interactions', when the system in question is given a natural interpretation in the light of familiar assumptions about experimental intervention and observation." And Wharton's "Lagrangian-only" approach sets the Lagrangian density equal to zero as an adynamical global constraint. He differs from RBW in that his approach is mediated (by classical field configurations), but his goal is that these field configurations

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[2] Cramer's retrocausal transactional interpretation (TI) was one of the first of this sort in recent history (Cramer, J: The transactional interpretation of quantum mechanics. Reviews of Modern Physics 58, 647-687 (1986)). On this account the wavefunction is taken realistically and time-symmetrically. In the case of a simple EPR set-up, we have an "offer- wave (function)" and a "retarded/confirmation-wave (function)" sent out from the point where the initial wavefunction (corresponding to the EPR state) is emitted (the source) and the point where it is absorbed (the detectors). A "transaction" is completed once both "offer" and "retarded" waves meet and they bounce back and forth until all the boundary conditions are met. If one takes the talk of waves realistically then this would certainly be an example of an interpretation that adds a retrocausal mechanism to the block universe. But as Cramer says himself the backwards-causal elements of his theory are "only a pedagogical convention," and that in fact "the process is atemporal" (Cramer, 1986, p. 661). For more on TI see Silberstein *et al*. (2008). In Kastner's "possibilist" extension of TI (PTI) she escapes the redundancy of adding a retrocausal mechanism to the block universe because PTI abjures future boundary conditions. In PTI the offer waves and confirmation waves do not 'live' in spacetime but in possibility space. On her view the past is populated by empirical observations/actualized transactions, but the future is not actualized. It is filled with offer waves that have not yet arrived. Kastner calls this 'space' of unactualized possibilities 'prespacetime' and it has the properties of Hilbert space. Thus Kastner dispenses with future boundary conditions and the block universe. In this paper we focus only on the subset of retrocausal accounts that make use of future boundary conditions, since Kastner's PTI belongs on another branch of retrocausal accounts, we will not discuss it here.

will not satisfy a differential equation, i.e., they will only satisfy a least action principle. Price on the other hand, talks about dynamical and causal explanations as "perspectival(18)" from within the block universe and he champions a deflationary interventionist or manipulationist account of causation just as Evans notes. So while the Price & Wharton school of retrocausation does not add new retro-dynamics to the universe *a la* the Two State Vector Formalism (TSVF), it does heavily emphasize the interventionist agent-focused account of causation, however deflationary it may be. The point is that while Price and Wharton are squarely in the global 4D camp, they do think it is important to recognize said causal regularities and counterfactuals.

It is reasonable to ask, given their allegiance to the 4D camp, why Price and Wharton choose to label themselves retrocausal as opposed to adynamical/global constraint. Other people have raised this concern, for example Corry(19) says to invoke the notion of a "single, indivisible non-local event" is to "deny a causal explanation." We assume their thinking is thus: if you have an interventionist account of causation (robust or deflationary), then a "global constraint" model becomes retrocausal because your choice of a future event is correlated with an earlier event. So there is nothing more to retrocausation than global constraint plus our ability to intervene. Withholding the label of causation might suggest that there is something more required for causation, which given the package of beliefs outlined by Evans, both Price and Wharton deny. An agent can choose a different measurement apparatus, which (via the global constraint) determines the 'initial' likelihood of actual outcomes. Thus, Bell's statistical independence assumption is explicitly violated, because the final measurement geometry is an external 'choice of the agent', and it constrains the past.

If we have properly captured the thinking of Price and Wharton, then RBW counts as retrocausal[3]. We certainly agree with their thinking in these matters and are happy to fly the retrocausal flag. Perhaps the biggest difference between RBW and Price-Wharton is just a matter of emphasis. From the very beginning, we have chosen to emphasize not the agent's perspective, not the causal or dynamical perspective, but the global 4D perspective. Thus, we have chosen to focus on constructing fundamental physics based on an adynamical global constraint. Of course, our decision to do so has certainly made it harder to sell RBW to those squarely ensconced in dynamism. We must also note that Price and Wharton no doubt do not share all the preceding six features we listed as essential to RBW. But most importantly, we do share the same basic goal of coming up with a physical model of

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[3] Regarding the Price/Wharton program an anonymous referee has said: "I do not see how anything truly 'retrocausal,' in a dynamical sense, can occur given global time-symmetric constraints on spacetime. The authors seem to me to be too charitable here, a future boundary condition implies an adynamical block world, in which talk of dynamics or intervention is superfluous at best, and inconsistent at worst." Given how deflationary their notion of causation and intervention are, we can appreciate the superfluous charge.

adynamical explanation from the global 4D perspective that underwrites dynamical laws and causal regularities. So we ask ourselves, can we find an adynamical 4D global constraint explanation fundamental to the entire experimental process? This paper describes our answer to that question. Herein we will provide a detailed physical model for the AGC that underwrites dynamical and causal explanations. We will then apply that model to the standard conceptual and foundational problems alleged to plague quantum physics. As their work has certainly been instrumental to us, we hope Price and Wharton will view our work favorably and consider it helpful in their quest, as there are few others who are trying to help birth this potentially new paradigm.

In order to illustrate our AGC, a concept that is central to RBW, we will bring our "modified lattice gauge theory"(MLGT) to bear on the twin-slit analysis. Lattice gauge theory is the study of QFT on a discrete spacetime lattice. We modify lattice gauge theory to allow for the direct exchange of energy between sources[4] which we term "unmediated exchange." This modification to lattice gauge theory is a graphical form of "field-free theory" or "direct-action theory" (Kastner has recently reviewed that concept in this journal[(20)], so we will not repeat the history here). We then assume lattice gauge theory is fundamental to QFT, contrary to convention. Since QM is obtained from QFT, the AGC of MLGT ultimately underwrites QM. However, MLGT is computational overkill for most QM problems including the twin-slit experiment. We are only using MLGT here because it provides an excellent illustration of how the AGC ultimately underwrites QM. As we showed elsewhere[(21)], MLGT becomes useful for quantum gravity, unification, and for suggesting kinematic corrections to Regge calculus (a discretized approach to general relativity). For example, using this modification to Regge calculus for the Einstein-deSitter cosmology model provided a fit of the Union2 Compilation supernova data equal to that of ΛCDM[(22)]. Our "modified Regge calculus" version of the Einstein-deSitter cosmology model does not harbor accelerating expansion, so it does not require a cosmological constant or dark energy. Thus, MLGT is not without its benefits.

The paper is divided into two main parts. The first part (section 2) contains a largely conceptual and philosophical introduction to RBW's most prominent features, i.e., adynamism, relationalism/contextualism, and the unmediated exchange of energy. Since Danan, Farfurnik, Bar-Ad, and Vaidman (DFBV) also deny the existence of continuous worldlines for the photons in their experiment[(23)], "Asking Photons Where They Have Been," we start by comparing and contrasting RBW with their TSVF interpretation of that experiment. We follow by contrasting RBW with Sorkin's Many Histories interpretation of Dowker's GHZ set-up, as it involves PI[(24)]. In both cases, we rely almost exclusively on conceptual and philosophical explanation. At this stage what little formalism we

[4] We use the term "source" as in quantum field theory to mean source or sink. When we want to specify a "source of energy" rather than a sink, we will use "Source."

do employ in the DFBV experimental analysis is just a simple interferometer computation of probability amplitudes and we avoid Sorkin's quantum measure theory entirely. Our goal with section 2 isn't to convince anyone to give up their favorite QM interpretation in favor of RBW. Rather, we are simply trying to motivate an understanding of and, hopefully, an appreciation for RBW as a viable interpretation of QM. By the time we get to the end of paper, the formal details of the RBW model will be made explicit. For now, we want to reveal RBW slowly, one aspect at a time, so that the impending formalism in the second main part of the paper (section 3) does not overwhelm the reader's understanding of the main conceptual points. We believe that ultimately the selling point of any QM interpretation resides in its ability to resolve foundational and empirical anomalies and produce new physics. At the end of the paper (section 4) we will make explicit how we resolve the conceptual and foundational issues that haunt quantum physics. The new physics, in our case, is a novel approach to quantum gravity, unification, and cosmology mentioned above. Again, that work is published or forthcoming, so here (section 3) we will only introduce our AGC via coupled harmonic oscillators, then use its associated MLGT to analyze the industry standard QM interpretational experiment, i.e., twin-slit. While MLGT is computational overkill for a twin-slit analysis, it does illustrate how the AGC is used in MLGT (to construct the graphical transition amplitude) that underwrites QFT (to obtain the generating function) whence (the probability amplitude for) QM. Thus, the AGC per the global 4D perspective is the ultimate explanatory mechanism for QM phenomena per RBW.

2. RBW as an Interpretation of QM

2.1 The DFBV experiment and Dowker's GHZ set-up.

RBW might be thought of as a retrocausal approach focusing on adynamical global constraints as fundamental that utilizes a path integral formalism without paths. The "particle paths" employed by some forms of PI, e.g., quantum measure theory, are replaced by graphical gradients *a la* MLGT. RBW supplies the AGC underneath quantum theory and relativity.

We first introduce adynamism and unmediated exchange via the DFBV experiment, contrasting RBW with TSVF. As we will see, Danan *et al*. posit quantum entities (photons) without continuous worldlines, as in our unmediated exchange, and TSVF employs future boundary conditions. We want to stress that for us what does the ultimate explaining, what underwrites dynamical and causal patterns, and what explains the particular structure of the block universe we inhabit, is the AGC. We agree that talk of causal and dynamical explanation is all "perspectival" within the block universe (the "time-evolved" or "retro-time-evolved" view)[5]. But, in the 4D view of RBW the "all at once" patterns within

[5] Obviously this is no place to discuss the phenomenology of temporal experience in a block universe at length, but for those interested in our view see Michael Silberstein's "Experience Unbound" in the special issue of *Mind and*

the block universe itself, obtained per the AGC in the 4D view, explain the causal and dynamical experience of time-evolved beings as viewed from their perspective within the block universe, not the converse. With all that said, we can discuss the DFBV experiment.

The DFBV experimental set-up is shown in their Figures 1A – E below. In the configuration of Figure 1A, constructive interference obtains through the outer and nested interferometers from the Source to detector D. In the configuration of Figure 1B, mirror B is moved so that destructive interference obtains between the nested interferometer and mirror F. The question is of course, how is it that information about the vibratory frequencies of mirrors A and B gets to detector D in the configuration of Figure 1B? And, if information about mirrors A and B gets to detector D, why not information about mirrors E and F? Their ontological answer is shown their Figure 1E below. In their own words,

> In conclusion, we have performed direct measurements which shed new light on the question: Where were the photons passing through an interferometer? The main results are presented in Fig. 1B. The photons themselves tell us where they have been. And the story they tell is surprising. The photons do not always follow continuous trajectories. Some of them have been inside the nested interferometer (otherwise they could not have known the frequencies f_A and f_B), but they never entered and never left the nested interferometer, since otherwise they could not avoid the imprints of frequencies f_E and f_F of mirrors E and F leading photons into and out of the interferometer. Only the description with both forward and backward evolving quantum states provides a simple and intuitive picture of pre- and postselected quantum particles.

In this experiment, Danan *et al*. performed a so-called "weak measurement" of photons in the interferometer. As pointed out by Danan *et al*., as well as Saldanha[25], the result shown in Figure 1B can be explained via photon leakage per classical electromagnetism, taking into account the transverse (second) degree of freedom created by the oscillating mirrors. Saldanha's analysis employs a classical EM wave connecting the source to all beam splitters, mirrors, and detector D, but is applicable to the quantum wavefunction as well. In fact, Saldanha concludes that "the wave (be it classical or quantum) must pass through both arms of the large interferometer to explain the experimental results, and that the fact that some mirrors affect the average photon detection position and some do not can be understood in terms of wave interference in a simple way." Interference is a physical effect that evokes different interpretations amongst foundationalists. In contrasting our RBW interpretation of the interference effect in the Danan *et al*. experiment with that of TSVF, we are not claiming that either Danan *et al*. or ourselves have established discontinuity of the photon's path. Providing an

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interpretation is precisely what Saldanha has done and he writes, "This interpretation, that clearly shows that it is essential that the wave propagates through all parts of the interferometer to describe the experimental results, is complementary to the one using the two-state vector formalism of quantum theory [16, 17] presented in [Danan *et al*.]" Thus, the Danan *et al*. conclusion that "The photons do not always follow continuous trajectories," is a matter of interpretation following from the TSVF analysis. In that analysis, TSVF's associated single degree of freedom (first approximation to the full-fledged account of Saldanha) is merely used to show how the supervening (weak) transverse degree of freedom is conveyed to detector D via a strong measurement channel. The TSVF analysis also connects all beam splitters, mirrors, source, and detector D using either or both of the forward and backward time-evolved wavefunctions. However, Danan *et al*. choose to ascribe ontological significance only to the overlap between forward and backward time-evolved waves which leads to their conclusion. We are not here to argue for or against the TSVF analysis(26), but merely to provide an RBW alternative. As we will show, the first approximation to the relative intensities for Figures 1A and 1B can also be obtained via simple interferometer techniques for the calculation of amplitudes connecting Source to detector through each mirror[6]. This alternate calculation does not rely on "forward and backward evolving quantum states." In fact, one can compute these amplitudes in either temporal direction, so there is no necessary relationship between the computational algorithm and a time-evolved explanation of the experiment. Thus, the future boundary conditions employed by both TSVF and RBW do not require a time-evolved story, i.e., using future boundary conditions does not require information coming from the future via some dynamical or causal mechanism. The take home message is that the weak value analysis of Danan *et al*. suffices to explain the relative intensities in Figures 1A and 1B, but it's not a compelling argument for their spectacular ontological claim. Indeed, one doesn't need the full-fledged analysis to see that the effect can be explained via interference per Saldanha's conclusion, i.e., interference is clearly evident in our counterparts to the weak values below and can be seen in the construct of the pre- and post-selection states used in the computation of weak values in Danan *et al*. That is, their Eq (1) follows from their Figure 3 precisely because of destructive interference of the forward time-evolved wavefunction in route to mirror F and of the backward time-evolved wavefunction in route to mirror E. And, our fundamental ontological element (spacetimesource element) relates all mirrors throughout the interferometer, as with Saldanha's wavefunction. Thus, we see that both first approximations reproduce the experimental results of Figures 1A and 1B very well

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[6] We will not resort to the formalism of MLGT or quantum optics here. The simple analysis we use here is superficial, but sufficient to make our point. We do note that each factor in the amplitude computation corresponds to a component of the spacetimesource element and, as will be clear with the twin-slit analysis, satisfies the AGC of MLGT.

when compared to the full-fledged analysis, they are both based on simple interference and they both require a connection between all mirrors in the interferometer. We're not using Danan *et al*. to establish an argument for a discontinuous photon path. We merely note that they are sympathetic to that interpretative possibility. The photon ontology in this experiment is still open to interpretation, as we pointed out. Rather, we want to attack *Danan et al*. on another front, i.e., the necessity of either a forward or backward time-evolved explanation. Thus, we generated the following non-time-evolved counterparts to their weak values in this experiment.

Starting with the amplitude associated with mirror E in Figure 1B

$$\left(i\frac{\sqrt{2}}{\sqrt{3}}\right)\left(\left(i\frac{1}{\sqrt{2}}\right)(i)\left(i\frac{1}{\sqrt{2}}\right)(i)\left(i\frac{\sqrt{2}}{\sqrt{3}}\right)+\left(\frac{1}{\sqrt{2}}\right)(i)\left(\frac{1}{\sqrt{2}}\right)(i)\left(i\frac{\sqrt{2}}{\sqrt{3}}\right)\right)=0 \qquad (1)$$

where the amplitude connecting the Source to mirror E is $\left(i\frac{\sqrt{2}}{\sqrt{3}}\right)$ due to reflection at a 2-1 beam splitter. Thereafter the interferometer splits through two segments, one with mirror A and one with mirror B, in connecting mirror E to detector D. Notice we would obtain this same result if we traced from detector D to mirror E then multiplied by the amplitude having traced from the Source to mirror E. In the 4D view, the order that one computes the amplitude need not have anything to do with the time evolution of a wave or any other entity moving through the experimental device. [If mirror B is moved so as to create constructive interference between the nested interferometer and mirror F, an additional factor of $e^{i\pi} = -1$ appears in the amplitude for the segment associated with mirror B. In that case the amplitude for mirror E is 2/3.]

Continuing, we have for mirror A

$$\left(-i\frac{1}{\sqrt{3}}\right)\left(\left(i\frac{1}{\sqrt{2}}\right)(i)\left(i\frac{\sqrt{2}}{\sqrt{3}}\right)\right)=-\frac{1}{3} \qquad (2)$$

since the amplitude connecting the Source to mirror A is $\left(-i\frac{1}{\sqrt{3}}\right)$ due to reflection at a 2-1 beam splitter, reflection at mirror E, and reflection at a 1-1 beam splitter. And from there we have reflection at a 1-1 beam splitter, reflection at mirror F, and reflection at a 2-1 beam splitter to connect mirror A to detector D. [If mirror B is moved so as to create constructive interference between the nested interferometer and mirror F, the amplitude for mirror A is unaffected.] Similarly for mirror B we have

$$\left(-\frac{1}{\sqrt{3}}\right)\left(\left(\frac{1}{\sqrt{2}}\right)(i)\left(i\frac{\sqrt{2}}{\sqrt{3}}\right)\right)=\frac{1}{3} \qquad (3)$$

[If mirror B is moved so as to create constructive interference between the nested interferometer and mirror F, the amplitude for mirror B is –1/3.] For mirror F we have

$$(0)\left(\left(i\frac{\sqrt{2}}{\sqrt{3}}\right)\right) = 0 \tag{4}$$

since the amplitude connecting mirror F to the Source is zero. [If mirror B is moved so as to create constructive interference between the nested interferometer and mirror F, the amplitude for mirror F is 2/3, as with mirror E.]

And for mirror C

$$\left(\frac{1}{\sqrt{3}}\right)\left(\left(\frac{1}{\sqrt{3}}\right)\right) = \frac{1}{3} \tag{5}$$

since the amplitude connecting mirror C to the Source is $\left(\frac{1}{\sqrt{3}}\right)$ due to transmission at a 2-1 beam splitter. And from there we have transmission at a 2-1 beam splitter to connect mirror C to detector D. [If mirror B is moved so as to create constructive interference between the nested interferometer and mirror F, the amplitude for mirror C is unaffected.] The squares of these amplitudes (with normalization) give precisely the same results for the relative intensities in the weak measurements of Figures 1A and 1B as the corresponding weak values per TSVF (their Eqs (3), (11), (13), and (14)). So, the destructive interference between the nested interferometer and mirror F only serves to stop information transfer about mirrors E and F, not mirrors A and B. In order to stop information transfer for mirrors A and B, a block can be placed between them and detector D (Figure 1D) or the energy transmission channel can be blocked (Figure 1C), in which case no information reaches detector D.

Thus, we have obtained the same (first approximation) results for the relative intensities of the weak measurements in the DFBV experiment as the corresponding weak values per TSVF without invoking either forward or backward time-evolved entities, which proves that a retro-time-evolved story for this experiment is not mandated by the formalism[7]. The 4D view is summed up nicely by Geroch[(27)]:

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[7] An anonymous referee and Peter Lewis have both suggested to us that there may not really be any functioning retrocausal mechanism in TSVF and thus that TSVF is not necessarily dynamical as opposed to adynamical. True, TSVF has these two vectors that evolve forward and backward in time, but it is unclear how DFBV characterizes them ontologically or thinks of them, they could be construed as simply a kind of heuristic device. Thus, what is real in TSVF is the discontinuous photon trajectory where the two vectors overlap. That is, you could construe DFBV and us as proposing alternative methods of constructing one and the same thing, an adynamical global constraint (AGC). On this construal of TSVF, the only thing we know without further elaboration from DFBV is that whatever is represented by the regions of overlap of the two waves is what they call a "photon." We agree with both commenters that the formalism of TSVF is open to this interpretation and that it is unclear what the intended ontological story is. For this paper we assumed a dynamical interpretation of TSVF for the purposes of contrast with RBW. We will say however that RBW is formally and conceptually robustly adynamical and is not merely a heuristic device. In short, TSVF is dynamical as we defined it because TSVF adds a new dynamical mechanism to the block universe whereas we do not – we use an AGC that requires no new dynamics, heuristic or otherwise. In any case one does not need

> There is no dynamics within space-time itself: nothing ever moves therein; nothing happens; nothing changes. In particular, one does not think of particles as moving through space-time, or as following along their world-lines. Rather, particles are just in space-time, once and for all, and the world-line represents, all at once, the complete life history of the particle.

Per the 4D view, all that is needed to explain a 4D pattern in the block universe is to provide an adynamical rule that leads computationally to that 4D pattern. So, a time-evolved story from the 3D view about entities, information or anything else traveling from the past or the future to "cause" events, when added to the rule for the 4D pattern, is superfluous or secondary for explanation. Assuming you can come up with such a rule, knowing the rule for the 4D patterns in the block universe suffices to explain them. The adynamical rule explains the 4D patterns of the block universe and the patterns explain the experience of dynamical beings therein, not the converse. Therefore, in the 4D view, explanation ultimately resides in the adynamical rule for the 4D patterns of the block universe.

We do however agree that photons emitted by the Source and detected at D in the DFBV experiment do not follow continuous paths through the interferometer. We also think that once you admit the necessity of future boundary conditions in your explanation (it's a block universe) and you admit that particles do not always follow continuous paths, then you should *seriously* begin to question the retro-time-evolved view and its restriction to dynamical rules as in the case of DFBV. In our adynamical 4D view, the quantum exchange of energy is accomplished in unmediated fashion by amalgams of space, time, and sources we call "spacetimesource elements." These elements constitute our beables, they are *of* spacetime (not *in* spacetime), so they are 4D in nature and constitute a hidden variable. In the case of the DFBV experiment, there is a single spacetimesource element (represented spatially by the red line in figure 1A) that connects the Source, all the mirrors, all the beam-splitters, and the detector D. We next apply this idea of unmediated exchange to Dowker's GHZ set-up, then we conclude section 2.1 with our claim that RBW provides a realist psi-epistemic account of QM.

In Dowker's GHZ set-up (Figure 2), the GHZ state $|\Psi>=|\uparrow\uparrow\uparrow>+|\downarrow\downarrow\downarrow>$(in the z basis) proceeds from the Source through three Stern-Gerlach (SG) magnets oriented in the *x* direction, but with no detectors following. Rather, each possible outcome at each SG *x* magnet is recombined then redirected to a SG magnet oriented in the *y* direction where a measurement is made. She then reasons as follows.

The GHZ state is an eigenstate of the following four operators:

$$P=\sigma_x\sigma_y\sigma_y$$
$$Q=\sigma_y\sigma_x\sigma_y$$
$$R=\sigma_y\sigma_y\sigma_x$$

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both a new dynamical mechanism and an AGC, and in the paper we argue why the latter ought to be fundamental. If TSVF is read as an AGC, then presumably DFVB agree.

$$X = \sigma_x \sigma_x \sigma_x$$

where

$$P|\Psi\rangle = -|\Psi\rangle$$

$$Q|\Psi\rangle = -|\Psi\rangle$$

$$R|\Psi\rangle = -|\Psi\rangle$$

$$X|\Psi\rangle = |\Psi\rangle$$

so PQRX = – 1. Since the individual eigenvalues for σ_x and σ_y are $s_x = \pm 1$ and $s_y = \pm 1$, we seek a set Ω = {s_x, s_y, s_x, s_y, s_x, s_y} for the s_x and s_y values of particles 1, 2, and 3, respectively, that satisfies P = $s_x s_y s_y = -1$, Q = $s_y s_x s_y = -1$, R = $s_y s_y s_x = -1$, X = $s_x s_x s_x = 1$, and PQRX = $(s_x s_y s_y)(s_y s_x s_y)(s_y s_y s_x)(s_x s_x s_x) = -1$. The set Ω is a Mermin "instruction set" for the three entangled particles in a GHZ state(28) and we see immediately that it is impossible to construct such a set because s_x and s_y for each particle in PQRX is squared. That Ω is impossible to construct means it cannot be the case that each of the three particles moving through the set-up of Figure 2 possesses definite values for s_x and s_y. Since each Ω corresponds to a particular spacetime history (set of three paths) for Figure 2, Dowker concludes that "The physical world cannot be a single history." This prompts her to ask, "If not a single history, then what?" She then says, "We don't know the answer to this question, it's a work in progress." Since Sorkin's PI formalism (quantum measure theory) uses paths, she and Sorkin introduce more than one set of paths to answer the question, i.e., Multiple Histories.

It is normal to create an ontology by reifying the model used in the formalism. In the DFBV experiment, the authors' retrocausal ontology reifies their TSVF formalism of forward and backward time-evolved waves. Since we have source-to-source connections via our MLGT, we do the same thing and simply reify the spacetimesource elements used as models for the MLGT computation, e.g., Figures 3 and 7. Since the metaphysics is underdetermined by the physics, this is usually the most straightforward way to generate metaphysics. The problem with doing that for paths from quantum measure theory in Dowker's GHZ set-up is that quantum measure theory assigns a zero measure to any single combination of three paths (no way to construct Ω), which means any single collection of three paths (single history) can't happen per their so-called "Preclusion Rule." In order to avoid that problem and keep paths, Sorkin and Dowker have to add more paths. Our ontology of spacetimesource elements avoids their dilemma associated with counterfactual definiteness of the non-existent spin *x* measurement because the calculation of the probability amplitude for a spacetimesource element does not depend on aspects of the experimental configuration that are not germane to the spatiotemporal context between the Source emission event and the detection event(s). If instead of combining the two possible spin *x* outcomes into one spin *y* SG magnet, they had placed a spin *y* SG magnet for each possible spin *x* outcome, then the spacetimesource element for the experimental configuration would have to account for the spin *x* SG magnet. Thus, the RBW answer to Dowker's question is clear: We don't need to *increase* the number of particle paths to explain the experiment, we need to *decrease* the number of paths to zero. The spacetimesource element for any particular outcome (uuu, udd, duu, …) is constructed as in Figure 3 and a corresponding amplitude is computed without reference to counterfactual spin *x* measurements. Each outcome represents a different spatiotemporal distribution of mass/energy per this particular quantum exchange, and the amplitude squared gives the relative probability of occurrence. The ontological explanatory advantage of unmediated exchange will be further displayed in explaining twin-slit interference (section 3).

We are now ready to draw these (conceptual) threads together and make our claim that RBW provides a realist psi-epistemic account of QM. In our adynamical 4D view, the emission and absorption events in the context of the worldtubes of the experimental set-up (Source, magnets, beam splitters, mirrors, detectors, etc.) are part of a single, indivisible spacetimesource element, which is the fundamental ontological entity per RBW. The spacetimesource element represents an unmediated exchange of energy and these elements do not contain information about environmental aspects not germane to the experimental context, e.g., spin *x* measurements in Dowker's GHZ set-up, so there is no counterfactual definiteness in RBW. The distribution of experimental outcomes is given by the probability amplitude of the spacetimesource element computed (ultimately) via the AGC. Even though there are no Mermin "instruction sets" or "quantum worldlines" associated with the spacetime region between Source and sink, there is an ontological "fact of the matter" about the relationship between the Source emission event and the detector events, i.e., the spacetimesource element. Thus, RBW is a realist account of QM, so the only question remains, is it psi-epistemic? The answer is "yes" as follows.

If you construct the differential equation corresponding to the path integral, the time-dependent foliation gives the wavefunction $\psi(x,t)$, which becomes of interest only when you don't know when the outcome is going to occur. Once you have an outcome, both the configuration x_o and time t_o are fixed, so the wavefunction $\psi(x,t)$ of configuration space becomes the probability amplitude $\psi(x_o,t_o)$ in spacetime, i.e., a probability amplitude for the spacetimesource element. The time-evolved story in configuration space isn't an issue with the path integral formalism because we compute $\psi(x_o,t_o)$ directly, i.e., we specify the future boundary conditions. Accordingly, quantum physics is simply providing a 4D probability amplitude for the experimental equipment and process from initiation to termination, to include a particular outcome. Thus, RBW is both a realist and a psi-epistemic account of QM without counterfactual definiteness where the graphical structure of spacetimesource elements and the AGC are the hidden variables. The best way to characterize our view is that RBW constitutes ontic structural realism in a block universe.

2.2 Ontic structural realism in a block universe.

We are all familiar with quantum contextuality generally and with claims about the failure of counterfactual definiteness in some specific interpretations of QM. RBW certainly possesses quantum contextuality and implies the failure of counterfactual definiteness. To see exactly what quantum contextuality means for us (or rather spacetimesource contextuality in our case) will require the fuller formal introduction of spacetimesource elements to come. Keeping it as general as possible, let us say that an observable is contextual if and only if the measured value depends in some way on how the measurement is performed. If a property or observable is contextual, that typically implies that it is not an intrinsic property. But when we say RBW is fundamentally relational or contextual we go further, we are rejecting intrinsic properties and the like all together. We mean something akin to ontological structural realism (OSR).

OSR rejects the idea that reality is ultimately *composed of things*, i.e., self-subsisting entities, individuals or trans-temporal objects with intrinsic properties and "primitive thisness," haecceity, etc. According to OSR the world has an objective modal *structure* that is ontologically fundamental, in the sense of not supervening on the intrinsic properties of a set of individuals. In Einstein's terminology, given OSR, particles do not have their own "being thus." The objective modal structure of the world and the abstract structural relations so characterized are fundamental features of reality relative to *entities* such as particles, atoms, etc. This is not anti-realism about objects or relata, but a denial of their fundamentality. Rather, relations are primary while the things are derivative, thus rejecting "building block" atomism or Lego-philosophy. Relata inherit their individuality and identity from the structure of relations. According to OSR, entities/objects and their properties are secondary to relational structure. As Kuhlmann puts it(29), "so proponents of ontic structural realism say we might as well dispense with things and assume that the world is made of structures, or nets of relations." While the standard conception of structure is either set theoretic or logical, OSR holds that graph theory provides a better formal model for the nature of reality because relations (links) are fundamental to nodes therein. Certainly, it is difficult to think about structure without "hypostatizing" individuals or relata as the bearers of structure, but it does not follow that relata are truly ontologically fundamental. The point is not that there are no relata, but that relata are not fundamental. Kuhlman also starts to capture our view about entanglement when he says(30), "instead of considering particles primary and entanglement secondary, perhaps we should think about it the other way round."

More specifically, our RBW version of OSR agrees with Ladyman that(31) "The relata of a given relation always turn out to be relational structures themselves on further analysis." Note again that OSR does not claim there are relations without relata, just that the relata are not individuals (e.g., things with primitive thisness and intrinsic properties), but always ultimately analyzable as relations as well (Figure 4). OSR already somewhat violates the dynamical bias by rejecting *things* with intrinsic properties as fundamental *building blocks* of reality – the world isn't fundamentally *compositional* – the deepest conception of reality is not one in which we decompose things into other things at ever smaller length and time scales[8]. Our beables as we will see (spacetimesource elements) are certainly a violation of a compositional picture of realty, since their properties are inherited from their classical context. We however go even further than OSR in rejecting dynamism, not merely because it is a block universe, but because the fundamental modal structure, the fundamental AGC, is not a dynamical law or even spacetime symmetries.

A good deal of the OSR literature focuses on philosophical concerns about scientific realism and intertheoretic relations, rather than being motivated by physics itself[(32)]. There has also been much debate in the philosophical literature as to whether OSR provides any real help in resolving foundational issues of physics such as interpreting QM or in advancing physics itself. Consider the following claims for example:

> OSR is not an interpretation of QM in addition to many worlds-type interpretations, collapse-type interpretations, or hidden variable-type interpretations. As the discussion of the arguments for OSR from QM in section 2 above has shown, OSR is not in the position to provide on its own an ontology for QM, since it does not reply to the question of what implements the structures that it poses. In conclusion, after more than a decade of elaboration and debate on OSR about QM, it seems that the impact that OSR can have on providing an answer to the question of what the world is like, if QM is correct, is rather limited. From a scientific realist perspective, the crucial issue is the assessment of the pros and cons of the various detailed proposals for an ontology of QM, as it was before the appearance of OSR on the scene[(33)].

And:

> While the basic idea defended here (a fundamental ontology of brute relations) can be found elsewhere in the philosophical literature on 'structural realism', we have yet to see the idea used as an argument for advancing physics, nor have we seen a truly convincing argument, involving a real construction based in modern physics, that successfully evades the objection that there can be no relations without first (in logical order) having things so related[(34)].

RBW is a counterexample to Esfeld's claim and it provides exactly the physical model that Rickles & Bloom are looking for. As they say in the following passage, OSR has the potential to re-ground physics, dissolve current quagmires and lead to new physics[(35)]:

> Viewing the world as structurally constituted by primitive relations has the potential to lead to new kinds of research in physics, and knowledge of a more stable sort. Indeed, in the past those theories that have adopted a broadly similar approach (along the lines of what Einstein labeled 'principle theories') have led to just the kinds of advances that this essay competition seeks to capture: areas "where thinkers were 'stuck' and had to

[8] This is an ontological claim. Computationally, of course, the spacetime lattice of lattice gauge theory is "composed of" hypercubes with fields on nodes and links.

> let go of some cherished assumptions to make progress." Principle theory approaches often look to general 'structural aspects' of physical behaviour over 'thing aspects' (what Einstein labeled 'constructive'), promoting invariances of world-structure to general principles.

Rickles & Bloom lament the fact that OSR has yet to be so motivated and further anticipate our theory almost perfectly when they say[36]:

> The position I have described involves the idea that physical systems (which I take to be characterized by the values for their observables) are exhausted by extrinsic or relational properties: they have no intrinsic, local properties at all! This is a curious consequence of background independence coupled with gauge invariance and leads to a rather odd picture in which objects and [spacetime] structure are deeply entangled. Inasmuch as there are objects at all, any properties they possess are structurally conferred: they have no reality outside some correlation. What this means is that the objects don't *ground* structure, they are nothing independently of the structure, which takes the form of a (gauge invariant) correlation between (non-gauge invariant) field values. With this view one can both evade the standard 'no relations without relata' objection and the problem of accounting for the appearance of time (in a timeless structure) in the same way.

For example, consider the particle tracks in a high energy physics detector. The tracks are worldlines, so they constitute what we mean by time-evolved "classical objects" and each worldline can be deduced one detection event (click) at a time in succession using $\psi(x,t)$, as shown by Mott for alpha particles in a cloud chamber[37]. Therefore, a probability amplitude could be computed for each worldline using spacetimesource elements detection event by detection event *a la* our twin-slit analysis below, with each click providing empirical evidence of an otherwise unobservable, underlying spacetimesource element. However, as shown by Mott, after the first click the remaining clicks follow a classical trajectory with high probability, so as it will become clear, the only real quantum computation needed is for the probability amplitude of the spacetimesource element of the set of first clicks, i.e., the first click for each worldline in the collection (again, a single spacetimesource element can have many components and represent many detection events and still be considered a unity, see Figures 3 and 7). And, the properties (mass, charge, momentum, energy, etc.) for that spacetimesource element would simply be the properties of the subsequent worldlines (particles) defined relationally in the context of the accelerator Source and particle detector. Basically, we are claiming that the worldtube of any particular classical object in space and time (defined relationally by its surrounding classical objects) can be decomposed into spacetimesource elements of space, time, and sources organized per an adynamical global constraint (AGC) using the context of those surrounding classical objects.

Accordingly, a particle physics detector event is one giant interference pattern (interference *a la* RBW, see section 3), and the way to understand a particular pattern involving thousands of clicks can only realistically be accomplished by parsing an event into smaller subsets, and the choice of subsets is empirically obvious, i.e., spacetime trajectories. These trajectories are then characterized by mass, spin, and charge. Per RBW's adynamical explanation, the colliding beams in the accelerator and the detector surrounding the collision point form the graphical input that, in conjunction with the AGC, dictate the 4D distribution of configurations of spacetimesource elements responsible for particle trajectories.

This severely undermines the dynamical picture of perturbations moving through a continuum medium (naïve field) between sources, i.e., it undermines the naïve notion of a particle as traditionally understood. In fact, the typical notion of a particle is associated with the global particle state of n-particle Fock space and per Colosi & Rovelli[(38)] "the notion of global particle state is ambiguous, ill-defined, or completely impossible to define." What we mean by "particle" is a collection of detector hits forming a spacetime trajectory resulting from a collection of adynamically constrained spacetimesource elements in the presence of colliding beams and a detector. And this doesn't entail the existence of an object with intrinsic properties, such as mass and charge, moving through the detector to cause the hits.

Our view of particles agrees with Colosi & Rovelli on two important counts. First, that particles are best modeled by local particle states rather than n-particle Fock states computed over infinite regions, squaring with the fact that particle detectors are finite in size and experiments are finite in time. The advantage to this approach is that one can unambiguously define the notion of particles in curved spacetime as excitations in a local M4 region, which makes it amenable to Regge calculus. Second, this theory of particles is much more compatible with the quantum notion of complementary observables in that every detector has its own Hamiltonian (different sized graph with different properties), and therefore its own particle basis (unlike the unique basis of Fock space). Per Colosi & Rovelli[(39)], "In other words, we are in a genuine quantum mechanical situation in which distinct particle numbers are complementary observables. Different bases that diagonalize different H_R [Hamiltonian] operators have equal footing. Whether a particle exists or not depends on what I decide to measure." Thus, in our view, particles simply describe how detectors and Sources are relationally co-defined via the AGC, which we now provide.

3. The Formalism

3.1 The Adynamical Global Constraint.

Given this new adynamical, graphical, contextual ontology, we propose a commensurate break with narrative explanation, i.e., a break with the continuous evolution of the state of objects with intrinsic properties. Carroll sums up nicely what we mean by a dynamical approach[(40)]:

> Let's talk about the actual way physics works, as we understand it. Ever since Newton, the paradigm for fundamental physics has been the same, and includes three pieces. First, there is the "space of states": basically, a list of all the possible configurations the universe could conceivably be in. Second, there is some particular state representing the universe at some time, typically taken to be the present. Third, there is some rule for saying how the universe evolves with time. You give me the universe now, the laws of physics say what it will become in the future. This way of thinking is just as true for quantum mechanics or general relativity or quantum field theory as it was for Newtonian mechanics or Maxwell's electrodynamics.

While it is true that least action principles have been around for a long time, some assume these methods are formal tricks and not fundamental to dynamical equations. As Ballentine puts it[(41)],

> Lastly, we raise the question of the physical status of the infinity of Feynman paths (as the possible histories are often called). Does the system really traverse all paths simultaneously? Or does it sample all paths and choose one? Or are these Feynman paths merely a computational device, lacking any physical reality in themselves? In the case of imaginary time path integrals it is clear that they are merely a computational device. This is most likely also true for real time path integrals, although other opinions no doubt exist.

While our adynamical approach employs mathematical formalism akin to dynamical theories, e.g., lattice gauge theory, we redefine what it means to "explain" something in physics. Rather than finding a rule for time-evolved entities per Carroll, the AGC leads to the self-consistency of a graphical spacetime metric and its relationally defined sources. While we do talk about "constructing" or "building" spatiotemporal objects in our view, we are not implying any sort of "evolving blockworld" as in causet dynamics[(42)]. Our use of this terminology is merely in the context of a computational algorithm. So, one might ask for example, "Why does link X have metric G and stress-energy tensor T?" A dynamical answer might be, "Because link X-1 has metric G -1 and stress-energy tensor T-1 and the law of evolution thereby dictates that link X has metric G and stress-energy tensor T." Notice how this answer is independent of future boundary conditions; indeed, it's independent of conditions anywhere else on the graph other than those of the 3D hypersurface in the immediate past. Contrast this with an adynamical answer such as, "Because the values G and T on X satisfy the AGC for the graph as a whole, given input anywhere in the past, present, and/or future of X."

Weinstein among others anticipated adynamical global constraint explanation when he wrote[(43)]:

> What I want to do here is raise the possibility that there is a more fundamental theory possessing nonlocal constraints that underlies our current theories. Such a theory might account for the mysterious nonlocal effects currently described, but not explained, by quantum mechanics, and might additionally reduce the extent to which cosmological models depend on finely tuned initial data to explain the large scale correlations we

> observe. The assumption that spatially separated physical systems are entirely uncorrelated is a parochial assumption borne of our experience with the everyday objects described by classical mechanics. Why not suppose that at certain scales or certain epochs, this independence emerges from what is otherwise a highly structured, nonlocally correlated microphysics?

As he says, every extant fundamental theory of physics assumes the non-existence of such nonlocal constraints[(44)]:

> Despite radical differences in their conceptions of space, time, and the nature of matter, all of the physical theories we presently use, non-relativistic and relativistic, classical and quantum, share one assumption: the features of the world at distinct points in space are understood to be independent. Particles may exist anywhere, independent of the location or velocity of other particles. Classical fields may take on any value at a given point, constrained only by local constraints like Gauss's law. Quantum field theories incorporate the same independence in their demand that field operators at distinct points in space commute with one another. The independence of physical properties at distinct points is a theoretical assumption, albeit one that is grounded in our everyday experience. We appear to be able to manipulate the contents of a given region of space unrestricted by the contents of other regions. We can arrange the desk in our office without concern for the location of the couch at home in our living room.

RBW provides an exact model in which precisely this type of locality fails to obtain, thereby allowing us to explain a diverse range of phenomena from quantum interference to so-called dark energy. So, let us now motivate and detail the AGC via coupled harmonic oscillators[9].

The Lagrangian for the coupled masses of Figure 5 is

$$L = \frac{1}{2}m\dot{q}_1^2 + \frac{1}{2}m\dot{q}_2^2 - \frac{1}{2}k\left(q_1 - q_2\right)^2 \tag{6}$$

so our transition amplitude is ($\hbar = 1$)

$$Z(J) = \int Dq(t)\exp\left[i\int_0^T dt\left[\frac{1}{2}m\dot{q}_1^2 + \frac{1}{2}m\dot{q}_2^2 - \frac{1}{2}kq_1^2 - \frac{1}{2}kq_2^2 + kq_1q_2 + J_1q_1 + J_2q_2\right]\right] \tag{7}$$

giving

[9] We will introduce an adynamical view of lattice gauge theory in what follows, but since lattice gauge theory is QFT on a spacetime lattice, it is couched in the dynamical language of coupled oscillators.

$$\bar{\bar{K}} = \begin{bmatrix} \left(\frac{m}{\Delta t} - k\Delta t\right) & \frac{-m}{\Delta t} & 0 & k\Delta t & 0 & 0 \\ \frac{-m}{\Delta t} & \left(\frac{2m}{\Delta t} - k\Delta t\right) & \frac{-m}{\Delta t} & 0 & k\Delta t & 0 \\ 0 & \frac{-m}{\Delta t} & \left(\frac{m}{\Delta t} - k\Delta t\right) & 0 & 0 & k\Delta t \\ k\Delta t & 0 & 0 & \left(\frac{m}{\Delta t} - k\Delta t\right) & \frac{-m}{\Delta t} & 0 \\ 0 & k\Delta t & 0 & \frac{-m}{\Delta t} & \left(\frac{2m}{\Delta t} - k\Delta t\right) & \frac{-m}{\Delta t} \\ 0 & 0 & k\Delta t & 0 & \frac{-m}{\Delta t} & \left(\frac{m}{\Delta t} - k\Delta t\right) \end{bmatrix} \tag{8}$$

on the graph of Figure 6[10]. The null space (space of eigenvalues 0) is spanned by the eigenvector $[111111]^T$. The space orthogonal to the null space of $\bar{\bar{K}}$ is called the row space[11] of $\bar{\bar{K}}$. Therefore, any source vector $\bar{J}$ in the row space of $\bar{\bar{K}}$ has components which sum to zero and this is referred to in graphical approaches to physics as "divergence-free $\bar{J}$." If $\bar{J}$ is a force, this simply reflects Newton's third law. If $\bar{J}$ is energy, this simply reflects conservation of energy. We will use $\bar{J}$ on spacetimesource elements to underwrite conserved properties exchanged by interacting classical objects, so we require that $\bar{J}$ reside in the row space of $\bar{\bar{K}}$, as well as represent an interaction with conserved source across a spacetimesource element. Thus, $\bar{\bar{K}}$ must be constructed so as to possess a non-trivial null space, which is the graphical equivalent of gauge invariance. These requirements constitute our AGC.

So, in summary, that $\bar{\bar{K}}$ possesses a non-trivial null space is the graphical equivalent of gauge invariance and restricting $\bar{J}$ to the row space of $\bar{\bar{K}}$ provides a natural gauge fixing, i.e., restricting the path integral of the transition amplitude to the row space of $\bar{\bar{K}}$. That $\bar{\bar{K}}$ possesses a non-trivial null space also means the determinant of $\bar{\bar{K}}$ is zero, so the set of vectors constituting the rows of $\bar{\bar{K}}$ is not linearly independent. That some subset of these row vectors is determined by its complement follows from having the graphical set relationally constructed. Thus, divergence-free $\bar{J}$ follows from relationally defined $\bar{\bar{K}}$ as a direct result of our AGC. Consequently, we agree with Rovelli that[(45)],

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[10] $\bar{\bar{K}}$ can be constructed from boundary operators using the link weights shown in Figure 6 and Q_n resides on the n^{th} node. These mathematical details are not necessary for understanding RBW as an interpretation of QM, but the interested reader may refer to Stuckey *et al.* (2015), which includes $\bar{\bar{K}}$ for the Klein-Gordon, Dirac, Maxwell, and Einstein-Hilbert actions, with extension to the Standard Model of particle physics.

[11] The column space is equal to the row space here, since $\bar{\bar{K}}$ is symmetric.

"Gauge is ubiquitous. It is not unphysical redundancy of our mathematics. It reveals the relational structure of our world."

Now that we have explained the AGC, our choice of gauge fixing is obvious. The discrete, graphical counterpart to Eq (7) is

$$Z = \int_{-\infty}^{\infty}\ldots\int_{-\infty}^{\infty} dQ_1 \ldots dQ_N \exp\left[i\frac{1}{2}\vec{Q}\cdot\vec{\vec{K}}\cdot\vec{Q} + i\vec{J}\cdot\vec{Q}\right] \tag{9}$$

with solution

$$Z = \left(\frac{(2\pi i)^N}{\det(K)}\right)^{1/2} \exp\left[-i\frac{1}{2}\vec{J}\cdot\vec{\vec{K}}^{-1}\cdot\vec{J}\right] \tag{10}$$

However, $\vec{\vec{K}}^{-1}$ does not exist because $\vec{\vec{K}}$ has a non-trivial null space. This is the graphical characterization of the effect of gauge invariance on the computation of $Z(J)$. Because we require that $\vec{J}$ reside in the row space of $\vec{\vec{K}}$, the graphical counterpart to Fadeev-Popov gauge fixing is clear, i.e., we simply restrict our path integral to the row space of $\vec{\vec{K}}$. Nothing of physical interest lies elsewhere, so this is a natural choice. In the eigenbasis of $\vec{\vec{K}}$ with our gauge fixing Eq (9) becomes

$$Z = \int_{-\infty}^{\infty}\ldots\int_{-\infty}^{\infty} d\tilde{Q}_2 \ldots d\tilde{Q}_N \exp\left[\sum_{n=2}^{N}\left(i\frac{1}{2}\tilde{Q}_n^2 a_n + i\tilde{J}_n\tilde{Q}_n\right)\right] \tag{11}$$

where $\tilde{Q}_n$ are the coordinates associated with the eigenbasis of $\vec{\vec{K}}$ and $\tilde{Q}_1$ is associated with eigenvalue zero, a_n is the eigenvalue of $\vec{\vec{K}}$ corresponding to $\tilde{Q}_n$, and $\tilde{J}_n$ are the components of $\vec{J}$ in the eigenbasis of $\vec{\vec{K}}$. Our gauge independent approach revises Eq. (10) to give

$$Z = \left(\frac{(2\pi i)^{N-1}}{\prod_{n=2}^{N} a_n}\right)^{1/2} \prod_{n=2}^{N}\exp\left[-i\frac{\tilde{J}_n^2}{2a_n\hbar}\right] \tag{12}$$

Thus, we find that the adynamically constrained, co-construction of space, time, and divergence-free, interacting sources entails gauge invariance and gauge fixing.

3.2 The Twin-Slit Experiment.

In order to illustrate the AGC, we now apply it to the quintessential foundational example, i.e., the twin-slit experiment. As will quickly become apparent, our MLGT approach is computational overkill in this context, but it provides an excellent illustration of how the AGC ultimately underwrites QM. The computation is in three parts and the goal is to produce a non-relativistic, source-to-source QFT probability amplitude ψ for the spacetimesource element in the twin-slit experiment per MLGT. First, we use the transition amplitude for the Klein Gordon (KG) action in the non-relativistic limit to produce a propagator D(x – x') between point sources from the generating function W(J). Next, we relate D(x – x') to the probability amplitude ψ of the Schrödinger Equation (SE), even though the SE is homogeneous (has no source terms). Lastly, we discretize the transition amplitude of the non-relativistic KG action with source terms and use the AGC to find our MLGT counterpart to W(J), and thus ψ, for the spacetimesource element. A modification to the discretization process is required by the AGC since there is an undifferenced (non-relational) term ψ^* in the non-relativistic KG action. The AGC also tells us which eigenmode of our difference matrix is relevant. Essentially, the second and third parts justify and explain our use of the propagator D(x – x') between point sources in non-relativistic QFT in computing the probability amplitude ψ for the spacetimesource element of the twin-slit experiment.

The spacetimesource element for an exchange of mass *m* in the context of a pair of slits is shown in Figure 7. The goal of the following computation is to obtain the amplitude for that spacetimesource element, component by component, and plot the resulting intensity as function of angular displacement on the detector for some mass, slit spacing, Source to slit distance, and slit to detector distance. As will become evident in the analysis below, the construct of $\vec{\vec{K}}$ for the Schrödinger action is related to the previous example of coupled mechanical oscillators by virtue of the shared quadratic form of their actions, i.e., we are not modeling quantum exchanges literally as coupled mechanical oscillators. Thus, the manner in which the AGC is applied to the construct of $\vec{\vec{K}}$ for the Schrödinger action here is the same manner in which it can be applied to the construct of $\vec{\vec{K}}$ for the quadratic form in the Klein-Gordon, Dirac, Maxwell, and Einstein-Hilbert actions, with extension to the Standard Model of particle physics. Let us begin.

The non-relativistic limit of the Klein-Gordon (KG) equation gives the free-particle Schrödinger equation (SE) by factoring out the rest mass contribution to the energy *E*, assuming the Newtonian form for kinetic energy, and discarding the second-order time derivative[46]. To illustrate the first two steps, plug $\varphi = Ae^{i(px-Et)/\hbar}$ into the KG equation and obtain $\left(-E^2 + p^2c^2 + m^2c^4\right) = 0$, which tells us *E* is the total relativistic energy. Now plug $\psi = Ae^{i(px-Et)/\hbar}$ into the free-particle SE and obtain $\frac{p^2}{2m} = E$, which tells us *E* is only the Newtonian kinetic energy. Thus, we must factor out the rest energy of the particle, i.e., $\psi = e^{imc^2t/\hbar}\varphi$, assume the low-velocity limit of the relativistic kinetic energy, and discard the relevant term from our Lagrangian density (leading to the second-order time derivative) in going from φ of the KG equation to ψ of the free-particle SE. We will make these changes to *Z*(*J*) for the KG equation and obtain ψ(x,t), which we will then compare to ψ(x,t) from QM (with a source) in order to produce our probability amplitude.

For the KG equation we have

$$Z(J)=\int D\varphi \exp\left[i\int d^4x\left[\frac{1}{2}(\partial\varphi)^2-\frac{1}{2}\overline{m}^2\varphi^2+J\varphi\right]\right] \tag{13}$$

(overall factor of ħ in exponent = 1) which in (1+1)D is

$$Z(J)=\int D\varphi \exp\left[i\int dxdt\left[\frac{1}{2}\left(\frac{\partial\varphi}{\partial t}\right)^2-\frac{c^2}{2}\left(\frac{\partial\varphi}{\partial x}\right)^2-\frac{1}{2}\overline{m}^2\varphi^2+J\varphi\right]\right] \tag{14}$$

($\overline{m}\equiv\frac{mc^2}{\hbar}$). Making the changes described above with $\psi=e^{i\overline{m}t}\sqrt{\overline{m}}\varphi$, Eq (14) gives the non-relativistic KG transition amplitude corresponding to the free-particle SE[47]

$$Z(J)=\int D\psi \exp\left[i\int dxdt\left[i\psi^*\left(\frac{\partial\psi}{\partial t}\right)-\frac{c^2}{2\overline{m}}\left(\frac{\partial\psi}{\partial x}\right)^2+J\psi\right]\right] \tag{15}$$

Now integrate the second term by parts and obtain

$$Z(J)=\int D\psi \exp\left[i\int dxdt\left[i\psi^*\left(\frac{\partial\psi}{\partial t}\right)+\frac{\hbar}{2m}\psi^*\frac{\partial^2\psi}{\partial x^2}+J\psi\right]\right] \tag{16}$$

This gives

$$Z(J)=\int D\psi \exp\left[i\int dxdt\left[\frac{1}{2}\psi^*K\psi+J\psi\right]\right] \tag{17}$$

where

$$K=\left(2i\frac{\partial}{\partial t}+\frac{\hbar}{m}\frac{\partial^2}{\partial x^2}\right) \tag{18}$$

The solution to this is

$$Z(J)=Z(0)\exp\left(-\frac{i}{2}\iint dxdx'J(x)D(x-x')J(x')\right)\equiv Z(0)\exp(iW(J)) \tag{19}$$

where x and x' are each shorthand for both a spatial dimension and a temporal dimension,

$$W(J)=-\frac{1}{2}\iint dxdx'J(x)D(x-x')J(x') \tag{20}$$

is the generating function and

$$\left(2i\frac{\partial}{\partial t}+\frac{\hbar}{m}\frac{\partial^2}{\partial x^2}\right)D(x-x')=\delta(x-x') \tag{21}$$

That is, $D(x-x')$ is the Green's function, aka the QFT propagator. A solution is

$$D(x-x')=\frac{-1}{(2\pi)^2}\iint\frac{e^{i\boldsymbol{k}\cdot(\boldsymbol{x}-\boldsymbol{x}')}e^{i\omega(t-t')}d\omega dk}{2\omega+\hbar k^2/m} \tag{22}$$

(where $\boldsymbol{x}$ and $\boldsymbol{x}'$ are just spatial on the RHS). Notice from Eq (19) that $D(x - x')$ *is worthless in the absence of a source*. This is important in an RBW approach where Nature is understood to be classical objects defined relationally and contextually via "quantum interactions," so there is no truly "sourceless" physics.

That $D(x - x')$ is worthless without sources is significant because the QM free-particle propagator[(48)] with $\psi(x,0) = \delta(x)$ gives

$$\psi_o(x,t) = \sqrt{\frac{m}{2\pi\hbar it}} \exp\left[\frac{imx^2}{2\hbar t}\right] \tag{23}$$

and this gives

$$\left(2i\frac{\partial}{\partial t} + \frac{\hbar}{m}\frac{\partial^2}{\partial x^2}\right)\psi_o(x,t) = 0 \tag{24}$$

Thus, $\psi_o(x,t)$ obtained from the QM free-particle propagator is a solution of the SE without a source, i.e, $J = 0$ in Eq (19). So, QM's $\psi_o(x,t)$ in Eq (23) is not physically relevant in RBW per QFT's $Z(J)$. That is, since $Z(J) = Z(0)e^{iW(J)}$, the sourceless solutions $\psi_o(x,t)$ would appear in the exponent of $Z(0)$ which Zee describes as[(49)], "often of no interest to us."

In order to obtain a physically relevant "free-particle amplitude" related to non-relativistic QFT, the SE must have a "source." Essentially, in our MLGT approach, we want a particle of mass m created at the Source and annihilated at the sink (detector) – with no worldline connecting them – and this happens at sources J. We can write the SE[(50)]

$$\left(2i\frac{\partial}{\partial t} + \frac{\hbar}{m}\frac{\partial^2}{\partial x^2}\right)\psi(x) = 2V(x)\psi(x) \tag{25}$$

so that

$$\psi(x) = \int dx'\, D(x - x') 2V(x')\psi(x') \tag{26}$$

With $2V(x')\psi(x') = \delta(x' - x_i)$ we have

$$\psi(x) = D(x - x_i) \tag{27}$$

We could still add solutions $\psi_o(x)$ of the sourceless equation, but again they are associated with $Z(0)$ and therefore of "no interest to us."

To find the QFT counterpart to Eq (27), we use Eq (20) with point sources $J(x')$ at x_i (Source) and $J(x)$ at x_f (sink/detector) to obtain the generating function

$$W(J) = -\frac{1}{2}\iint dx dx'\, \delta(x - x_f) D(x - x') \delta(x' - x_i) = -\frac{1}{2} D(x_f - x_i) \tag{28}$$

So, with $D(x - x')$ given by Eq (22) we have our QFT derivation of the "free-particle" QM probability amplitude in terms of the generating function, i.e., $\psi(x) = -2W(J)$, which is $\vec{J} \cdot \vec{\vec{K}}^{-1} \cdot \vec{J}$ on the graph of MLGT. That we must always supply $J(x)$, and that $J(x)$ is always coupled to $J(x')$ via $D(x - x')$ in $Z(J)$, is consistent with the relational ontology of RBW. Now we formulate our graphical MLGT counterpart to this result to explain it.

Since ψ^* appears undifferentiated in Eq (15), we do not have a fully relational form. We imagine that this is because ψ needs to be underwritten by a "coordinate field" that reveals the underlying relational form of the action. For example, if one writes the spring potential of the coupled harmonic oscillators supra in terms of the displacement x from equilibrium, one obtains the term $\frac{1}{2}kx^2$ in the action, but this obscures the relational structure revealed using coordinates q, i.e., $\frac{1}{2}k(q_1 - q_2)^2$. So, we replace ψ^* with a relational structure $\psi^* \to (\psi_2^* - \psi_1^*)$ in the following discretizations (with extrapolations):

$$i\psi^*\left(\frac{\partial\psi}{\partial t}\right) \to i(\psi_2^* - \psi_1^*)\left(\frac{\psi_2 - \psi_1}{\Delta t}\right)$$

$$-\frac{c^2}{2\overline{m}}\left(\frac{\partial\psi}{\partial x}\right)^2 \to -\frac{\hbar}{2m}\left(\frac{\psi_3^* - \psi_1^*}{\Delta x}\right)\left(\frac{\psi_3 - \psi_1}{\Delta x}\right)$$

where ψ_2 is at node $\psi_1 + \Delta t$, ψ_3 is at node $\psi_1 + \Delta x$, and ψ_4 is at node $\psi_1 + \Delta x + \Delta t$. We obtain for $\vec{\vec{K}}$ in $\frac{1}{2}\vec{\psi}^* \cdot \vec{\vec{K}} \cdot \vec{\psi}$:

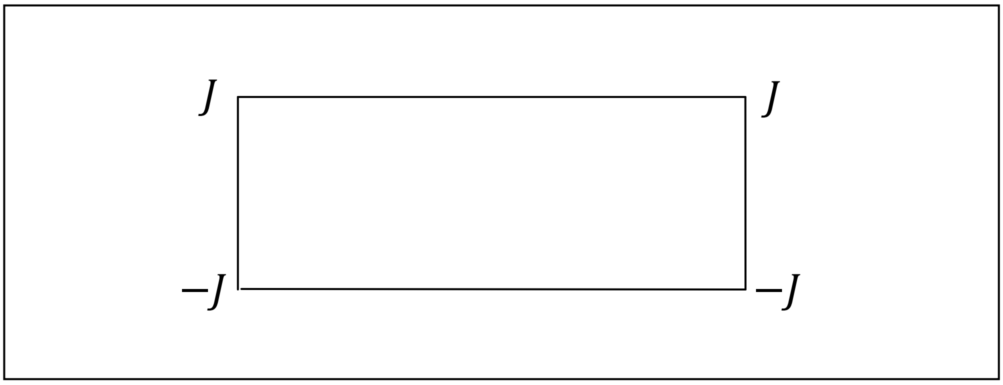
$$\vec{\vec{K}} = \begin{bmatrix} \left(\frac{2i}{\Delta t} - \frac{\hbar}{m\Delta x^2}\right) & -\frac{2i}{\Delta t} & \frac{\hbar}{m\Delta x^2} & 0 \\ -\frac{2i}{\Delta t} & \left(\frac{2i}{\Delta t} - \frac{\hbar}{m\Delta x^2}\right) & 0 & \frac{\hbar}{m\Delta x^2} \\ \frac{\hbar}{m\Delta x^2} & 0 & \left(\frac{2i}{\Delta t} - \frac{\hbar}{m\Delta x^2}\right) & -\frac{2i}{\Delta t} \\ 0 & \frac{\hbar}{m\Delta x^2} & -\frac{2i}{\Delta t} & \left(\frac{2i}{\Delta t} - \frac{\hbar}{m\Delta x^2}\right) \end{bmatrix} \tag{29}$$

ignoring the volume element $\Delta x \Delta t$. The eigenvalues are $\{0, \frac{4i}{t}, -\frac{2\hbar}{mx^2}, \frac{4i}{t} - \frac{2\hbar}{mx^2}\}$, where we have dropped the Δ for simplicity, and the eigenvectors are {(1,1,1,1), (-1,1,-1,1), (-1,-1,1,1), (1,-1,-1,1)}, i.e., a Hadamard structure that is repeated in both the KG and Dirac actions[(51)]. These eigenvectors correspond to the following four modes, respectively:

Mode 1

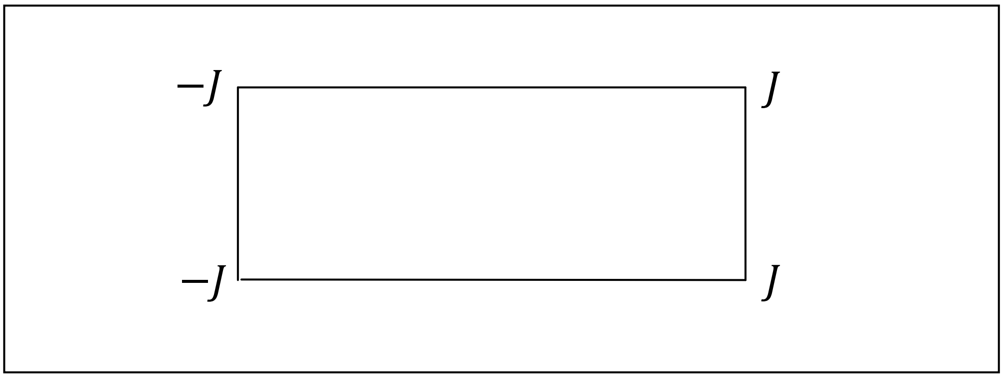
There is no spatial or temporal variation in $\vec{J}$, so $\vec{J}$ is not divergence-free and therefore does not reside in the row space of $\bar{\bar{K}}$. This source does not satisfy the AGC.

Mode 2



There is only temporal variation in $\vec{J}$. While $\vec{J}$ resides in the row space of $\bar{\bar{K}}$ and is therefore divergence-free in the mathematical sense, it is not conserved within the element. Therefore, this source does not satisfy the AGC.

Mode 3



There is only spatial variation in $\vec{J}$. While $\vec{J}$ resides in the row space of $\bar{\bar{K}}$ and is conserved within the element, it does not represent an interaction. Therefore, this source does not satisfy the AGC.

Mode 4

There is both spatial and temporal variation in $\vec{J}$, which resides in the row space of $\vec{\vec{K}}$, is conserved in the element, and represents an interaction. This source satisfies the AGC.

In the eigenspace of $\vec{\vec{K}}$, the source associated with mode 4 is $\vec{J}$ = (0, 0, 0, J_o), where J_o is complex in general, so it is easily seen that (with our gauge fixing)

$$\vec{J}\cdot\vec{\vec{K}}^{-1}\cdot\vec{J} = \frac{J_o^2}{\left(\frac{4i}{t}-\frac{2\hbar}{mx^2}\right)} \tag{30}$$

Eqs (27) and (28) tell us that Eq (30) is the MLGT counterpart to Eq (22), i.e.,

$$\frac{J_o^2}{\left(\frac{4i}{t}-\frac{2\hbar}{mx^2}\right)} = \frac{-1}{(2\pi)^2}\iint \frac{e^{ikx}e^{i\omega t}\,d\omega dk}{2\omega+\hbar k^2/m} \tag{31}$$

where t and x represent the temporal and spatial extent of the element, respectively, and $J_o^2 = J_o \cdot J_o$ (not $J_o^* \cdot J_o$). The LHS of Eq (31) simply explains the graphical origin of the RHS which gives the following amplitude for each component of the spacetimesource element in Figure 7:

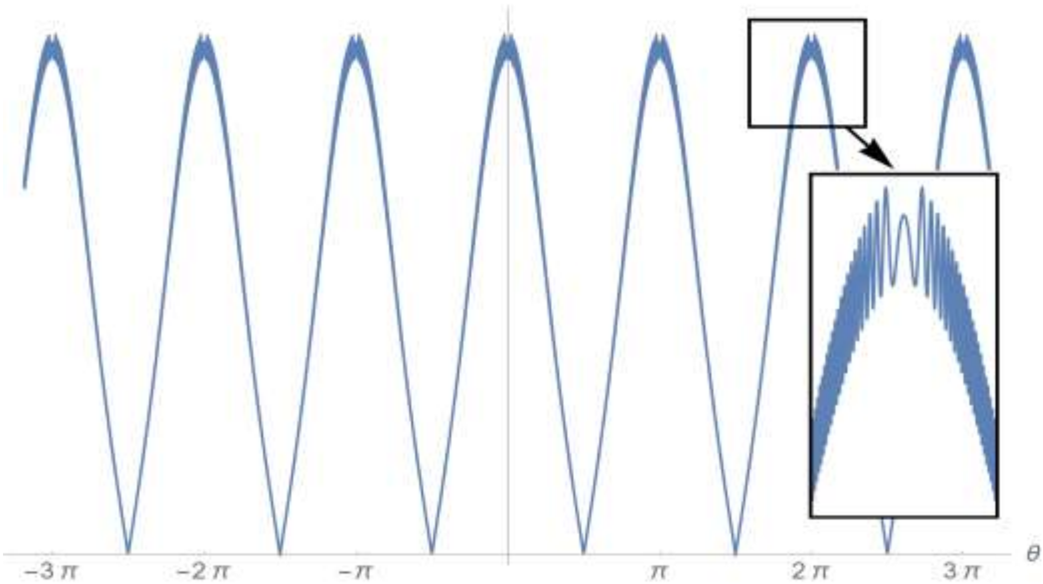
$$A(x,t,m) = -\frac{1}{4}\sqrt{\frac{m}{\pi\ \hbar\ t}}\left[i\mathrm{C}\left(\sqrt{\frac{m\ x^2}{\pi\ \hbar\ t}}\right)+\mathrm{S}\left(\sqrt{\frac{m\ x^2}{\pi\ \hbar\ t}}\right)\right]\exp\left(\frac{i\ m\ x^2}{2\ \hbar\ t}\right) \tag{32}$$

where $C(z) = \int_0^z \cos\left(\frac{\pi}{2}u^2\right)du$ and $S(z) = \int_0^z \sin\left(\frac{\pi}{2}u^2\right)du$ are Fresnel integrals. Now to construct the amplitude A_{total} for the entire spacetimesource element in Figure 7 for an outcome in the twin-slit experiment we have:

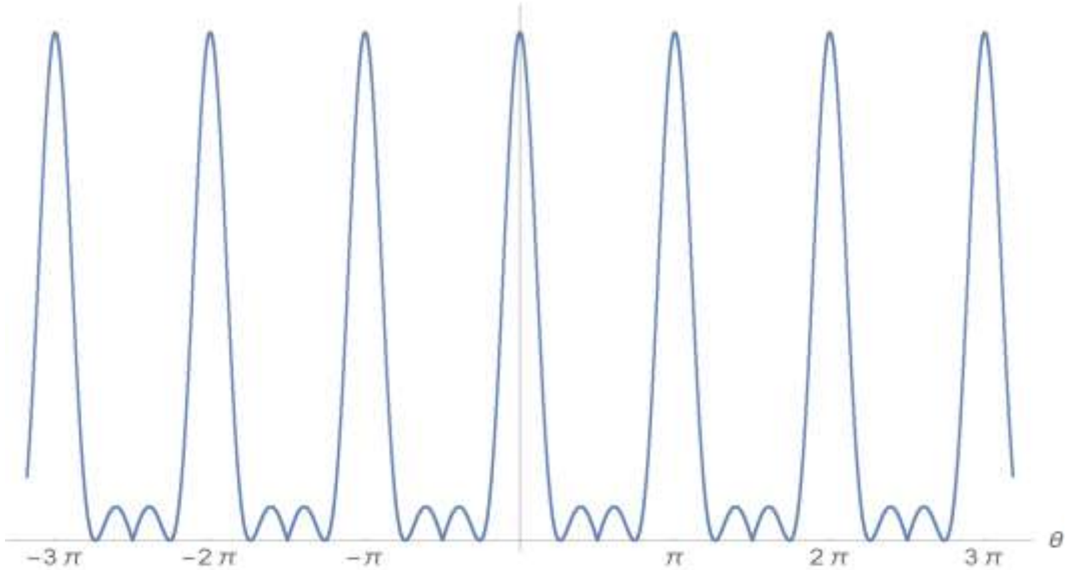
$$A_{\text{total}} = A(x_1, t_1, m)A(x_3, t_3, m) + A(x_2, t_2, m)A(x_4, t_4, m) \tag{33}$$

where x_1 and t_1 are the distance and time from Source to Slit 1, x_2 and t_2 are the distance and time from Source to Slit 2, x_3 and t_3 are the distance and time from Slit 1 to the Detection Event, and x_4 and t_4 are the distance and time from Slit 2 to the Detection Event. For an electron traveling at 1.00 m/s through the device (dynamic language) we obtain the plots below. [Note: The amplitudes of Eqs (23) and (32) were computed for the properties of space, time and mass. In order to model the data for their twin-slit experiment with electrons, Bach *et al*.[52] had to modify the "free space" amplitude to include other properties. Modifications included an electromagnetic potential at the double slits, an image charge potential at the collimation slit, and incoherent sources associated with the electron gun. Therefore, differences in the plots below are not expected to be experimentally observable for electrons. The point of this exercise is only to illustrate the manner by which RBW underwrites QM via the AGC.]

Thus, RBW provides a new and simple answer to the question, waves or particles? TSVF says "waves," Many Histories says "particles" and de Broglie-Bohm says "both." RBW completes the set of possibilities by answering "neither." This option avoids dilemmas associated with counterfactual definiteness, as we showed in Dowker's GHZ set-up, and discharges other QM mysteries rather simply, as we will now show.



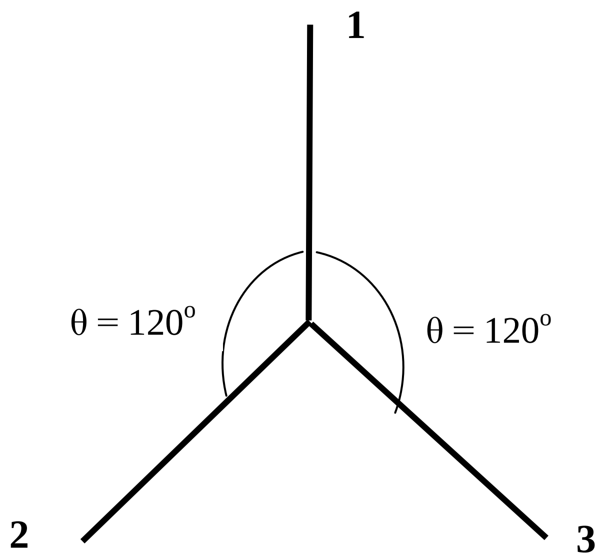
Intensity versus angular displacement in radians for electrons with λ = 728 μm, slit separation of 1.00 mm, screen-to-detector distance of 50.0 cm, and Source-to-slits distance of 50.0 cm. This is the RBW result. There is an oscillatory substructure that is suppressed by the horizontal scale (see inset).



Intensity versus angular displacement in radians for electrons with λ = 728 μm, slit separation of 1.00 mm, screen-to-detector distance of 50.0 cm, and Source-to-slits distance of 50.0 cm. This is the free-particle SE result without a source given by Eq (23). Both graphs extend beyond the physically relevant range [-π, π] to show their periodicity on that range.

4. RBW Deflates Mysteries of QM

RBW can be thought of as a *realist* psi-epistemic hidden variable account with the graphical spacetimesource element and the AGC of MLGT as the hidden variables, so there is no hidden instrumentalism here. There is no measurement problem in this account, as it is psi-epistemic and there is no configuration space, only spacetime. The fundamental ontological entity, i.e., the spacetimesource element, provides a new ontology for quantum interference and the mystery of wave-particle duality – it's not particles or waves or both, but neither. This "unmediated exchange" avoids dilemmas associated with counterfactual definiteness because environmental aspects that are not germane to the experimental context between the Source emission event and the detection event(s) are not represented in a spacetimesource element or the AGC. The AGC explains space-like separated, correlated outcomes that violate Bell's inequality (per entanglement) as 4D patterns in the block universe. This acausal explanation doesn't require an additional time-evolved or retro-time-evolved story, the AGC explanation of the 4D pattern is the ultimate explanation. For example, consider spin measurements on the state $\frac{1}{\sqrt{2}}(|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle)$ with the Stern-Gerlach (SG) magnets oriented in one of three positions with relative angles given by 0^o or 120^o (state is the same for any of the three bases).



The 4D pattern that needs to be explained is the set of experimental trials (initiation to termination to include outcomes) in which the 0^o relative SG orientations (11, 22, 33) always produce like outcomes (50% ↑↑ and 50% ↓↓) and the 120^o relative SG orientations (12, 13, 23, 21, 31, 32) only produce like outcomes 25% of the time (12.5% ↑↓ and 12.5%↓↑). Mermin "instruction sets" corresponding to counterfactual definiteness fail to produce the observed correlations (4D pattern) in this experiment[(53)], thereby producing a "quantum myster[y] for anybody." The spacetimesource element for any particular trial (which includes detector settings and outcomes) does not contain reference to unrealized measurements, i.e., no Mermin "instruction sets," no counterfactual definiteness. The AGC explains the observed distribution of the spacetimesource elements, i.e., the 4D pattern, via OSR (*a la* Rickles & Bloom) and nonlocal constraints (*a la* Weinstein), thus the mystery is deflated. This explanation does not employ superluminal worldlines, so there is no possibility of conflict with special relativity, i.e., no non-locality in that sense.

Since spacetimesource elements represent unmediated exchanges, i.e., they do not contain worldlines of counterfactual definiteness, there is no "screened off quantum entity" that must decohere to behave classically. So per RBW, environmental/dynamical decoherence is a theory to explain the suppression of quantum interference that is only useful in the Hamiltonian time-evolved perspective. In the twin-slit experiment for example, the interference pattern results from a collection of 4-component spacetimesource elements each with a Source emission event connected to two slits and a detector detection event. The interference pattern at the detector does not obtain for a collection of two successive 1-component spacetimesource elements with a Source emission event connected to a slit detection event followed by a slit emission event connected to a detector detection event. The same holds true for the tracks in the detector of a particle physics experiment, as we explained supra. The set of clicks composed of the first click for each particle worldline is a spacetimesource element for the initial quantum exchange. These spacetimesource elements can exhibit quantum interference, meaning different sets of particle outcomes can interfere with each other (as given by particle physics computations per QFT). Given a particular initial spacetimesource element, subsequent clicks in the subsequent spacetimesource elements for each worldline follow the trajectories of classical physics, as explained theoretically by Mott. These spacetimesource elements do not exhibit quantum interference. Thus, the RBW counterpart to environmental decoherence is simply the manner in which the amplitude for the second spacetimesource element in a sequence is contingent upon the first spacetimesource element in the sequence, when the second spacetimesource element does not exhibit quantum interference. However, as we will see, this is not what RBW associates with quantum versus classical behavior *per se*.

Another typical characterization of quantum versus classical behavior is the algebraic non-commutivity of observables. Per RBW, the non-commutivity of observables is represented by mutually exclusive arrangements of spacetimesource elements, but the mutually exclusive arrangement of spacetimesource elements does not in and of itself characterize quantum versus classical behavior. For example, there is no representation for the *x*-oriented SG magnet in the spacetimesource element of Figure 3 because no spin *x* measurement is made, so there is only one spacetimesource element for Dowker's GHZ set-up (the spin *y* measurement). If there is a spin *x* measurement followed by a spin *y* measurement, you need sequential spacetimesource elements. These are mutually exclusive 4D configurations, just like the interference and non-interference configurations supra. The algebraic counterpart to this is that the *x* and *y* spin operators don't commute. However, in the interference example for twin-slit, the interference configuration was quantum while the non-interference of two or more sequential spacetimesource elements was classical. In the case of sequential *x* and *y* spin measurements, each of the sequential spacetimesource elements is quantum. And in fact, one can have interference and non-interference configurations both representing quantum exchanges. For example, Zeilinger has constructed mutually exclusive experimental quantum configurations representing the non-commutivity of position (non-interference) and momentum (interference) operators for entangled photons[(54)].

So, the RBW characterizations of interference versus non-interference and commutivity versus non-commutivity do not account for its distinction between quantum and classical behavior. Rather, we would say that the distinction resides in the probabilistic nature of sequentially related events in sequential spacetimesource elements. For example, the set of first detection events of each worldline in a set of particle trajectories is the first spacetimesource element in a sequence in the particle detector, as explained above for particle physics. That first set of outcomes is highly probabilistic, as with the first event on the alpha particle trajectory in the cloud chamber per Mott. Subsequent detection events however fall along the classical trajectory with high probability, as shown by Mott and used computationally to assign particle masses and charges in particle physics detector events. Since there isn't any 'thing' moving through the detector to cause the sequential clicks (a trajectory) per RBW, this probabilistic assessment is all that is available to RBW to make the quantum versus classical distinction. That means sequential spin x measurements produce a classical trajectory, since the outcome of the second and subsequent clicks is given with probability 1. If we follow a spin x measurement with a spin y measurement, the probability for either y outcome is 50%, so we have quantum behavior. This is contrary to standard thinking whereby spin is purely a quantum property. Indeed, if we immerse the spin measurement equipment in a cloud chamber to create particle trajectories through the SG magnet, we'd expect to find what is typically called classical behavior (Figure 8). Per RBW, this is precisely in accord with Colosi & Rovelli's characterization of particles above, i.e., they're not entities with intrinsic properties as defined by n-particle Fock space. Rather, they're defined relationally/contextually by their experimental context. So, given two different detectors (immersed in a cloud chamber or not) we can get two different "particles," i.e., two different classical trajectories defined by relational properties, even though we have the same Source (of electrons, say). Consistent with this RBW distinction between quantum and classical ontology is the RBW distinction between quantum and classical statistics, as characterized by the Born rule.

The manner by which classical trajectories are decomposed per spacetimesource elements requires cancellation of possibilities *a la* PI whereby the spacetime path of extremal action (classical trajectory) is obtained by interference of non-extremal possibilities which contribute with equal weight[(55)]. Classical statistics doesn't provide for this so-called quantum interference. In fact, per RBW, the reason classical statistics works for classical objects is precisely because a classical object is a set of definite (high probability) quantum exchanges, as we just explained. That is, classical statistics assumes a distribution of classical objects and each classical object obtains from quantum statistics having removed non-extremal possibilities. Therefore, classical statistics follows from quantum statistics as the classical ontology of trajectories follows from the quantum ontology of spacetimesource elements. As with all the other mysteries of QM, the Born rule is vexing if one assumes the fundamental ontology is a distribution of worldlines for time-evolved objects with intrinsic properties that interact via forces in accord with those properties. Moving to the 4D perspective allows one to consider an entirely new fundamental ontology, one without worldlines based on an adynamical global constraint. Since the fundamental ontological entities aren't themselves classical objects, there's no reason to believe the statistics for their distribution must be classical. All that is required is that the statistics governing the distribution of non-classical fundamental objects leads necessarily to classical objects and their associated classical statistics. Per RBW, quantum statistics as characterized by the Born rule does precisely that.

5. Conclusion

We updated our Relational Blockworld (RBW) account of quantum physics and argued that it provides a *realist* psi-epistemic account of quantum mechanics (QM) as called for by Leifer. RBW employs spacetimesource elements and an adynamical global constraint (AGC) as ‘hidden variables’ in a global perspective which avoids the need for counterfactual definiteness in a realist account. Instead of an equation of motion governing time-evolved entities, the AGC is used in a “modified lattice gauge theory” (to construct the graphical transition amplitude) which underwrites quantum field theory (to obtain the generating function) whence (the probability amplitude for) QM. Thus, the AGC is the ultimate explanatory mechanism for QM phenomena per RBW. We illustrated this by using our modified lattice gauge theory to analyze the twin-slit experiment. We provided a conceptual and philosophical introduction to RBW’s most prominent features, i.e., adynamism, relationalism/contextualism, and the unmediated exchange of energy, by comparing and contrasting our 4D adynamical approach with the dynamical, retro-time-evolved explanation of the authors’ Two State Vector Formalism in the DFBV experiment. We also contrasted our unmediated energy exchange via spacetimesource elements with Sorkin’s Many Histories account of Dowker’s GHZ set-up, arguing that rather than multiple paths per Many Histories, what is called for is no paths per RBW. We concluded with a brief dismissal of the measurement problem and an RBW explanation of entanglement, environmental decoherence, quantum non-commutivity, the distinction between quantum and classical behavior, and the Born rule.

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Figure 1
(With Permission of the Author)
The DFBV Experiment

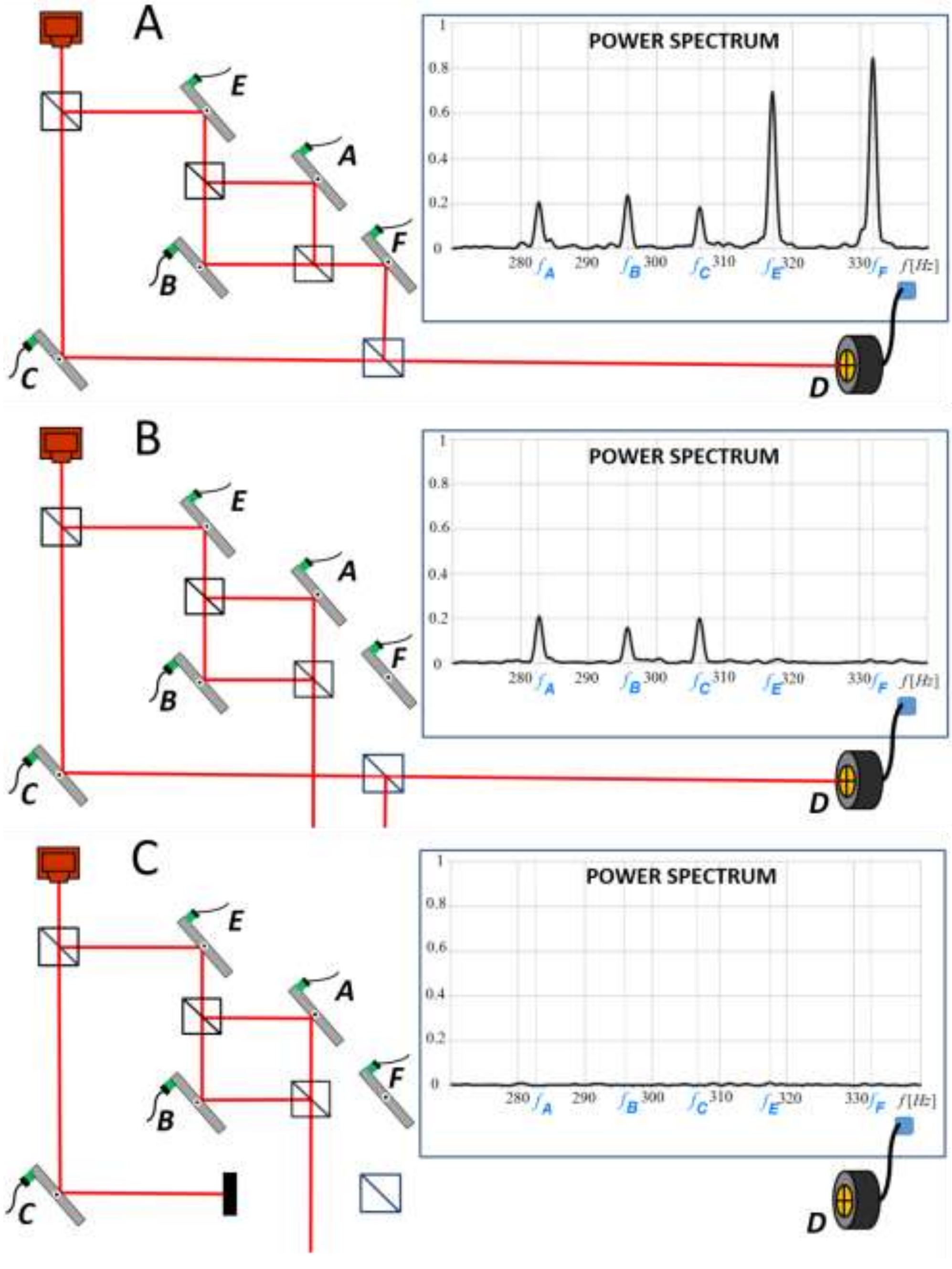


FIG. 1:(A) Measured power spectrum of the signal from the quad-cell photo detector shows frequencies of oscillation of all internal mirrors of the interferometer. (B) When the inner interferometer is tuned in such a way that the beam of light passing through it does not reach the photo detector, the power spectrum of the signal in the photo-detector still shows frequencies of the mirrors of this inner interferometer. (C) These frequencies (and all other signals) disappear when we, without changing anything in the upper arm, block the lower arm of the large interferometer.

1D

Additional measurement with mirror *F* blocked

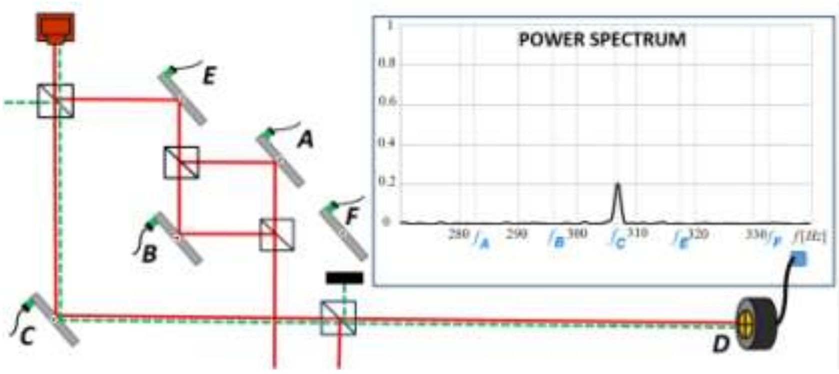


FIG. 1D: The forward and backward evolving states are present together only at mirror C and thus, the only peak in the power spectrum is at fC. Since according to the naïve approach the presence of peaks at fA and fB in Figure 1B is very counterintuitive, one might suspect that these peaks may result from some unrelated electronic noise. A block between mirror F and the last beam splitter absorbs the backward evolving wave moving towards mirrors F, A, B, and E. In the language of the forward wave function only, it absorbs the leakage of the wave from the inner interferometer. Thus theoretically, according to the standard and the TSVF approaches, the block ensures the absence of peaks at the corresponding frequencies. Therefore, this experiment provides a decisive test for the absence of electronic noise in Figure 1B.

1E

TSVF Conclusion

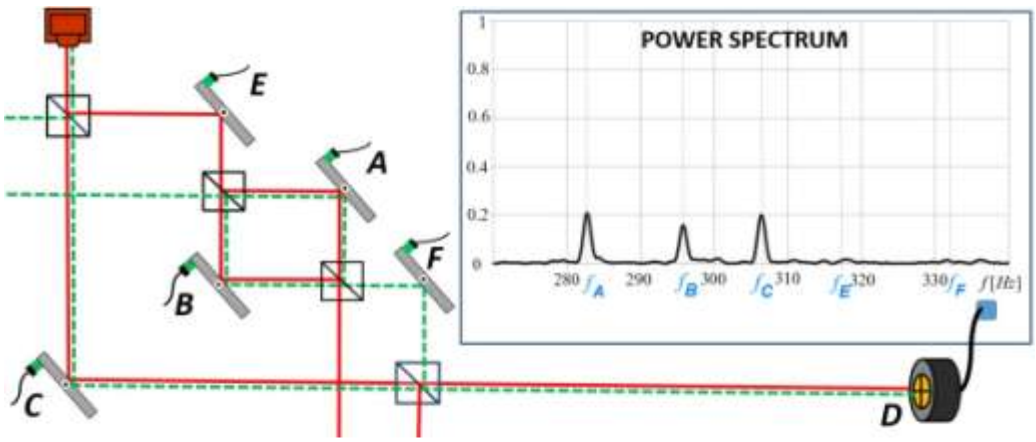


FIG. 1E: The two-state vector description of the photon inside the interferometer includes the standard forward evolving quantum state (red line) and the backward evolving quantum state (green dashed line) of the photon detected by the quad-cell photo-detector. It provides an explanation of the observed power spectrum: frequencies f_C, f_A, and f_B are present while f_E and f_F are not. The photon was present only where both forward and backward quantum wavefunctions do not vanish.

Figure 2
Dowker's GHZ Set-Up

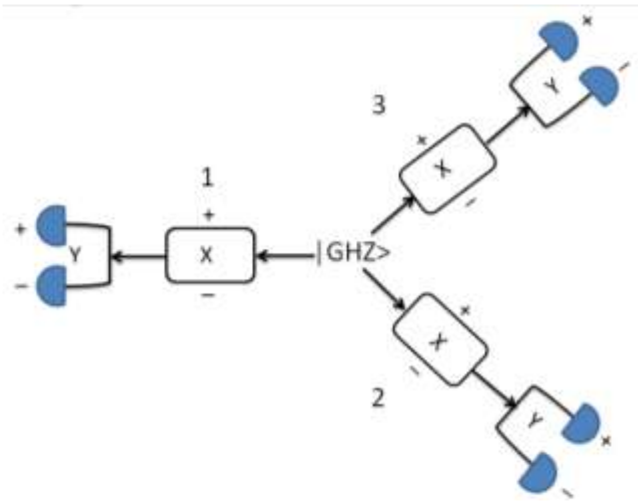


Figure 3
Spacetimesource Element for an Outcome in Dowker's GHZ Set-up

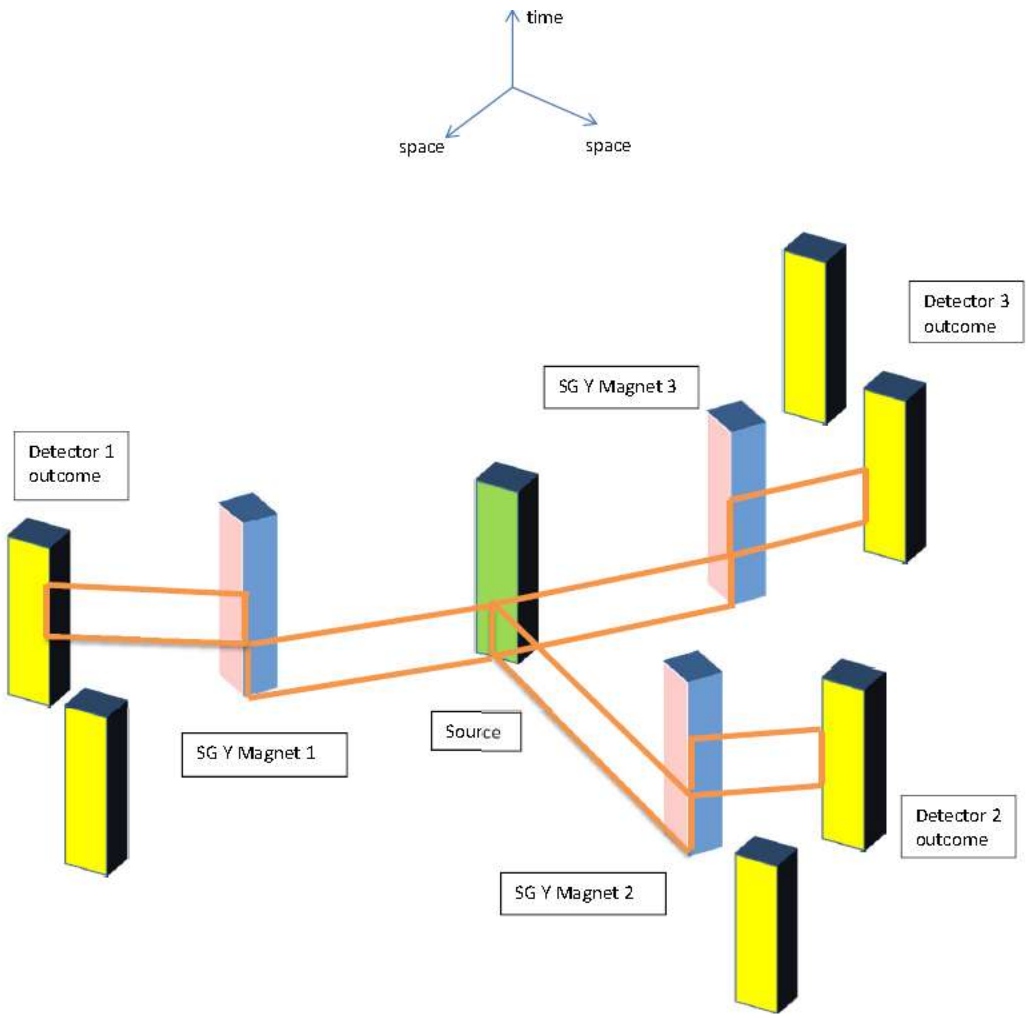
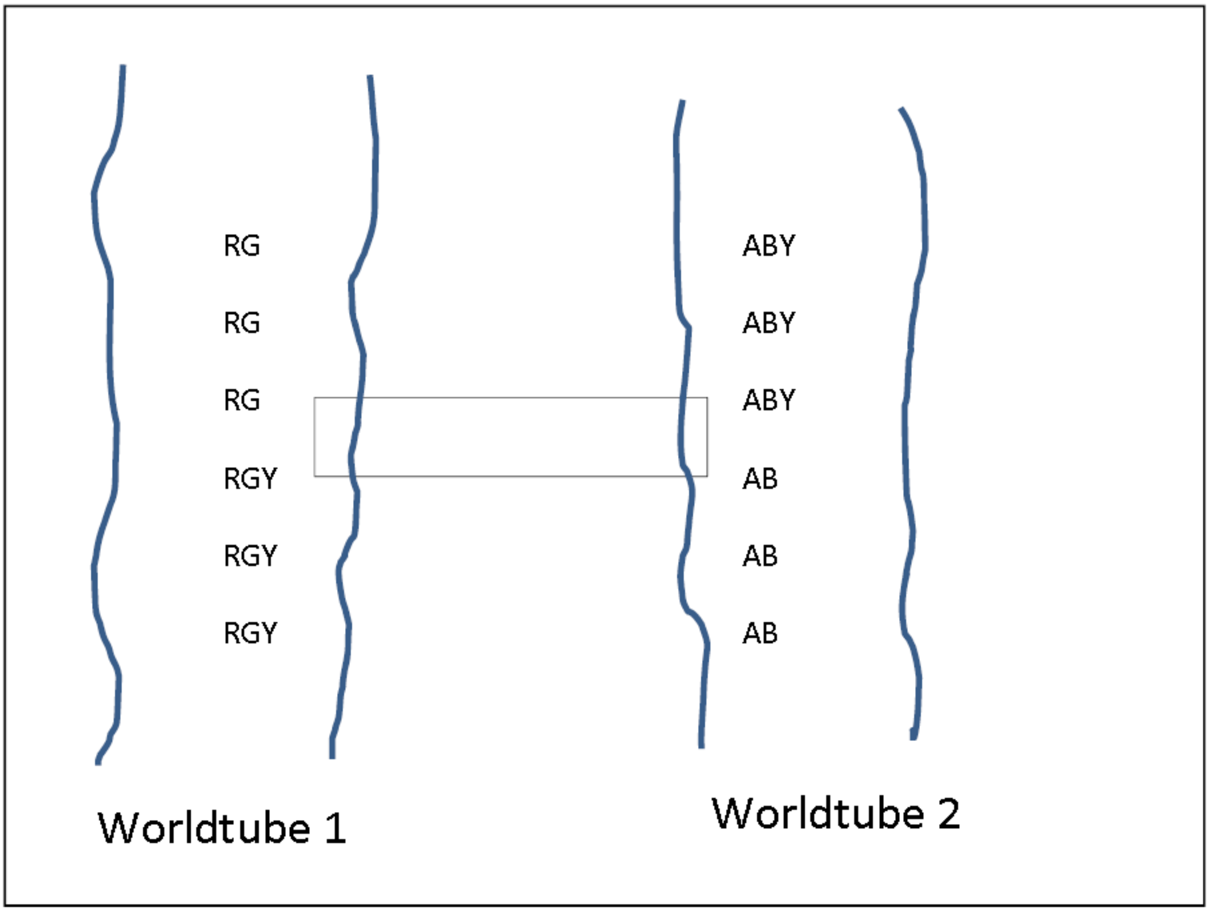


Fig 3. The orange blocks depict components of the spacetimesource element for a particular outcome in Dowker's GHZ set-up.

Figure 4



Quantum Exchange of Energy-Momentum – The property Y is associated with the source on the spacetimesource element (rectangle) shared by the worldtubes. As a result, property Y disappears from Worldtube 1 (Y Source) and reappears later at Worldtube 2 (Y detector) without mediation. That is, there is no third worldtube/line needed to explain the exchange of energy-momentum associated with property Y between Worldtube 1 and Worldtube 2. While these properties are depicted as residing in the worldtubes, they don't represent something truly intrinsic to the worldtubes, but are ultimately contextual/relational, i.e., being the Source of Y only makes sense in the context of (in relation to) a "Y detector", and vice-versa. The A, B, R, and G properties shown might be established with respect to classical objects not shown in this Figure, for example.

Figure 5

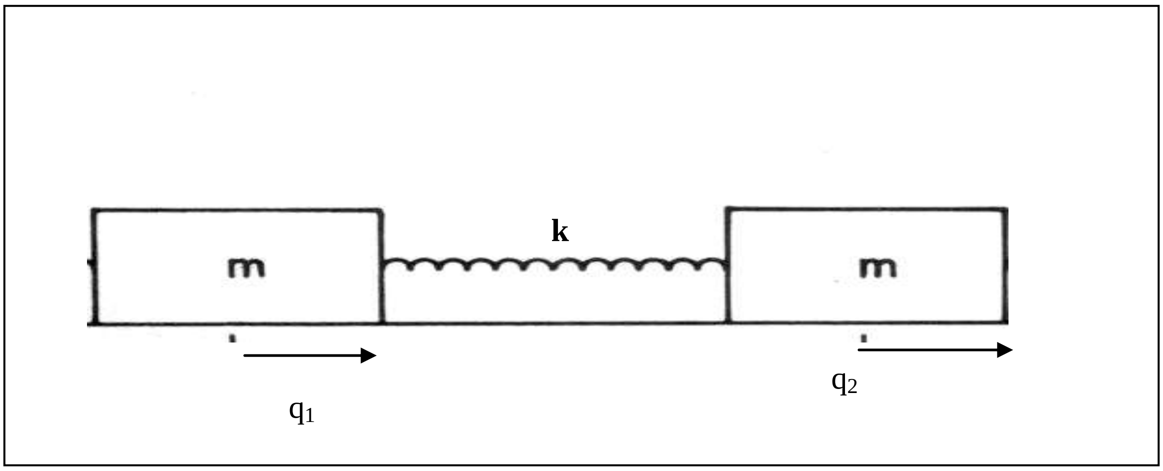


Figure 6

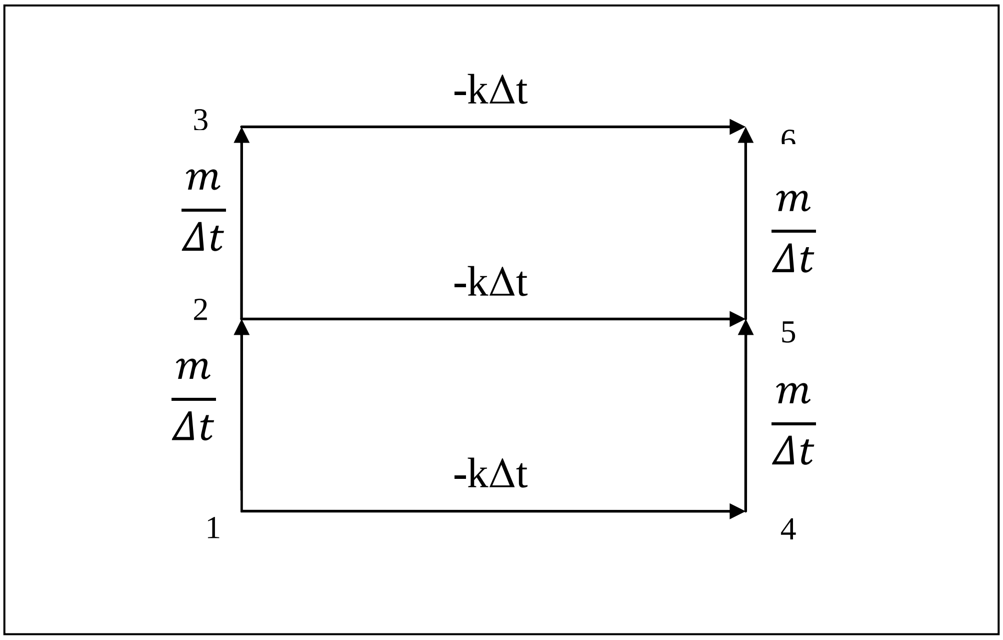


Figure 7
Twin-Slit Interference

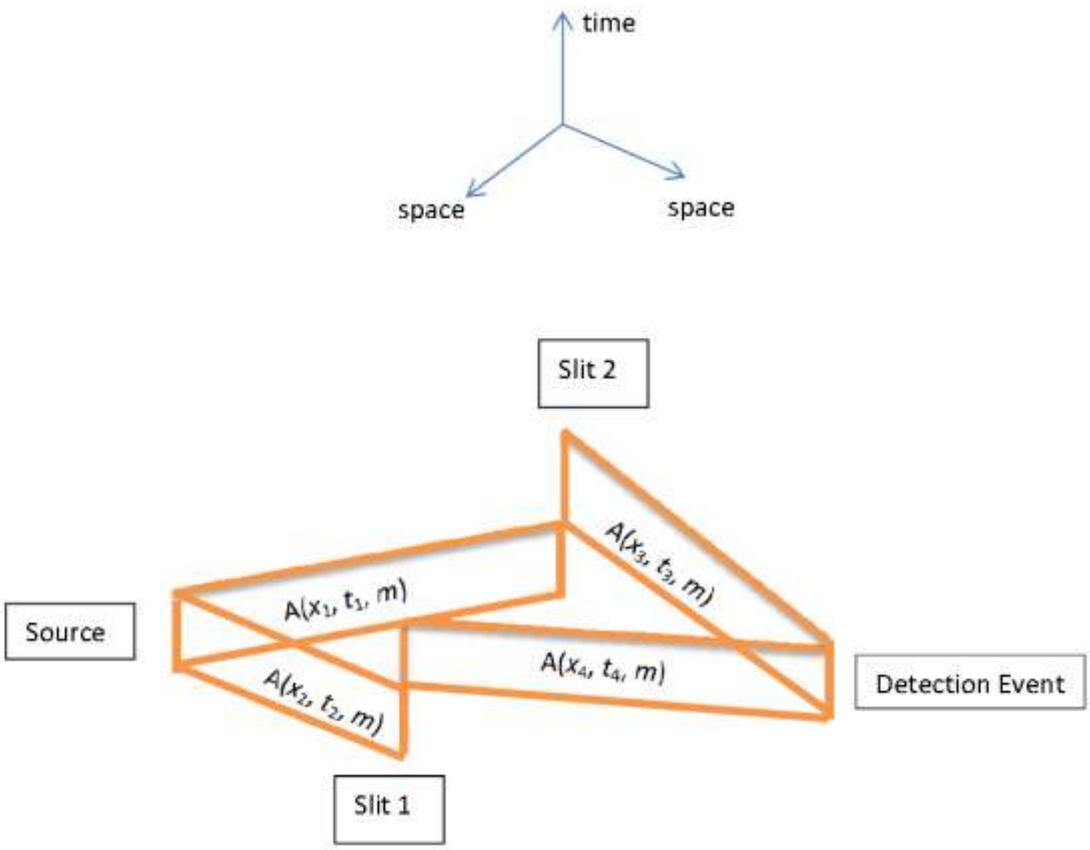


Fig 7. The boxes are the components of the spacetimesource element depicting mass *m* loss at the Source emission event and mass *m* gain at the Detection Event contributing to an interference pattern at the detector.

Figure 8

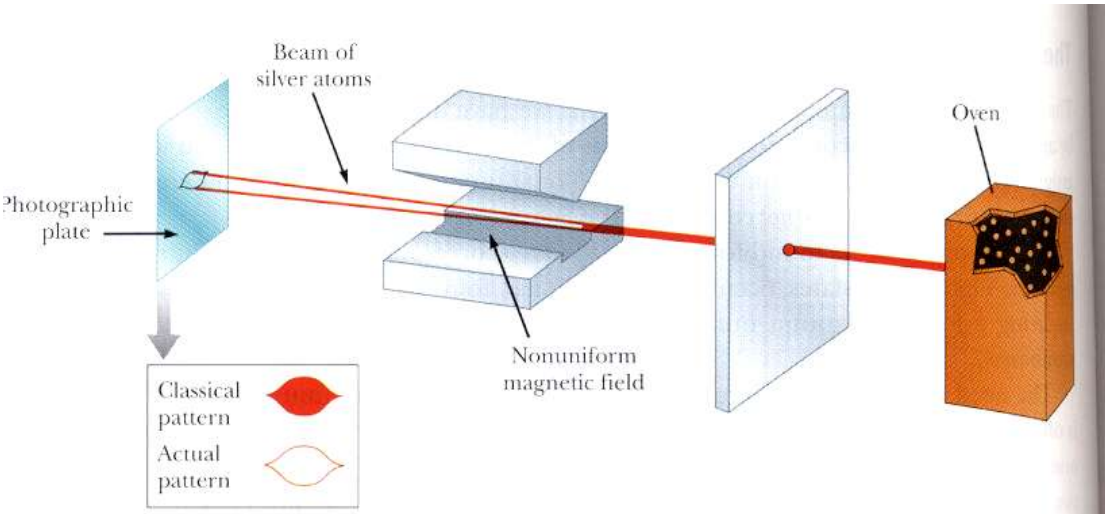


Figure 42.17 The technique used by Stern and Gerlach to verify space quantization. A beam of silver atoms is split in two by a nonuniform magnetic field.

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