The Answer to Zeilinger's "Very Fundamental Question": QR/TOPI

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ABSTRACT

In the 1990s, Anton Zeilinger, a superb experimentalist "trying to understand Nature", endeavored to elevate *information* to "a foundational principle for quantum mechanics". Three decades later, upon earning the 2022 Nobel Prize in Physics with Alain Aspect and John F. Clauser, Zeilinger inspired me to select this article's name after saying: "The very fundamental question — what does this really mean in a basic way? — is unanswered and is an avenue for new research." Albeit visibly not content with his "foundational principle", he still stated during his Nobel lecture: "Maybe, we need a Unification between the Concepts of Reality and Information". I agree with Zeilinger against 'many-worlds' but utterly disagree with his vision of *Information* as a "foundational principle" for a theory about the *physical* world.

QR/TOPI integrates Quantum Theory (**Q**T) with Special Relativity (**R**T) by modifying their Ontology, Foundation, Structure, and Interpretation. QR/TOPI shows RT is not the ultimate account of spacetime structure, provides the "radical conceptual renewal" requested by John Bell, and answers the "very fundamental question" posed by Zeilinger.

Zeilinger's 'Total Information Content' is shown to be a derivative of the notion of State. Ergo, it cannot be deemed foundational. Zeilinger's "fundamental question" is answered by reviewing several experimental epitomes of quantum 'quirkiness', whose physical meanings proposed to date -if not stranger than the phenomena themselves- are incoherent and overly contrived. Explanatory catchphrases like 'wave-particle duality', 'interaction-free detection', 'availability of path-information', 'retrocausality', 'erasing the past', 'changing the path of a photon millions of years ago', etc. are proven wrong.

Keywords

Reality, Relativity, Quantum Theory, Many-Worlds, Foundational Information, Ontic Probability.

Statement on other Authors' Excerpts

Unless otherwise indicated: underscore, italics, and hyperlinks appearing in other authors' excerpts were inserted by the present author for emphasis and understanding.

List of Acronyms

RT	**Special** Relativity Theory	GRT	**General** Relativity Theory
QT	Quantum Theory	EPR	Einstein/Podolsky/Rosen Paper
EPRB	EPR-Bohm Experiment	TOPI	The Ontic Probability Interpretation
QT/TOPI	Non-Relativistic QT under TOPI	QR/TOPI	Theory integrating RT and QT
QFT	Quantum Field Theory	PI	Physical Interaction
MB	Milieu Basis	R-Time	Time as conceived in RT
R-Event	Event per RT (actual & evincing)	QR-Time	Time as conceived in QR/TOPI
QR-Event	Event as conceived in QR/TOPI	QR-Sync	Absolute Sync of Probable States
IF	Inertial Frame per RT	PD	Probability Distribution
SD	Standard Deviation of a PD	PTI	Pure-Transformation Interaction
PDI	Pure-Detection Interaction	GI	Gauge Interaction (PTI+PDI)
TM	True Measurement	QEI	Quanton Emission Interaction
PEI	Pure-Entanglement Interaction	ITI	Intrinsic Tele-Interaction
BI	Bell Interaction	BS	Beam Splitter
PF	Polarizing Filter	PBS	Polarizing Beam Splitter
MZI	Mach-Zehnder Interferometer	MWI	Many Worlds Interpretation

Introduction – The Background Leading to QR/TOPI

In 1935, Einstein published one of the most influential papers in history (EPR [1]) denouncing the stochasticity and the 'two-particle nonlocality' inherent in Quantum Theory (QT) – thereby 'concluding' it was an 'incomplete' theory. EPR's influence is undeniable: during his 2022 Nobel Prize Lecture[2], Anton Zeilinger pointed out that EPR is (nine decades later) cited twice per day despite being "very difficult to read". True: I read it over ten times in a year before I could decipher the valuable philosophical essence hidden by its convoluted logic. In 2020, Parts I [2] and II [3] of my 'The Ontic Probability Interpretation of Quantum Theory' (QT/TOPI) showed that EPR removed nonlocality from QT's Ontology by fiat, ergo fating its alleged incompleteness. This, of course, does not take away the vast relevance EPR has had as a powerful engine for scientific, philosophical, and technological progress. In 1987, 52 years after EPR, John S. Bell said:

> "It may be that a real synthesis of quantum and relativity theories requires not just technical developments but radical conceptual renewal." [4]

In 1990, during a colloquium Bell gave at CERN on January 22nd, he was asked if he thought Relativity and Quantum theories could be incompatible, and he responded:

> "No, I can't say that, because I think someone will find one day a way to demonstrate that they are compatible... To me, it's very hard to put them together, but I think somebody will put them together, and we'll just see that my imagination was too limited."[3]

[2] Zeilinger Nobel Prize Lecture: https://www.youtube.com/watch?v=ct2uWbI2vF8.

[3] As cited by Antoine Suarez in 'What is Science', 22nd International Interdisciplinary Seminar "Science and the Quest for Truth", Clarendon Laboratory, Oxford, January 2nd, 2020.

In 1994, Tim Maudlin, after trying to merge Special Relativity (RT) with QT, glumly uttered:

> "Indeed, the cost exacted by those theories which retain Lorentz invariance is so high that one might rationally prefer to reject Relativity as the ultimate account of space-time structure." [5]

As vividly related by Colin Bruce in the chapter "The New Age Warrior: Anton Zeilinger" of his book *Schrödinger's Rabbits* [6], he had years back asked Zeilinger which interpretation of Quantum Theory he favored, to which Zeilinger said:

> "I think there is a need for something completely new. Something that is too different, too unexpected, to be accepted as yet." [6]

Bruce also recounts that after asking him if that 'something' would be "some variant of many-worlds", Zeilinger "brought his hand down on the table with a thump and gave a monstrous Teutonic snort" uttering: "No, I do not think many-worlds is right at all. Absolutely not!" [6].

In fact, in the mid-1990s, Zeilinger (a superb experimentalist "trying to understand Nature"[4]) initiated a line of basic research attempting to elevate the arguably *anthropic* notion of *information* [7] [8] to the status of "a foundational principle for quantum mechanics" [9] [10] [11] [12] [13] [14] [15] [16] [17] [18] [19] [20] [21] [22] [23]. I wholeheartedly agree with Zeilinger against many-worlds (MWI) but utterly disagree with him on his vision of *Information* as a "foundational principle" for a theory about the *physical* world. Some three decades later, upon winning the 2022 Nobel Prize in Physics together with Alain Aspect and John F. Clauser "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science", Zeilinger inspired me to select the name for this article after saying:

> "The very fundamental question — what does this really mean in a basic way? — is unanswered and is an avenue for new research."[5]

Ironically, and very far from attempting to diminish the Nobel laureates' professional merit, Zeilinger is apparently admitting that -after almost three decades- he was not fully satisfied with his "Information as a Foundational Principle". Even so, at the end of his Nobel Prize lecture[6], he stated: "Maybe, we need a Unification between the Concepts of Reality and Information" – timidly insinuating that for his "Foundational Principle" to be accepted as such, there is a need to establish a solid nexus (perhaps indistinguishability?) between our elusive but cherished *ontic* notion of Reality and our eminently pragmatic *epistemic* concept of Information. Something new (albeit still closely related to *Information*) must be in the works: upon being asked to share what he was now elucubrating, he uttered a resounding "NO… my ideas are very premature, maybe in a year".[7]

Using the acronym QT to loosely cover all the theories/interpretations/formulations developed in the past 100 years to match the accurate predictions of orthodox (Copenhagen) quantum theory while trying to explain away its perceived 'unrealistic' features, it is palpable that we have been left with a powerful suite of predictive tools – though with absolutely ***no*** clue as to what they fundamentally mean, let alone how to put them together with RT (much less with GRT).

As defined and developed in my previous articles [2] [3] [24] [25], the acronym **QR**/TOPI refers to this long awaited integration of **Q**T with **R**T, which is the result of decades of research

[4] Zeilinger in a 2021 *Nova* broadcast: https://www.pbs.org/wgbh/nova/video/einsteins-quantum-riddle/.
[5] https://www.quantamagazine.org/pioneering-quantum-physicists-win-nobel-prize-in-physics-20221004/.
[6] Zeilinger Nobel Prize Lecture: https://www.youtube.com/watch?v=ct2uWbI2vF8.
[7] Nobel Prize Conversations: https://www.youtube.com/watch?v=XzWd38AxmAM.

and writing on the Foundations and Philosophy of Science [26] [27] [28] [29] [30] [2] [3] [24] [25]. **QR**/TOPI offers at once the needed "radical conceptual renewal" and the "basic" physical meaning behind its synthesis of QT and RT. By drastically modifying the Ontology, Foundation, Structure, and Interpretation of both QT and RT, QR/TOPI shows that Relativity is not the "ultimate account of space-time structure" – though a fundamental part of it.

I genuinely hope Professor Zeilinger finds my QR/TOPI answer to his "very fundamental question" to be sensible and powerful – prompting him to utter his highly valued "why didn't I think of that?"[8], and opening a productive collaborative "avenue for new research".

1. Zeilinger's "Foundational Principle" vis à vis QR/TOPI

To assess my criticism of Zeilinger's 'Foundational Principle', it is vital to understand that, in contrast to the status quo, under QR/TOPI, the quanton's current *State* and *Milieu* are independent. The current *Milieu* may seem to change the current *State*, but it does ***not***; the *Milieu* only changes the MB, i.e. that unique *representation* for the current ontic *State* which exposes the PD for the next *State* via the simpler Born Rule. The *physical* State is non-contextual simply because it includes all possible contexts; its *mathematical* expansion using the MB is the one that is different for each context (Milieu). Different Milieus entail different MBs but the reality of the quanton's *State* is prior to, and independent of, any future PI. And being the *current* State all-inclusive in the above sense, all *next* states in all possible MBs and all state-transition PDs are determining parts of the *current* State and, ergo, ontic as well. The terms 'previous', 'current', and 'next' in a state-transition equation refer to QR-Time because some or all of the states can be ontically probable; only when they are actual their meanings agree with R-Time. Hence, the quanton's *state* transition PD for a *Milieu* to be established in the future depends upon such future *Milieu* and the quanton's *State* by then. Ergo, QR/TOPI is neither deterministic, nor epistemically stochastic, nor retrocausal, nor 'future-input-dependent', nor 'superdeterministic' – much less 'fatalistic' [25].

In 1999, Zeilinger wrote *A Foundational Principle for Quantum Mechanics* [10], whose Abstract is very revealing:

> "In contrast to the theories of relativity, quantum mechanics is not yet based on a generally accepted conceptual foundation. It is proposed here that the missing principle may be identified through the observation that all knowledge in physics has to be expressed in propositions and that therefore the most elementary system represents the truth value of one proposition, i.e., it carries just one bit of *information*. Therefore an elementary system can only give a definite result in one specific measurement. The irreducible *randomness* in other measurements is then a necessary consequence. For composite systems *entanglement* results if all possible *information* is exhausted in specifying joint properties of the constituents." [10]

By "can only give a definite result in one specific measurement", Zeilinger means 'reproducibility', i.e. the probability is one or zero. But being only true for specific State-Milieu pairs, altering them, the elementary system can give a continuum of 'definite' results in a continuum of specific 'measurements'. Even if a 'result' means just the eigenvalue, for a qubit's State there are two 'measurements' (e.g. two directions of a PF) for which the 'result' is 'definite'.

Zeilinger suggested a "Principle of Quantization of Information": "An elementary system represents the truth value of one proposition", which he considered equivalent to "An elementary

[8] Idem footnotes 6 and 7.

system carries 1 bit of information”. He then immediately generalized his principle to: “N elementary systems represent the truth values of N propositions”, or “N elementary systems carry N bits”. He claims that “nonlocality comes in naturally” from his Principle:

> “We remark that our principle does not make any statement of how the information contained in the *N* propositions (the *N* bits of information) is distributed over the *N* systems. After the interaction the *N* bits might still be represented by the *N* systems individually or, alternatively, they might all be represented by the *N* systems in a joint way, in the extreme with no individual system carrying any information on its own. In the latter case we have complete entanglement… Note that we have sketched a natural understanding of quantum entanglement as a consequence of our fundamental principle. Also note that we do not make any statement as to the relative time ordering of the observations on the two systems, their relative space arrangement, and the like. Thus nonlocality comes in naturally” [15].

Zeilinger puts our ability to predict measurement results at the heart of his philosophical stance on Reality, clarifying the terms “represents” and “carries”: “We stress, again, that by proposition we mean something which can be verified directly by experiment. In order to avoid misconceptions, I would like to underline that notions such as that a system ‘represents’ the truth value of a proposition or that it ‘carries’ one bit of information only implies a statement concerning what can be said about possible measurement results.” [10]

Per QR/TOPI, an elementary system ‘carries’ much more than the answer to one question only, e.g. the qubit’s State carries the answer to what happens in any direction in space. For Zeilinger, a PD per se seems not to be *information*. If the only *information* carried by a quanton with a spin along the z-axis is about the result of a ‘measurement’ along the z-basis, why is the PD ‘definitely’ different for other directions? [2] [3] [24] [25]. As for the ontology behind the Principle, he says:

> “In fact, the object therefore is a useful construct connecting observations… As a result we may arrive at intersubjective agreement on the model, thus lending a sense of objectivity to the mentally constructed objects.” [10]

Zeilinger seems to imply that *objectivity* is somehow equivalent to *intersubjective* agreement. The former certainly implies the latter (as a desideratum) but not vice versa; otherwise, we could easily fall into a collective state of delusion. Phenomenalism/instrumentalism/operationalism are clearly present in the philosophical underpinnings of his Foundational Principle. Taken to the extreme, such a stance becomes: ***no*** subject and ***no*** measurement → ***no*** real object. But he says:

> “... It is evident that one of the immediate consequences is that in physics we cannot talk about reality independent of what can be said about reality. Likewise it does not make sense to reduce the task of physics to just making subjective statements, because any statements about the physical world must ultimately be subject to experiment. Therefore, while in a classical worldview, reality is a primary concept prior to and independent of observation with all its properties, in the emerging view of quantum mechanics the notions of *reality* and of *information* are on an equal footing. One implies the other and neither one is sufficient to obtain a complete understanding of the world.” [10]

Zeilinger appears to associate “what can be said about reality” (“subjective statements”) with *information*, and the results of experiment with *reality* – declaring by fiat that (as opposed to classical physics) they are “on an equal footing” and both necessary for “a complete understanding of the world”. I agree with Olimpia Lombardi that “there are no reasons to admit the existence of quantum *information* as qualitatively different from classical *information*" [31] so, as far as the relation between *reality* and *information* is concerned, I cannot see any difference betwixt classical and quantum worldviews. The positing of Reality can only be ab initio and primordial in both views. He allows though for some latitude in his Foundational Principle: "It is clear that it may be a matter of taste whether or not one accepts the suggested principle as self-evident, as I do. If not, then I simply propose to turn the reasoning around and, based on our known features of quantum physics, argue for the validity of the principle." [10]

I contend that the suggested principle is not self-evident, unless one argues that it is implicit in the structure of QT, i.e. unless we "turn the reasoning around" – in which case it would be a theorem, not a principle. Besides, even if I saw it as "self-evident", the irreducible randomness of individual events and entanglement are, in my humble opinion, non-sequiturs.

In sum, Zeilinger sees *information* as *knowledge* acquired by 'measurement', so he does not describe Reality but our *knowledge* of it. There is a deep difference between believing on one side that our description of Reality is only a gradual approach towards it and admitting on the other that (quoting Bohr): "There is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out how Nature is. Physics concerns what we can say about Nature." Zeilinger seems to fully agree with Bohr; I fully disagree.

1.1 Brukner/Zeilinger's Measure of Total Information Content

Around the year 2000, Brukner and Zeilinger published two articles: *Operationally Invariant Information in Quantum Measurements* [22] and *Conceptual Inadequacy of the Shannon Information in Quantum Measurements* [32], with a version uploaded to arxiv.org dated October 25, 2018 [18]. They contended that "the axiomatic derivation of Shannon's measure of information is not applicable in quantum measurements in general", and that "these difficulties in defining the information gain in quantum measurement by the Shannon measure of information arise whenever it is not possible, not even in principle, to assume that attributes observed are assigned to the quantum system before the observation is performed.". They also argued that Shannon's measure of information possesses "unnatural/strongly non-physical properties" which make it inadequate "to define the information gain in an individual quantum measurement". An alternative measure of information with 'natural' features was suggested at the end – whose key properties (unlike Shannon's) were invariance under unitary transformations and conservation in time.

1.1.1 Rationale behind the Total Information Content of an 'Elementary System'

The rationale behind their measure of information can be grasped from the features of the well-known ½-spin qubit for the electron, which is an "elementary system", i.e. its State-Space has dimension $n_D = 2$. Its behavior along any three $(n_D + 1)$ orthogonal axes in our physical space are sufficient to characterize its performance along any other direction (i.e. to specify its State):

$$MB_x = \{|s_{x1}\rangle, |s_{x2}\rangle\};\ Q_x|s_{x1}\rangle = +1|s_{x1}\rangle;\ Q_x|s_{x2}\rangle = -1|s_{x2}\rangle;\ \langle Q_x\rangle^2 = \cos^2\theta_x\ ;\ \Delta Q_x^2 = 1 - \langle Q_x\rangle^2$$

$$MB_y = \{|s_{y1}\rangle, |s_{y2}\rangle\};\ Q_y|s_{y1}\rangle = +1|s_{y1}\rangle;\ Q_y|s_{y2}\rangle = -1|s_{y2}\rangle;\ \langle Q_y\rangle^2 = \cos^2\theta_y;\ \Delta Q_y^2 = 1 - \langle Q_y\rangle^2$$

$$MB_z = \{|s_{z1}\rangle, |s_{z2}\rangle\};\ Q_z|s_{z1}\rangle = +1|s_{z1}\rangle;\ Q_z|s_{z2}\rangle = -1|s_{z2}\rangle;\ \langle Q_z\rangle^2 = \cos^2\theta_z\ ;\ \Delta Q_z^2 = 1 - \langle Q_z\rangle^2$$

Where $|s\rangle$, Q, MB, and θ generically and respectively stand for spin State, spin operator, Milieu Basis, and the angle between the spin State and the direction $\widehat{D}$ defined by the Milieu (magnetic field); $\langle Q\rangle$ and ΔQ are respectively the Mean and Standard Deviation (STD) of the spin property

[24] [25]. Clearly, $|\langle Q\rangle| = 1(0) \Rightarrow \Delta Q = 0(1)$ and the sum of the three squared Means is unity for every θ. Expressing the qubit's State $|s\rangle$ in the three orthogonal MBs we obtain:

$$|s\rangle = \begin{bmatrix} |s_{x(y)(z)1}\rangle \\ |s_{x(y)(z)2}\rangle \end{bmatrix} = \begin{bmatrix} cos\frac{1}{2}\theta_{x(y)(z)} & -sin\frac{1}{2}\theta_{x(y)(z)} \\ sin\frac{1}{2}\theta_{x(y)(z)} & cos\frac{1}{2}\theta_{x(y)(z)} \end{bmatrix} \begin{bmatrix} |s_{x1(y1)(z1)}\rangle \\ |s_{x2(y2)(z2)}\rangle \end{bmatrix}$$

$$|\langle s_{x1}|s_{y1}\rangle|^2 = |\langle s_{x2}|s_{y1}\rangle|^2 = |\langle s_{x1}|s_{z1}\rangle|^2 = |\langle s_{x2}|s_{z1}\rangle|^2 = |\langle s_{y1}|s_{z1}\rangle|^2 = |\langle s_{y2}|s_{z1}\rangle|^2 = 0.5$$

$$\Downarrow$$

$$|s\rangle = \begin{cases} |s_{x1(2)}\rangle \Rightarrow p_{x1(2)} = 1 \wedge p_{x2(1)} = 0 \ ; \ p_{y1} = 0.5 \wedge p_{y2} = 0.5 \ ; \ p_{z1} = 0.5 \wedge p_{z2} = 0.5 \\ |s_{y1(2)}\rangle \Rightarrow p_{y1(2)} = 1 \wedge p_{y2(1)} = 0 \ ; \ p_{x1} = 0.5 \wedge p_{x2} = 0.5 \ ; \ p_{z1} = 0.5 \wedge p_{z2} = 0.5 \\ |s_{z1(2)}\rangle \Rightarrow p_{z1(2)} = 1 \wedge p_{z2(1)} = 0 \ ; \ p_{x1} = 0.5 \wedge p_{x2} = 0.5 \ ; \ p_{y1} = 0.5 \wedge p_{y2} = 0.5 \end{cases}$$

$$\Downarrow$$

$$\langle Q_{x(y)(z)}\rangle^2 = \{\langle s|Q_{x(y)(z)}|s\rangle\}^2 = \{+1p_{x1(y1)(z1)} - 1p_{x2(y2)(z2)}\}^2 = \cos^2\theta_{x(y)(z)}$$

$$\Delta Q^2_{x(y)(z)} = \langle s|\{Q - \langle Q\rangle\mathcal{J}\}^2_{x(y)(z)}|s\rangle = 1 - \langle Q_{x(y)(z)}\rangle^2 = 4p_{x1(y1)(z1)}p_{x2(y2)(z2)}$$

$$\Downarrow$$

$$\langle Q_x\rangle^2 + \langle Q_y\rangle^2 + \langle Q_z\rangle^2 = \{1 - \Delta Q_x^2\} + \{1 - \Delta Q_y^2\} + \{1 - \Delta Q_z^2\} = 1 \quad \forall\, |s\rangle, \ \forall\, \widehat{D}_x, \widehat{D}_y, \widehat{D}_z$$

$$\Downarrow$$

$$\{p_{x1} - p_{x2}\}^2 + \{p_{y1} - p_{y2}\}^2 + \{p_{z1} - p_{z2}\}^2 = 1 \quad \forall\, |s\rangle, \ \forall\, \widehat{D}_x, \widehat{D}_y, \widehat{D}_z$$

$$\Downarrow$$

$$|s\rangle = \begin{cases} |s_{x1(2)}\rangle \Rightarrow (p_{x1(2)} - p_{x2(1)})^2 = 1 \ ; \ (p_{y1(2)} - p_{y2(1)})^2 = (p_{z1(2)} - p_{z2(1)})^2 = 0 \\ |s_{y1(2)}\rangle \Rightarrow (p_{y1(2)} - p_{y2(1)})^2 = 1 \ ; \ (p_{x1(2)} - p_{x2(1)})^2 = (p_{z1(2)} - p_{z2(1)})^2 = 0 \\ |s_{z1(2)}\rangle \Rightarrow (p_{z1(2)} - p_{z2(1)})^2 = 1 \ ; \ (p_{x1(2)} - p_{x2(1)})^2 = (p_{y1(2)} - p_{y2(1)})^2 = 0 \end{cases}$$

Notice that $1 - \Delta Q^2 = (p_1 - p_2)^2$ is an inverse measure of the spread of the spin's PD and, ergo, a direct measure of how much *information* we have about the particular result of a future 'measurement': it is maximal (unity) when any of the two probabilities is one, i.e. full *knowledge*, and minimal (zero) when both are equal (0.5), viz no *knowledge* at all. Hence, if we define $I_{x(y)(z)}(\vec{p}) = I(p_{x_1(y_1)(z_1)}, p_{x_2(y_2)(z_2)}) = 1 - \Delta Q^2_{x(y)(z)}$, we get:

$$I_{x(y)(z)}(\vec{p}) = (p_{x_1(y_1)(z_1)} - p_{x_2(y_2)(z_2)})^2 = 2\{(p_{x_1(y_1)(z_1)} - 0.5)^2 + (p_{x_2(y_2)(z_2)} - 0.5)^2\} \qquad (1)$$

From where it is evident that it is also a direct measure of the PD's deviation from the unbiased one (50/50). Based then on the above features of the qubit, Brukner and Zeilinger's definition of total information I_{Total} for an "elementary system" is "the sum of the individual amounts of information over a complete set of mutually complementary observables", videlicet:

$$\boldsymbol{I_{Total} = I_x(\vec{p}) + I_y(\vec{p}) + I_z(\vec{p}) = 1\ bit} \ \forall\, |s\rangle, \ \forall\, \widehat{\boldsymbol{D}}_x, \widehat{\boldsymbol{D}}_y, \widehat{\boldsymbol{D}}_z \qquad (2)$$

Still, Brukner/Zeilinger did not arrive at Definition 2 and its unity value directly from the ½-spin qubit; they applied heuristic arguments based on our ability to predict a given measurement's result after a finite number N of trials (governed by the Binomial Distribution with $\sigma^2 = Np_1p_2$). They thus "suggested" adding the number 4 so as to interpret $4\sigma^2/N = 4p_1p_2$ as the increase of the “amount of experimenter’s information” after “each individual experimental trial” – so that “the amount of information with respect to a single future experimental trial an experimenter possesses *before* the experiment is performed will be”: $1-4p_1p_2=(p_1-p_2)^2$. They remark the accuracy of this “experimenter’s prediction decreases as the probabilities approach equality [12].

First, note their heuristics leads to the precise behavior of a qubit. Second, the prediction power of QT for p_1 and p_2 is conflated with our ability to know a given ‘measurement’ (GI) result after a finite number N of trials. The former can only be checked for a large-enough number N of trials, with the meaning of “large-enough” depending on the particular values predicted by QT for the probabilities: it requires the largest N for $p_1=p_2=0.5$ and the smallest N when p_1 or p_2 is unity. Being QT accurate, we accurately know (can predict) those probabilities regardless of their values. It is the size of the needed experimental ensemble the one that changes from extremely small at the ends to extremely large at the center of the distribution. This mistake was also committed by EPR (the “Conceptual Confusion” [2]). No heuristics based on the actual experimenter’s work is necessary to accept $(p_1-p_2)^2$ as a measure of *information* as conceived by Zeilinger.

1.1.2 Total Information Content of an “N-Complex System”

To properly define ‘Total Information’ for a composite quanton, they state (my nomenclature):

> In a n_D-dimensional Hilbert space, one needs n_D^2-1 real parameters to specify a general density matrix ρ, which must be Hermitian and have $Tr(\rho)=1$. Since measurements within a particular basis set can yield only n_D-1 independent probabilities, one needs n_D+1 distinct basis sets to provide the required total number of n_D^2-1 independent probabilities. Ivanović (1981) showed that the required number n_D+1 of unbiased basis sets indeed exists if n_D is a prime number, and Wootters and Fields (1989) showed that it exists if n_D is any power of a prime number. This ever complete information represented by the density matrix is fully contained in a complete set of mutually complementary observables.” [19]

The authors admit using the prior concept of State (or density operator) to make their *Total Information* complete, conservative and unitary but, afterwards, they claim *Information* as fundamental – attempting to remove the term State from their discourse:

$$\{Q_1,\dots Q_i,\dots Q_{n_D+1}\}\ ;\ MB_i=\{|s_{i1}\rangle,..|s_{ij}\rangle,\dots|s_{in_D}\rangle\ ;\ |s\rangle=\textstyle\sum_{j=1}^{n_D}s_{ij}|s_{ij}\rangle\quad\forall\, i\in\{1,2,\dots n_D+1\}\}$$

$$|\langle s_{ij}|s_{kl}\rangle|^2=\begin{cases}1\ \ \forall\, i=k\in\{1,\dots n_D+1\}\,;\ \forall\, j=l\in\{1,\dots n_D\}\\ 0\ \ \forall\, i=k\in\{1,\dots n_D+1\}\,;\ \forall\, j\neq l\in\{1,\dots n_D\}\\ \frac{1}{n_D}\ \ \forall\, i\neq k\in\{1,\dots n_D+1\}\ ;\ \forall\, j,l\in\{1,\dots n_D\}\end{cases}$$

$$I_i(\vec{p})=I(p_{i1},\dots p_{ij}\dots p_{in_D})=log_2n_D\frac{n_D}{(n_D-1)}\sum_{j=1}^{n_D}\left(p_{ij}-\frac{1}{n_D}\right)^2\begin{cases}if\ \exists\, j\colon p_{ij}=1\ \Rightarrow I_i=log_2n_D\ bits\\ if\ \forall\, j\colon\ p_{ij}=\dfrac{1}{n_D}\ \ \Rightarrow I_i=0\ bits\\ Otherwise\Rightarrow 0<I_i<log_2n_D\ bits\end{cases}\quad(3)$$

$$\Downarrow$$

$$\boldsymbol{I_{Total}=\sum_{i=1}^{n_D+1}I_i(\vec{p})=log_2n_D\ bits\quad\forall\,|s\rangle,\ \ \forall\, MB\in\{MB_1,\dots MB_i,\dots MB_{n_D+1}\}}\qquad(4)$$

Notice that the factor ‘2’ in Equation 1 (part of the qubit behavior) is replaced in Equation 3 by ‘$n_Dlog_2n_D/(n_D-1)$’, so that the total information for the composite system in Equation 4 sums up to $log_2 n_D$ bits. Note as well that for a composite of N qubits we have $I_{Total} = log_2 2^N = N$ bits. Regarding the information content of systems whose dimension is neither a prime number nor the power of a prime number, Brukner and Zeilinger say:

> "The question whether or not one can find a complete set of mutually complementary observations in the general case of a Hilbert space of arbitrary dimensions is still open. If it should turn out to be the case, then the definition [Equation 4] can be applied to arbitrarily dimensional quantum systems. If, in contrast, such sets only exist if the dimension is the power of a prime number, then we suggest to take this seriously, as implying that the prime number alternatives are the most basic informational constituents of all objects… On the basis of this assumption the information content of a complex system of general dimension could be defined as a sum of the information contents of its individual constituents (each with the dimension of a prime number) plus the information contained in the correlations between them". [19]

Regardless of whether or not the above question is already settled in 2025 (I honestly do not know), the authors show again that they are trying to express the rich *information* (PDs are *information* to me) efficiently encrypted in the single notion of State of a composite quanton (interacting with any given Milieu) in terms of their measure of *Total Information* – which needs a multiplicity of special Milieus (already encoded in the State). It is even clearer when they say:

> "If we accept that the quantum state is no more than a representation of the *information* we have, then the spontaneous change of the state upon observation, the so-called collapse or reduction of the wave packet, is just a very natural consequence of the fact that, upon observation, our *information* changes and therefore we have to change our representation of the *information*, that is, the quantum state. From that position, the so-called measurement problem (Wigner, 1970) is not a problem but a consequence of the more fundamental role *information* plays in quantum physics as compared to classical physics…" [11]

Per QR/TOPI, there is no need of the *epistemic* notion of information: the concept of State is enough, the quanton is the object, the State is its fundamental *ontic* attribute – with its events being all actual albeit ***non***-evincing. And being so, it directly explains why the so-called measurement problem is not such and why *nonlocality* requires no transmission of information [24] [25].

2. Others' Criticism to Zeilinger/Brukner's "Foundational Principle"

Among the various critics of Zeilinger's philosophical stance are C.G. Timpson [33] [34], Shafiee et al [35], M. J. W. Hall [36], and A. Duwel [37]. Regarding Brukner/Zeilinger negative claims on Shannon's measure of information, Timpson said in [33]:

> "Of the three arguments that Brukner and Zeilinger have presented against the Shannon information, we have seen that the first two fail outright…With regard to the first we saw that, contrary to Brukner and Zeilinger, the existence of a pre-determined string is neither necessary nor sufficient for the interpretation of $H(\vec{p})$ as a measure of information. The objective of their second argument was to highlight classical assumptions in the grouping axiom that would prevent the axiomatic derivation of the Shannon information going through in the quantum case. This argument turned out to be based on an erroneous reading of the grouping axiom that appeals to joint experiments…The Shannon information is perfectly well defined and appropriate as a measure of information in the quantum context as well as in the classical."

Michael J. W. Hall [36] defended Shannon's grouping axiom with a similar argument, and A. Duwel concluded in general terms: "… the Shannon theory can be applied to any communication system regardless whether its parts are best described by classical mechanics, classical electrodynamics, quantum theory, or any other physical theory."[9]

As for Zeilinger's "An elementary system represents the truth value of one proposition" and "An elementary system carries one bit of information", Timpson stated:

> "Brukner and Zeilinger claim that this Principle can explain, amongst other things, the irreducible randomness of quantum measurement and the phenomenon of entanglement. It is not immediately obvious that FP1 and FP2 [the above two assertions] are actually equivalent, neither is it clear how the Foundational Principle might in fact be supposed to function. As it stands it does not appear to distinguish between classical and quantum; FP1 and FP2 seem to be as true of a single classical (Ising model) spin as of a qubit." [34]

Apropos, G. Weihs asked in *Quantum Physics from A(nton) to Z(eilinger)*[10]: "If the two-state system is the elementary quantum system as postulated by the informational principle, can a qutrit be elementary at all? A qutrit cannot be decomposed trivially into qubits… The only elementary three-state systems we know are the vector bosons of the strong and weak interactions (the photon being counted as two-state here). I wonder whether the vector bosons might be composite as well."

Timpson also identifies what I consider a major weakness of Zeilinger's Principle:

> "If we are to make a claim about the number of propositions required to describe a system, then, as we must when identifying an elementary system to figure in the Foundational Principle, we must already have made a choice of the set of concepts with which to describe the system. But this is worrying if the purpose of the Foundational Principle is to serve as a basis from which the structure of our theory is to be derived. If we already have to make substantial assumptions about the correct terms in which the objects of the theory are to be described, then it may be that the Foundational Principle will be debarred from serving its foundational purpose." [33]

Regarding Zeilinger's claim that the reason for irreducible randomness is that "an elementary system cannot carry enough information to provide definite answers to all questions that could be asked experimentally" [10], Timpson said:

> "Unfortunately, this does not constitute an explanation of randomness, even if we have granted the existence of elementary systems and adopted the Foundational Principle. For the following question remains: why is it that experimental questions exist whose outcome is not already determined by a specification of the finest grained state description we can offer?... Or again, why isn't one bit enough?... it has not been explained why the state of an elementary system cannot specify an answer to all experimental questions: this does not in fact appear to follow from the Foundational Principle. The Foundational Principle says nothing about the structure of the set of experimental questions, yet this turns out to be all-important." [33]

And Timpson unveils another fundamental flaw in the Foundational Principle:

[9] As cited by Olimpia Lombardi in [31].
[10] Statements from the *Quantum Physics of Nature* meeting in Vienna. http://arxiv.org/abs/quant-ph/0505187v4.

"… Of course, if one assumes that experimental questions are represented in the quantum way, as projectors on a Hilbert space, then even for the simplest non-trivial state space, there will be non-equivalent experimental questions, the answer to one of which will not provide an answer to another; but we cannot assume this structure if it is the very structure that we are trying to derive."… It appears from the way in which the Foundational Principle is supposed to be functioning in the attempted explanation of randomness, that something like the quantum structure of propositions is being assumed. But this is clearly fatal to the prospects of the Foundational Principle as a foundational principle." [33]

There are flawed criticisms as well. Shafiee et al [35] make two major points: (1) "The finiteness of information does not explain how objective results appear in experiments and what an instantaneous change in the so-called information vector (or catalog of knowledge) really means during the measurement."; and (2) they challenge Brukner/Zeilinger assertion:

"Independent of the various possibilities to encode information, the total information content of the system cannot fundamentally exceed the maximal possible amount of information that can be encoded in an individual observable." [32]

To that effect, Shafiee et al assumed the detector for a ½-spin had an efficiency $\eta < 1$ in all directions and that the spin initial State was along the x-axis. They then treat the qubit as a qutrit with probabilities of 'non-detection' given by $p_{x3} = p_{y3} = p_{z3} = 1 - \eta$. Hence: $p_{x1} = \eta$; $p_{x2} = 0$; $p_{x3} = 1 - \eta$; $p_{y1} = p_{y2} = \eta/2$; $p_{y3} = 1 - \eta$; $p_{z1} = p_{z2} = \eta/2$; $p_{z3} = 1 - \eta$. Note that the maximum encodable information is now $log_2 3 \cong 1.585$ bits. Nonetheless, to determine I_{total}, the authors calculated $I(\vec{p}_i),\ i = x, y, z$, arriving at $I_{total} = 3log_2 3/2\,(5\eta^2 - 6\eta + 2))$. They finally pointed out that, for $0 < \eta < 0.29$ and $0.91 < \eta < 1$, $I_{total} > 1.585$ bits. This is because the coefficient $3log_2 3/2 \cong 2.378$ remains valid $\forall\, \eta < 1$, while jumping discontinuously to $2log_2 2/2 = 1$ for $\eta = 1$. Hence, they conclude:

… Brukner and Zeilinger's definition of a new measure of information may lose its significance, when the spin measurement of an elementary system is treated realistically. Hence, the sum of the individual measures of information may not be a conserved value in real experiments." [35]

I am now compelled to strongly defend Brukner and Zeilinger because the authors' reasoning is multiply flawed. Starting from the least to the most serious defect: first, despite treating the qubit as a qutrit (State-Space $n_D = 3$), to calculate I_{total} as defined by Brukner/Zeilinger four unbiased conjugate 'measurements', i.e. four $I(\vec{p}_i), i \in \{1,2,3,4\}$ must be used, while Shafiee et al only used three of them (I_x, I_y, I_z); second, the authors erroneously assumed that the three perpendicular directions are still a complete set of unbiased 'measurements' so that, even if a fourth conjugate I_4 were added, measurements along the axes x, y, and z would not make sense near $\eta = 1$. This is because I_4 must be equal to $log_2 3 - 3log_2 3(5\eta^2 - 6\eta + 2)/2 = log_2 3(-15\eta^2/2 + 9\eta - 2)$, which is negative $\forall\, \eta > \sim 0.91$ – when actually all I_i are to be squared differences and, ergo, always positive. Being $n_D = 3$ prime, the 4 unbiased measurements do exist for every η but they do not necessarily include those along the three orthogonal axes.

Finally, the third and most serious mistake makes the other two irrelevant: it is precisely to believe that the inefficiency of our detectors could drastically morph the very physical nature of a ½-spin quantum object (a qubit) into a qutrit. The object is a qubit regardless of the imperfection of our instruments, so recalculating everything as such we obtain $I_x = 2\eta^2 - 2\eta + 1$; $I_y = I_z = \eta^2 - 2\eta + 1$ and ergo $I_{total} = \sum_1^3 I_i = 4\eta^2 - 6\eta + 3$. All of them now behave correctly in the neighborhood of $\eta = 1$: $I_x \sim 1$ bit (the initial spin was assumed along the x-axis); $I_y = I_z \sim 0$ bits; and $I_{total} \sim 1$ bit for all complete sets of unbiased measurements. Shafiee et al finish with:

> "… *information* is treated as the base for quantum physics in this interpretation. So, how can one reformulate the quantum dynamics with a notion of information which seems to be not physical in its essence?... Could the universe primarily be made of *information*? And if so, how does matter emerge from *information*?" [35]

3. The Answer to Zeilinger's "Very Fundamental Question": QR/TOPI

We will now answer Zeilinger's "very fundamental question" by reviewing in the light of QR/TOPI various experimental epitomes of quantum quirkiness, whose proposed physical meanings to date, if not stranger than the phenomena themselves, are incoherent, contrived, and highly debated. Examples of explanatory catchphrases are 'wave-particle duality' 'many-worlds', 'interaction-free detection', 'availability of path-information', 'retrocausality', 'erasing the past', 'changing the real trajectory of a photon millions of years ago', and whatnot.

It is paramount to keep in mind that under QR/TOPI, the ITIs of PTIs are fully reciprocal: they are relations among probabilities for the quanton's probable states; ergo, they may not conform to an IF-invariant *chronicle*. A *chronicle* involving spacelike PDI-Events is only valid for a particular IF, giving us the false impression of a better understanding (it pleases our prejudices) – while deceitfully disappointing us when it does not work for other IFs. But, as 'TOPI' in 'QR/TOPI' indicates, it is precisely those **a**temporal probabilities the ones that are ontic, objective, and absolute, i.e. valid regardless of the basis in Hilbert Space, of the IF, and of whether the GI-Events statistically revealing those probabilities are spacelike-separated or not [25].

3.1 Young's Experiment per Deutsch, Vaidman, Carroll, Tegmark, Wallace, Bruce…

David Deutsch [38], Lev Vaidman [39], Sean Carroll [40], David Wallace [41], Max Tegmark [42], and Colin Bruce [6] are supporters of MWI initially proposed by Hugh Everett in 1957, and to which Deutsch refers as the 'Multiverse'. To explain interference in the double-slit experiment, in his 1997 book 'The Fabric of Reality' [38], Deutsch introduces the notion of *tangible* and *shadow* particles, soon after disregarded as pedagogical, with a bold statement about himself:

> "Many of those Davids are at this moment writing these very words. Some are putting it better. Others have gone for a cup of tea."

And, using the homology between the double-slit set up and the MZI [24], Deutsch explains: "In all universes in which the experiment is done, the photon and its counterparts are traveling towards the interferometer along the same path… But as soon as the photon strikes the semi-silvered mirror [1st BS], the initially identical universes become differentiated. In half of them, the photon passes straight through and travels along the top side of the interferometer. In the remaining universes, it bounces off the mirror and travels down the left side of the interferometer… Thus they end up arriving simultaneously at the semi-silvered mirror on the bottom right [2nd BS] and interfere with one another… The versions of the photon in these two groups interfere strongly. The net effect depends on the exact geometry of the situation, but Figure 9.3 shows the case where in all universes the photon ends up taking the rightward-pointing path through the mirror, and in no universe is it transmitted or reflected downwards. Thus all the universes are identical at the end of the experiment, just as they were at the beginning." [38]

And, from above, he -with an unfathomable degree of confidence- concludes:

> "This remarkable non-random interference phenomenon is just as inescapable a piece of evidence for the existence of the multiverse as is the phenomenon of shadows. For the outcome that I have described is incompatible with either of the two possible paths that a particle in a single universe might have taken." [38]

Similar surprising states of confidence were shown by Carroll and Wallace when interviewed by Anil Ananthaswamy in his book *Through two Doors at Once* [43]. The author recounted: "To Carroll, worrying about the number of worlds is fruitless. "Let's grow up and move beyond that", he said." As for Wallace, after referring to Everett's interpretation as "crazy", he said to the author: "the attraction for me is that it's extremely conservative". Flabbergasting!

3.2 Young's Experiment under Zeilinger's Foundational Principle

About Young's experiment (Figure 1, photographic plate ***on***), Brukner and Zeilinger stated:

> "… It is argued here that quantum interference is a consequence of the finiteness of information. The observer has the choice whether that information manifests itself as path information or in the interference pattern or in both partially to the extent defined by the finiteness of information… In these experiments the loss of interference is due to the fact that path information is available, in principle, independent of the fact whether the experimentalist cares to read it out or not." [20]

Based on their measure of information for a qubit as defined in Equation 2, they assume the qubit first interacted with a Milieu $M1$ (e.g. a generic BS) characterized by:

$$M1\begin{cases} |s\rangle = s_1 e^{i\theta}|s_1\rangle + s_2|s_2\rangle \quad s_1, s_2, \theta \in \mathbb{R} \\ p_{11} = s_1^2 \;\; ; \;\; p_{12} = s_2^2 \;\; ; \;\; \boldsymbol{I_1} = (p_{11} - p_{12})^2 = 2\sum_{i=1}^{2}(p_{1i} - 0.5)^2 = 1 - 4s_1^2 s_2^2 \end{cases} \tag{5}$$

We see that *information* I_1 ranges from 0 bits when $p_{11} = p_{12} = 0.5$ to 1 bit when one of the two probabilities is unity. In between the latter two fully biased PDs, are the former fully unbiased and a continuum of partially biased PDs. In Zeilinger's lexis, when $I_1 = 0(1)$ bits we have no(full) *knowledge* of the quanton's path; and when $0 < I_1 < 1$ bits, we have a degree of *knowledge*. Under QR/TOPI our *knowledge* is irrelevant: regardless of $|s\rangle$ being ontically actual or probable, $|s_1\rangle$ and $|s_2\rangle$ are ontically probable unless s_1 or s_2 are unity or nil – in which case the ontic actual/probable character of $|s\rangle$ is transferred to $|s_1\rangle$ (if $s_1 = 1$) or to $|s_2\rangle$ (if $s_2 = 1$) [24] [25].

Brukner/Zeilinger also let the quanton interact with Milieu $M2 \supset M1$, consisting of probable states $|s_1\rangle$ and $|s_2\rangle$ under $M1$ entering a 50/50 symmetric BS, so the new representation for the same quanton's State $|s\rangle$ becomes:

$$M2\begin{cases} |s\rangle = s_{21}|s_3\rangle + s_{22}|s_4\rangle = \frac{\sqrt{2}}{2}\{s_1 e^{i\theta} + s_2 i\}|s_3\rangle + \frac{\sqrt{2}}{2}\{s_1 i e^{i\theta} + s_2\}|s_4\rangle \;\; s_{21}, s_{22} \in \mathbb{C} \\ p_{21} = \frac{1}{2}\{1 - 2s_1 s_2 \sin\theta\}\,; p_{22} = \frac{1}{2}\{1 + 2s_1 s_2 \sin\theta\}\,; \boldsymbol{I_2} = (p_{21} - p_{22})^2 = 2\sum_{i=1}^{2}(p_{2i} - 0.5)^2 = 4s_1^2 s_2^2 \sin^2\theta \end{cases} \tag{6}$$

Now the two probabilities depend on the phase θ, and I_2 ranges from 0 bits when s_1 or s_2 is zero or when $\theta = 0, \pi$, to a maximum of one bit when $|s_1| = |s_2|$ and $\theta = \pi/2, 3\pi/2$, i.e. when $|s_1\rangle$ and $|s_2\rangle$ are in quadrature. The first alternative for $I_2 = 0$ corresponds to only one slit open (ergo $I_1 = 1$) with the fraction s_2^2 (or s_1^2) of the total number of photons distributing 25% in each path of the second BS. In Zeilinger's lingo, the full *knowledge* of its path prevented *interference* (probabilities directly summed). The second alternative corresponds to $|s_1\rangle$ and $|s_2\rangle$ being in full phase or in contra-phase, making $|s_3\rangle$ and $|s_4\rangle$ to be in quadrature and each detector clicking again half the time ($p_{21} = p_{22} = 0.5$). But per Zeilinger, because $0 \leq I_1 < 1$ we have only partial or no path *knowledge,* so some or full interference should occur; however, $I_2 = 0$. For I_2 to be non-zero, s_1, s_2, and $\sin^2\theta$ must be non-zero producing different degrees of interference up to a maximum of 1 bit. In the latter case, being $|s_1\rangle$ and $|s_2\rangle$ in quadrature, $|s_3\rangle$ and $|s_4\rangle$ are in phase or contra-phase, producing fully constructive or destructive interference, with a continuum of intermediate cases in between. Except for the mentioned case, I_2 seems to be a measure of *interference* and if, as Zeilinger does, you believe that the notion of 'which-path' is sensible, then I_1 is its measure.

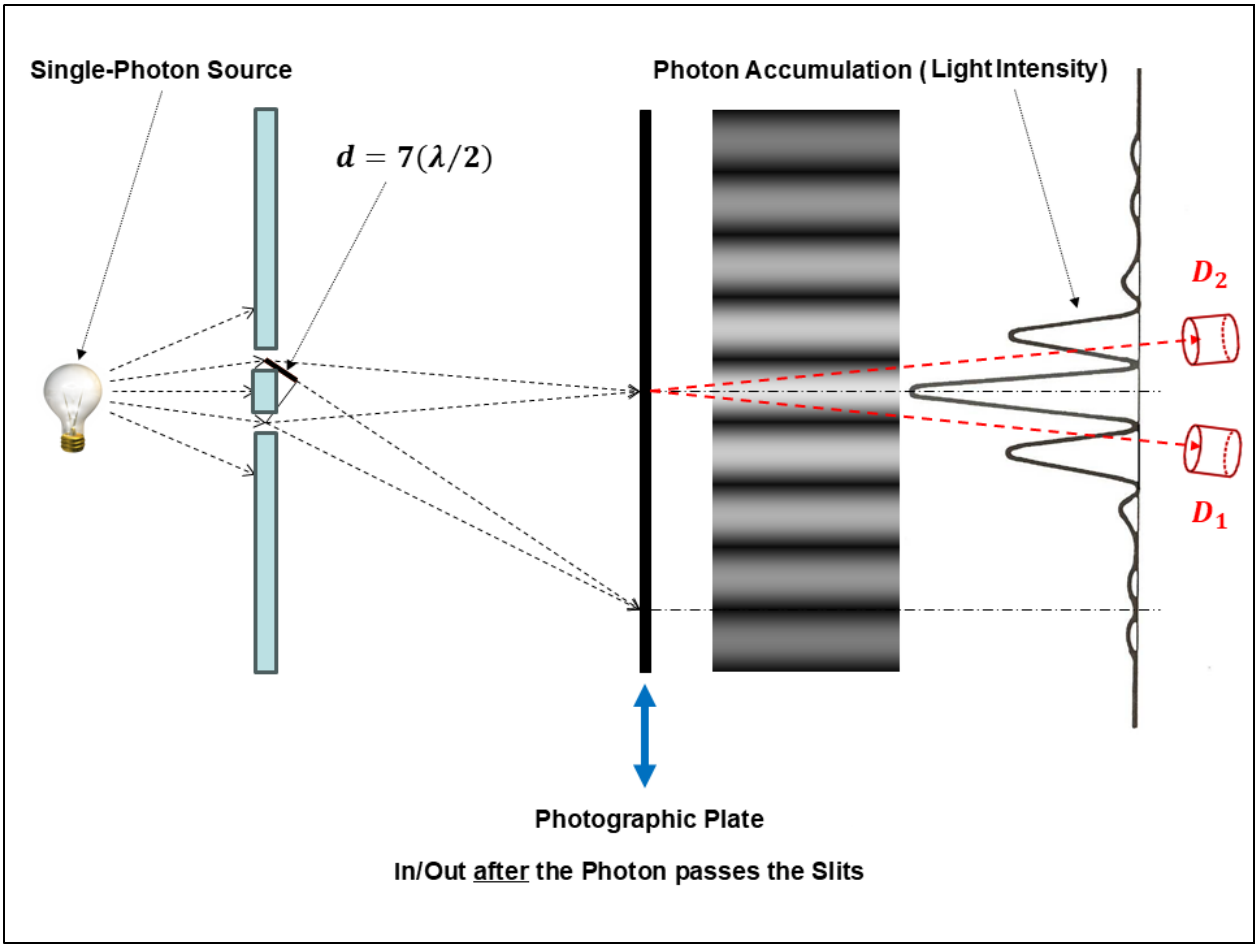

Figure 1: Standard and Wheeler's Delayed-Choice Double-Slit Experiment (Graphics from [25])

Note as well that when $I_1 = 1$ bit ('path fully known'), $I_2 = 0$ bits (no interference) but when $I_1 = 0$ bits ('no knowledge' of the path), I_2 is not inevitably equal to 1 bit. Finally, Brukner and Zeilinger know that to arrive at their total information content, they need one more Milieu with the specific property that when summed up with the other two amounts to 1 bit (a single qubit). So they define $M3$ with the same topology as $M2$ but with a different phase $(\theta + \pi/2)$. Therefore:

$$M3\begin{cases} |s\rangle = s_1 e^{i(\theta+\frac{\pi}{2})}|s_1\rangle + s_2|s_2\rangle = \frac{\sqrt{2}}{2} i\{s_1 e^{i\theta} + s_2\}|s_3\rangle - \frac{\sqrt{2}}{2}\{s_1 e^{i\theta} - s_2\}|s_4\rangle \\ p_{31} = \frac{1}{2}\{1 + 2s_1 s_2 \cos\theta\}; p_{32} = \frac{1}{2}\{1 - 2s_1 s_2 \cos\theta\}; \boldsymbol{I_3} = (p_{31} - p_{32})^2 = 2\sum_{i=1}^{2}(p_{3i} - 0.5)^2 = 4s_1^2 s_2^2 \cos^2\theta \end{cases} \quad (7)$$

Clearly all we said for $M2$ is now valid for $M3$ if we change 0 with $\pi/2$ and π with $3\pi/2$. Notice also that $I_2 + I_3 = 4s_1^2 s_2^2 = 1 - I_1 \; \forall\theta$, so they arrived at the desired relationship:

$$\sum_{i=1}^{3} \boldsymbol{I_i(\vec{p})} = (\boldsymbol{p_{11} - p_{12}})^2 + (\boldsymbol{p_{21} - p_{22}})^2 + (\boldsymbol{p_{31} - p_{32}})^2 = \mathbf{1} \quad \forall \; |\boldsymbol{s}\rangle, \boldsymbol{M1}, \boldsymbol{M2}, \boldsymbol{M3} \quad (8)$$

Whether or not *information* is a foundational principle, the above rationale allows for a full understanding of Bruckner and Zeilinger quoted assertion using the informational language. Their statement that "the loss of interference is due to the fact that path information is available" is of course debatable because they assert that such "loss" is caused by the "availability of path information" – as if the latter was physically there for us to grab. If it is, then they are right in that whether "the experimentalist cares to read it out or not" is immaterial. But then, information is more than just *knowledge*. Besides, we proved that $I_1 = 0$ does not imply $I_2 = 1$. They say:

> "… It is obvious that this can be extended to much more complicated situations, as for example to the notion of quantum entanglement [16]. From a fundamental perspective, this approach suggests that the most basic notion of quantum mechanics is *information*." [20]

Again, they replaced the quanton's State with its equivalent 'total information'. Ergo, its extension to other situations is a sequitur, while inferring it is "the most basic notion" is not.

3.2.1 "Wave-Particle Duality" of C_{60} Molecules

The above is the title of a multiply authored (including Zeilinger) paper proving that a molecule with 60 carbon atoms (despite its size, many internal degrees of freedom, and its coupling with the environment) exhibits *interference*. The fullerenes were sublimated at temperatures 900 K to 1000 K, collimated and made passed a grating with 50 nm-wide slits, a spatial period of 100 nm, and registered 1.2 m away with a spatially resolving detector [44]. The C_{60}'s de Broglie wavelength is ~2.76 pm, a few hundred times smaller than its diameter (~0.71 nm). The authors say:

> "…'which-path' information could be given by the molecules in scattering or emission processes, resulting in entanglement with the environment and a loss of interference. Among all possible processes, the following are the most relevant: decay of vibrational excitations via emission of infrared radiation, emission or absorption of thermal blackbody radiation over a continuous spectrum, Rayleigh scattering, and collisions… As shown above, the wavelengths involved are too large for single photon decoherence. Also, the scattering rates are far too small to induce sufficient phase diffusion. This explains the decoupling of internal and external degrees of freedom, and the persistence of interference in our present experiment." [44].

Brukner and Zeilinger also discussed the fullerenes in their paper on Young's experiment [20]. They wondered why *interference* existed if their emitted photons could be used "to trace the path of the fullerene". With basic reasonable assumptions, Brukner and Zeilinger calculated the *interference* visibility (V) from the inner product between the states of the emitted photons from the two paths (they serve as detectors) arriving at $V = |\sin Kd/Kd|^N$, where K is the photon's wavenumber ($\sim 0.1\mu m^{-1}$), d the distance between slits ($0.1\mu m$), and N the number of photons (2 or 3). Using these values, the visibility is $V = |\sin 0.01/0.01|^3 = 0.99997$, i.e. *interference* is unaffected, which they explained via the invariance of their information content:

> "The wavelength of the emitted photons is typically of the order of a few micrometers, which has to be compared to the path separation, which is much lower. Therefore, the states of the two photons emitted by a fullerene on either of the interfering paths are nearly identical, implying that the photons carry virtually no information into the environment." [20]

I surmise they mean: if the photons "carry" ***no*** *information* out of the fullerene, its information content (I_1) does not change, leaving I_2+I_3 and ergo the *interference* unchanged for any given arbitrary θ. Under QR/TOPI, we say that the emission of a few infrared photons while the fullerene travels to the intended detector does not constitute an intermediate PDI – which would prematurely convert its ontically probable states into one actual, thwarting *interference* [24] [25].

3.3 The Delayed 'Quantum Eraser' per Wheeler, Zeilinger, Greene…

Figure 1 schematizes two milieus; in black: a movable photographic plate is ON; in red: the photographic plate is OFF allowing one of two focused photodetectors to click. John A. Wheeler stated in 1978: "In the one case [black] the quantum will transform a grain of silver bromide and contribute to the record of a two-slit interference fringe. In the other case [red] one of the two counters will go off and signal in which beam—and therefore from which slit—the photon has arrived." [45]. Similarly, in 2004, Zeilinger said:

> "The important conclusion is that, while individual events just happen, their physical interpretation in terms of wave or particle might depend on the future; it might particularly depend on decisions we might make in the future concerning the measurement performed at some distant spacetime location in the future." [15]

The fallacy in those excerpts is that, with the black Milieu the quanton goes through the two slits like a wave contributing to an interference pattern, while with the red Milieu which detector clicks indicates which slit the quanton goes through like a particle. But then -if true- by delaying the choice of Milieu in each run, e.g. by suddenly inserting the photographic plate time-after the photon has passed (supposedly) through one of the slits, the interference pattern (so they say) could ***not*** develop – unless *retrocausality* was at play 'erasing' the past particle-behavior and making the photon pass through both slits. Mutatis mutandis for the plate's sudden removal. QR/TOPI does not need *retrocausality* or the anthropic concept of *information* to explain it "in a basic way" [24] [25]. There is nothing to 'erase': suddenly including the photographic plate is a Milieu-Event [25] that -besides adding a new PDI- instantly changes the PTI for the quanton – together with its inherent ITI amongst its probable states. Probability is ontic, reciprocal, **a**spatial, and **a**temporal.

And regarding Wheeler's famous quasar-galaxy argument, Zeilinger was quite less careful:

> "We decide, by choosing the measuring device, which phenomenon can become *reality* and which one cannot. Wheeler explicates this by example of the well-known case of a quasar, of which we can see two pictures through the gravity lens action of a galaxy that lies between the quasar and ourselves. By choosing which instrument to use for observing the light coming from that quasar, we can decide here and now whether the quantum phenomenon in which the

photons take part is interference of amplitudes passing on both sides of the galaxy or whether we determine the path the photon took on one or the other side of the galaxy." [16]

Our experimental decision "here and now" cannot affect whether a photon emitted millions of years ago "passes on both sides of the galaxy" or goes via only one side. I accept that a new better physical theory to be obtained in the future could make us reinterpret what happened in the past, but I reject that, depending on what Milieu we could subject the quanton to in the future, the physical interpretation given by one theory of what that quanton did in the past can be different. Under the very same theory, the physical interpretation of what actually happens now and here cannot depend on our future experimental caprice. This fallacy results from insisting for a century on the 'wave-particle duality' paradigm. Under QR/TOPI, quantons are neither *waves* nor *particles*: any physical interpretation in terms of wave or particle is doomed to failure by deceiving us into mistakenly accepting *retrocausality* (with the only purpose of not rejecting our prejudices).

On a more elaborated experiment introduced by Scully and Drühl in 1982, Brian Greene says in Section "Erasing the Past" of his book *The Fabric of the Cosmos*:

"If you can't change something that has already happened, can you do the best next thing and erase its impact on the present?... The quantum eraser, first suggested in 1982 by Marlan Scully and Kai Drühl hints at this kind of strangeness in quantum mechanics." [46]

Figure 2 sketches a possible implementation of the alluded experiment, which includes a PF (PTI) before the double-slit screen, retains the photographic plate (PDI) plus a polarization analyzer (PDI), and considers three Milieus (PTIs) for the photon to undergo time-before the PDIs. The first PF (common to all Milieus) simply assures the photon entering the double-slit screen has a fixed linear polarization [24]. Choosing a 45° PF maximizes both the vertical and horizontal components delivered by the two orthogonal PFs included right after the slits in Milieus II and III.

We formally analyzed this experiment in [25] showing there is nothing more here than the well-known fact that two PFs (PTIs) with orthogonal optic axes stop light, while inserting a third PF with a diagonal optic axis between them lets light to go through [24]. For Milieu I, we found:

$$Pr(Click/|s\rangle) = Pr(Click/|s_1'\rangle)\,Pr(|s_1'\rangle) + Pr(Click/|s_2'\rangle)\,Pr(|s_2'\rangle) + \boldsymbol{Interference}$$

As we know from [24] [25], the first(second) term is the probability for the detector to click if the lower(upper) slit is closed (red-dotted curves), while their sum corresponds to the click-probability when both slits are open but with a non-destructive PDI interacting with $|s_1'\rangle$ or/and $|s_2'\rangle$ before the photographic plate (red-solid curve). However, except for the photographic plate/polarization analyzer, Milieu I includes ***no*** PDI and that is why there is interference (black-solid curve). Formally analyzing Milieu II in [25] we found:

$$Pr(Click/|s\rangle) = Pr(Click/|s_1''\rangle)\,Pr(|s_1''\rangle) + Pr(Click/|s_2''\rangle)\,Pr(|s_2''\rangle) \Rightarrow \boldsymbol{No\ Interference}$$

As before, each term in the above sum (red-solid curve on the right) corresponds -for different positions in the photographic plate- to each one of the red-dotted curves. Upon repetition, they can be isolated from the solid PD by separating vertical from horizontal polarization data-points in the dataset. But now, due to the orthogonality betwixt the PFs' axes, there is ***no*** interference.

We also see that, after the 'H' and 'V' polarizers, the probable spatial State $|s_1''\rangle$ is associated with the *horizontal* polarization State, while $|s_2''\rangle$ is so with the *vertical* polarization State. Greene, like most physicists/philosophers, says that we have effectively 'marked' or 'tagged' the photon because by measuring its polarization at the detector's site, we could determine which slit the photon went through. So he asserts in [46]:

> "The new tagging devices allow which-path information to be gleaned, and which-path information singles out one history or another; the data show that any given photon passed through either the left slit or the right slit. And without the combination of left-slit and right-slit trajectories, there are no overlapping probability waves, so no interference pattern is generated."

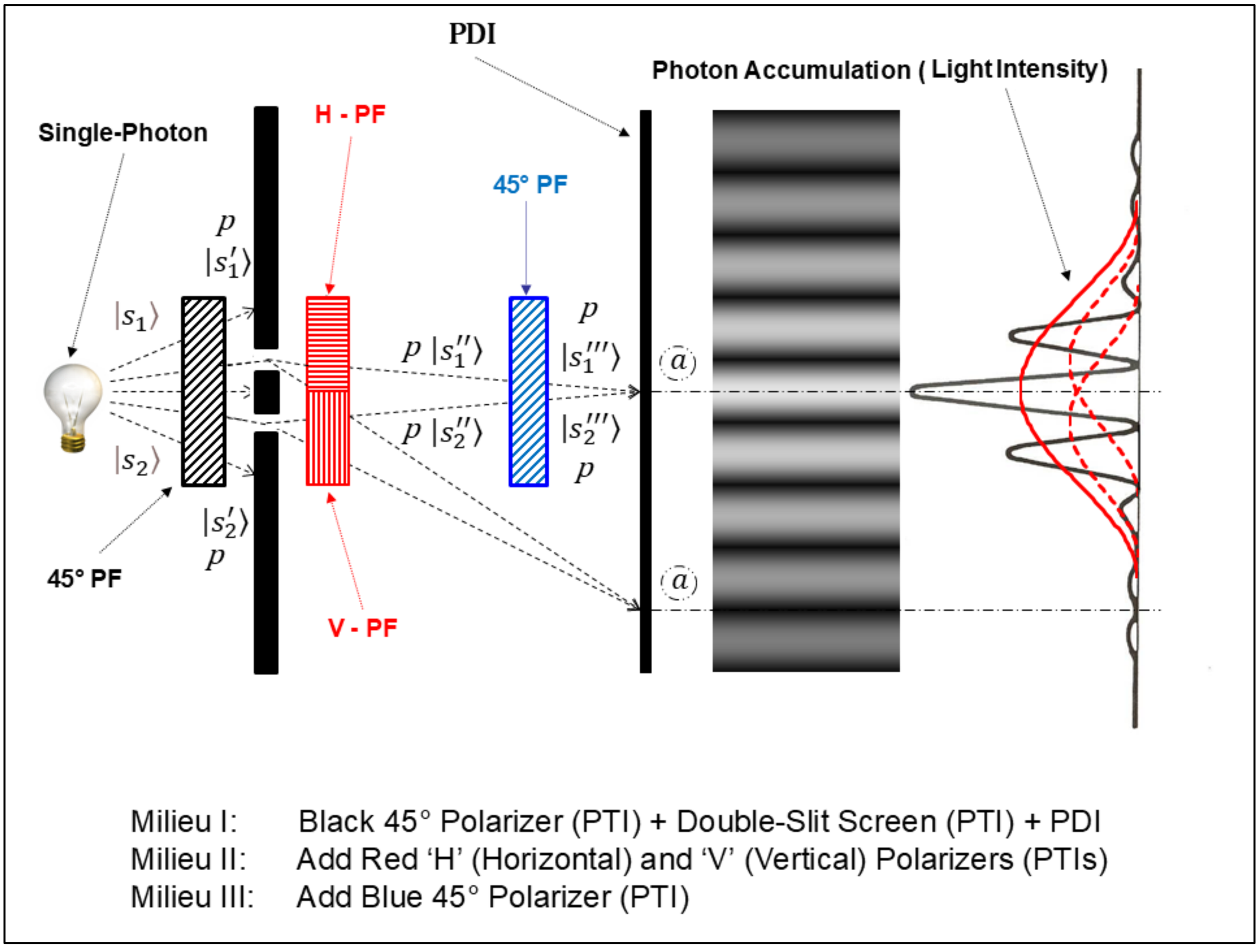

Figure 2: Alleged "Marking/Erasing" of "Which-Slit Information" (Graphics from [25])

Presuming the empirical data indicate the photon's past trajectory, Greene committed the same error Wheeler and Zeilinger did. Greene continues the information-narrative and wonders: *What if, just before the photon hits the detection screen, you eliminate the possibility of determining through which slit it passed by erasing the mark imprinted by the tagging device?* In [25] we proved for Milieu III that the interference cross-terms reappear because both spatial eigenstates $|s_1'''\rangle$ and $|s_2'''\rangle$ share the same polarization as $|s_1'\rangle$ and $|s_2'\rangle$ in Milieu I:

$$Pr(Click/|s\rangle) = Pr(Click/|s_1'''\rangle)\,Pr(|s_1'''\rangle) + Pr(Click/|s_2'''\rangle)\,Pr(|s_2'''\rangle) + \boldsymbol{Interference}$$

With very few exceptions, most physicists/philosophers erroneously agree that the function of another 45° PF (blue in Figure 2) acting on both paths is to 'erase' the which-way information and, ergo, 'explaining' why *interference* reappears. But such a stance opens again the door to *retrocausality* because -per their own doctrine- the photon must now behave as a *wave* (passing through the two slits when it is already too late). Once again, per QR/TOPI, the difference between all three Milieus only involves PTIs, which transform (via their ITIs) the quanton's ontic probable states in different ways. The onset of a new ITI is absolutely *simultaneous* with the Milieu-Event that sets the new PTI, so it only needs to be done right-before the PDI (the photographic plate plus the polarization analyzer). Nothing to erase in the past: the quanton is neither a wave nor a particle. Its current State and Milieu determine the PD for its next State [25].

3.4 Interferometric 'Interaction-Free' Bomb Detection: Vaidman/Bruce/Zeilinger

Colin Bruce describes in his book "Schrödinger's Rabbits" the Elitzur-Vaidman's "interaction-free bomb detector" [6] [39]. From our discussions in [24], by inserting a non-destructive PDI in one of the branches of the MZI, whether it clicks or not, one of the quanton's prior probable states before entering the second BS is actual and, ergo, if both BSs have split-ratio $a = 0.5$, the probability of firing for the 'bright' detector goes down from 100% to 50%, while the probability of firing for the 'dark' detector increases from 0% to 50%. Thus, whether the inserted PDI clicks or not, the efficiency of detecting its presence is $\eta = Pr\ (dark)/(Pr(dark) + Pr\ (Click)) = 0.5$. If, instead, the inserted PDI is destructive (fully absorbing or scattering the photon or, say, serving as a bomb detonator), only 50% of the photons can reach the second BS and the firing probability for the 'bright' detector goes down to 25% and that of the 'dark' detector goes up to 25%. Hence, $\eta = Pr\ (dark)/(Pr(dark) + Pr\ (blast)) = 0.25/(0.25 + 0.5) = 1/3$. Because a click of the 'bright' detector means nothing for the existence of the destructive PDI (bomb), this efficiency indicates that out of a large number of runs only 75% of them mean something: in 50% of the runs the bomb explodes and in 25% of them the 'dark' detector clicks sans a blast, signaling the existence of the bomb. Using **a**symmetrical BSs, the efficiency may increase up to 50% [25].

The term 'interaction-free' for a non-evincing PDI-Event (no blast) is commonly used, albeit incorrect because: (a) only if the inserted object is fully opaque, any photon detected by the otherwise 'dark' detector could be said to have 'gone' the other 'route'; and (b) per QR/TOPI, 'no-click' events are as real as 'click' ones, so the photon always interacts with the whole Milieu (both 'routes'). Even so, Bruce asks another variant of Zeilinger's "very fundamental question": "How can a photon that never went near the detonator tell us whether it is present?" And, while stressing the bomb detection's low efficiency, he resorts to the work of a respected "arch-opponent" to subtly imply that the only way to answer such a question is by means of MWI: "... It is ironic that a much more effective method has been devised and demonstrated by one of the arch-opponents of many-worlds, Anton Zeilinger" [6]. Bruce refers to the collaborative work between Los Alamos National Laboratory and Zeilinger's group at the University of Innsbruck [47].

3.4.1 Los Alamos/Innsbruck High-Efficiency Bomb Detection

In 1999 those two research groups showed how to obtain theoretical efficiencies close to 100% for the 'interaction-free' detection of the non-transmitting object (bomb), with practical values reaching 85%. They refer to their technique as a combination of Elitzur-Vaidman interferometric ideas with an application of the Quantum Zeno Effect [47]. In our QR/TOPI lingo, it corresponds to a recurring pure transformation of the quanton's actual State by means of the spatial probable states created by a PTI (MZI) and sustained by its ITI – unless the insertion of a PDI (bomb) in one of its arms randomly converts one of the probable states into actual, destroying their otherwise *coherence* and -upon exiting the MZI with no blast- going back to its original State.

Figure 3 depicts their conceptual schematic. An optic circuit is created by four (outer) mirrors in which a photon with horizontal ($|H\rangle$) polarization (blue) is somehow inserted and extracted after N cycles of clockwise circulation. In each cycle a polarization rotator (PTI) adds an angle $\Delta\theta = \pi/2N$ (blue) clockwise so that, because the polarizing MZI (top-right corner) does not change the photon's polarization [24], when extracted after N cycles its polarization is $N\pi/2N$, viz Vertical (green). Per QR/TOPI lexis, this is a global GI to which we refer as GI-NB (Milieu with No Bomb). Note that for all cycles, the photon has two co-extant probable states (blue 'p') inside the MZI and a single actual State outside the MZI (blue 'a').

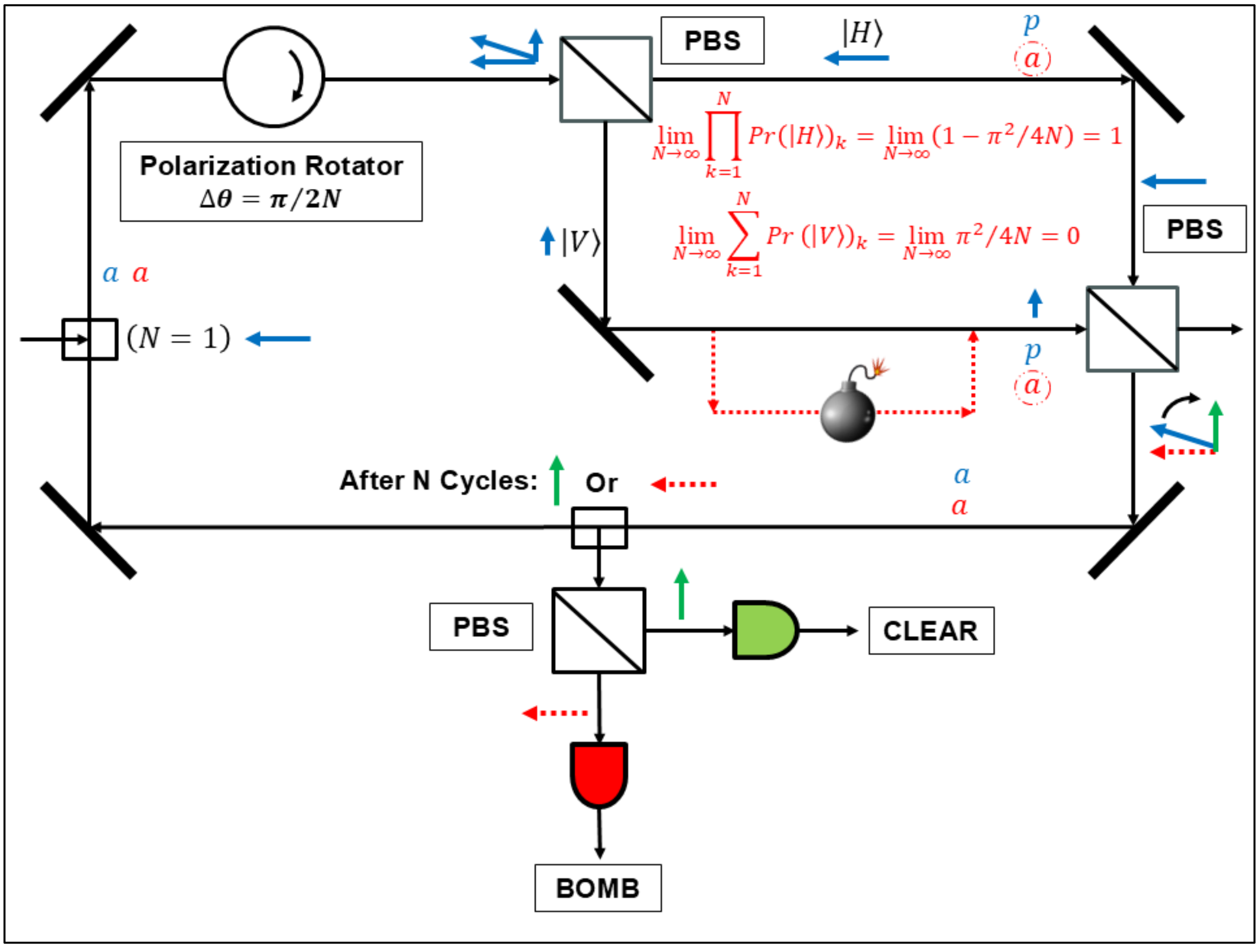

Figure 3: High-Efficiency "Interaction-Free" Bomb Detector (Graphics from [25])

But if the Milieu is changed to include the bomb (GI-B in dotted-red), whether exploding or not, the two co-extant probable states morph into a single actual one (dotted-encircled red 'a'), so the photon -if there is no blast- returns to its original polarization $|H\rangle$ irrespective of in which of the N cycles the Milieu-Event [25] occurred. Hence, subjecting the extracted photon to an external PBS, the non-existence/existence of a non-detonated bomb can be determined unambiguously: if $|V\rangle \Rightarrow$ No Bomb (GI-NB); if $|H\rangle \Rightarrow$ Bomb (GI-B). In [25] we proved that, in the ideal lossless case, the efficiency of this 'interaction-free' detection of the bomb is 100%. Going back to Bruce's "Schrödinger's Rabbits", given that the photon could meet the bomb in any cycle, the probability for a blast after N roundtrips is $Nsin^2(\pi/2N)$. Hence, if the photon's polarization rotates 1° each time, the odds of a blast after 90 trips are ~1/36 ($\{90 \cdot sin^2(1°)\}^{-1}$), and Bruce attempts to defend MWI by perplexingly portraying Nature's behavior as an anthropic 'impressive achievement':

> "We have achieved something even more impressive than exchanging information between one world and another. We have in some sense communicated a bomb warning from a small set of worlds where the bomb detonated to a set 36 times larger that remains safe." [6]

Obviously, Bruce firmly believes that Reality is nothing but *evincing* Actuality (***no*** Sherlock Holmes' dogs [25], much less ontic probabilities), so that the only way for us to know that something bad could have happened and in fact did not is for the latter 'worlds' (ours and another 35 more!) to receive a "warning" message from the (proportionally speaking) single 'world' in which the calamity did occur. In what possible sense is that a 'warning'? Unfathomable indeed.

3.5 Resonance 'Interaction-Free' Bomb Detection: Paul/Pavĭcić/Bruce

A properly designed (geometry/refractive index) block of transparent material can trap a high-intensity light wave -via Total Internal Reflection (TIR)- in a circulating path for considerable time. The condition for TIR is that all light incident angles θ inside the block verify $sin\theta > n_O/n_I$, with n_I the interior and n_O the exterior refractive indexes ($n_I/n_O > 1.41$ for a square ring). The light beam can be injected to and extracted from the crystal block with negligible losses (~0.3%) by partially 'frustrating' the TIR (FTIR) through optical tunneling from/to other blocks.

Dimming light intensity to the single-photon regime, Harry Paul and Mladen Pavĭcić in 1997 showed that "with an efficiency exceeding 99% one can use a monolithic total-internal-reflection resonator [MOTIRR] in order to ascertain the presence of an object [bomb] without transferring a quantum of energy to it." [48] [49]. Figure 4 is a conceptual drawing. The in/out tunneling of light is achieved by $P1$ and $P2$ FTIR prisms, whose tiny gaps/minimal reflectivity at their entrance/exit surfaces -plus the polarization of the incident beam- determine the reflectivity $R1$ towards detector 'B' (purple) and the transmissivity $(1 - R1)$ into and $(1 - R2)$ out of the monolith into detector 'NB' (green). The range $(10^{-5}, 0.99995)$ for reflectivity is doable. With high-intensity light and the optic ring's length being a multiple of light's wavelength, resonance (constructive interference) occurs. The bomb is submerged in a liquid of the same refractive index as the monolith.

Per QR/TOPI lexicon, we have two global GIs: GI-NB comprising of the MOTIRR, the two FTIR prisms, and the 'B' (purple) and 'NB' (green) detectors; and GI-B which includes the bomb inside the liquid cavity – with its labels and equations in red. Four sub-PTIs exist: the left prism/block coupling constitutes PTI-1 (a BS with two inputs and two outputs); the right prism/block coupling constitutes PTI-2 (a BS with one input and two outputs); reflector PTI-3; and reflector PTI-4. Being the bomb a Destructive detector (D-PDI), when the Milieu is GI-B, the optic feedback path breaks, light never undergoes PTI-4, and PTI-1 has only one input ($|s\rangle$). In sum, GI-NB has one input ($|s\rangle$) and two outputs; GI-B has the same single input but three outputs.

When a single photon enters GI-B [24] [28] [29] [30], the steady-state high-intensity ratios become probabilities for detection events (PDIs) while, between the latter, i.e. while the quanton undergoes PTIs, the probability *amplitudes* (the components of the quanton's probable states) are the ones that intermingle per the ITI characteristic of the network topology. In plain words: the probabilities predicted via QR/TOPI for the single-photon regime should agree with the detected intensity ratios for the high-intensity steady-state regime. We proved in [25] that calling I the high-intensity steady-state amplitude for the Incident wave and B the amplitude at the B-detector we have $|B|^2/|I|^2 = R_1$; $|NB|^2/|I|^2 = (1 - R_1)(1 - R_2)$; and the intensity ratio reaching the bomb is $(1 - R_1)R_2R_3$. For instance, if $R_1 = R_2 = 0.99$ and $R_3 = 1$, then 99% of the intensity will report at the B-detector, 0.01% at the NB-detector, and 0.99% would go to detonate the bomb, becoming the only way to (catastrophically) detect its existence.

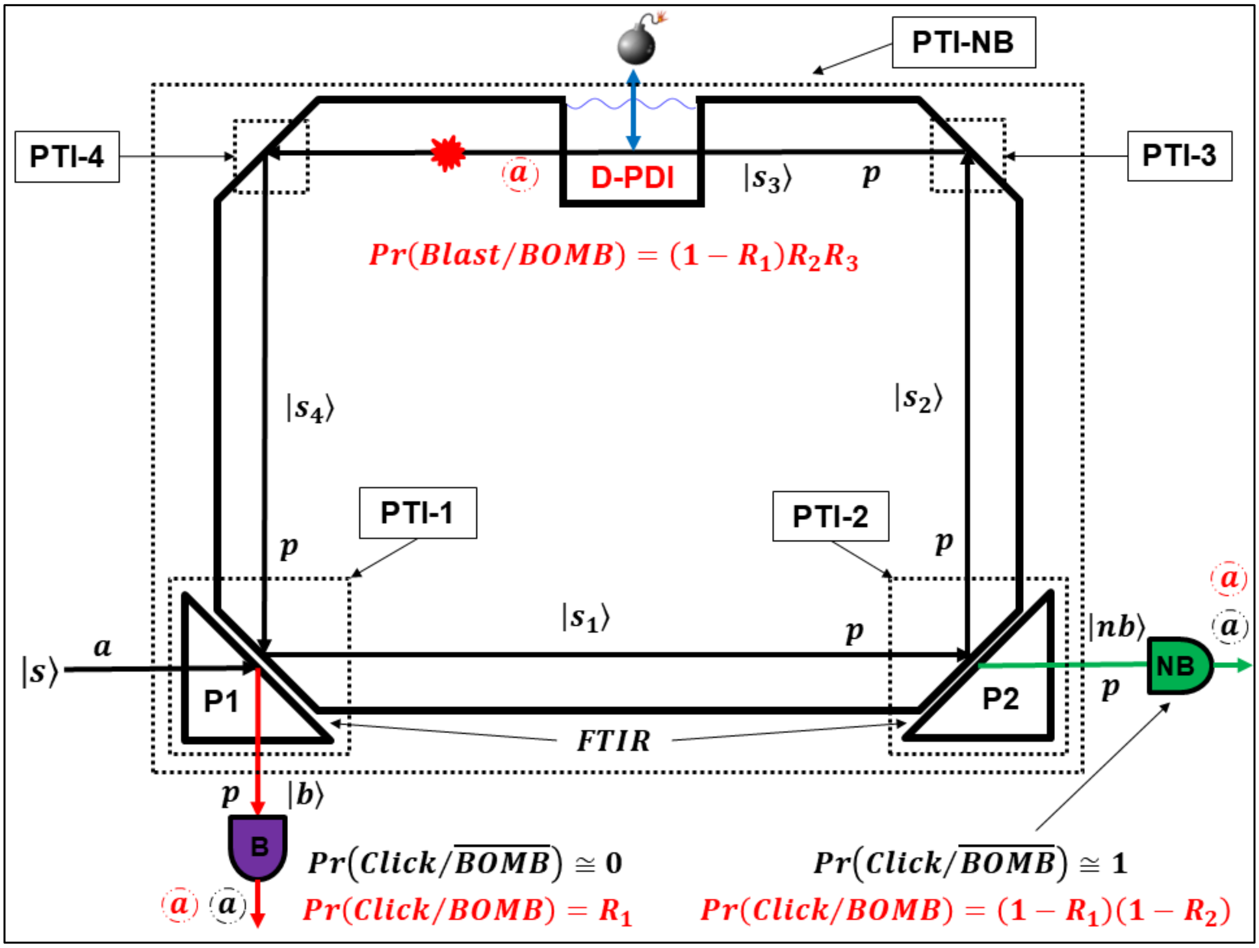

Figure 4: High Efficiency TIR 'Interaction-Free' Bomb Detector (Graphics from [25])

In the single-photon case, GI-B has one input ($|s\rangle$) and three output channels, one entering detector 'B', one entering detector 'NB', and the third entering D-PDI (the bomb). The photon's states in all of them are co-extant ontically probable; its states after the three detectors are mutually exclusive actual (red dotted-encircled 'a'). The relevant Milieu Bases are: MB-1 = $\{|b\rangle, |s_1\rangle\}$; MB-2 = $\{|nb\rangle, |s_2\rangle\}$; MB-3 = $\{|s_3\rangle, |l_3\rangle\}$; and MB-B = $\{|b\rangle, |nb\rangle, |s_3\rangle, |l_3\rangle\}$ – with $|l_3\rangle$ representing the losses in PTI-3. To predict the probabilities of interest under QR/TOPI, we need to express the photon's input State $|s\rangle$ in the global MB-B, so we start expressing the photon's State in MB-1, its component $|s_1\rangle$ in MB-2, and the latter's component $|s_2\rangle$ in MB-3; then we merge the three equations, expressing $|s\rangle$ in the MB-B to obtain [25]:

$$Pr(|b\rangle/BOMB) = R_1 \ ; \ Pr(|nb\rangle/BOMB) = (1 - R_1)(1 - R_2) \ ; \ Pr(Blast) = (1 - R_1)R_2R_3$$

Those probabilities agree with the corresponding high-intensity ratios. Note that they do no sum up to unity; the difference is the term $(1 - R_1)R_2(1 - R_3)$, which corresponds to the actual losses in PTI-3 (R_3 may also lump the losses in PTI-1 and PTI-2), i.e. the probability that the photon is absorbed/scattered instead of reflected. Figure 5 depicts them in red, blue, and green (for $R_1 = R_2 = R$ and $R_3 = 1$). Setting R close to unity, the probability to click for the B-detector nears unity, while the probabilities for a click of the NB-detector and for an explosion go to zero.

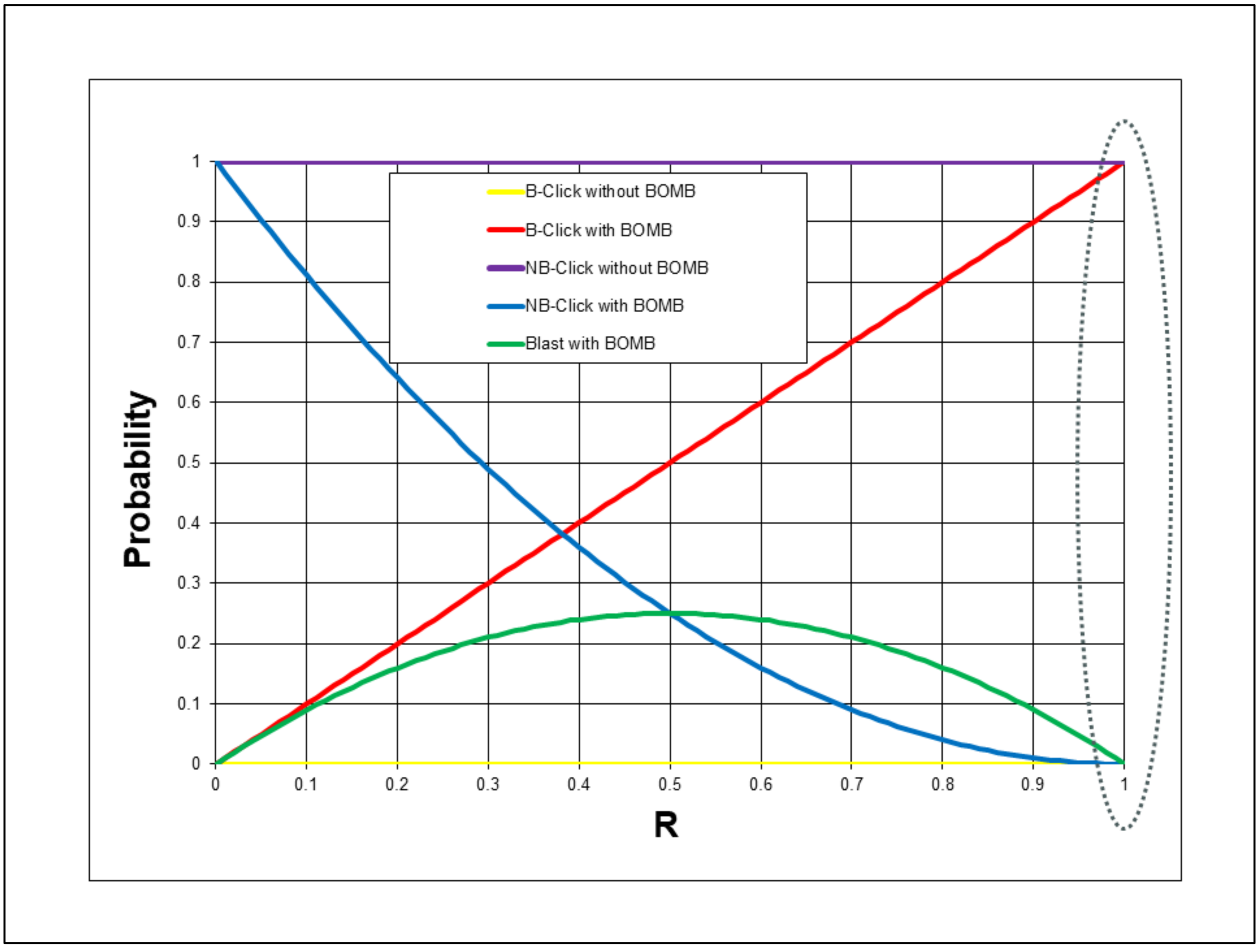

Figure 5: Ideal Detectors' click Probabilities without and with the Bomb (Graphics from [25])

The bomb detection efficiency using the B-detector is $\eta = Pr(|b\rangle)/[Pr(|b\rangle) + Pr(blast)] = 1/(2-R) \to 1$ when $R \to 1$, e.g. for $R = 0.999 \Rightarrow \eta \cong 99.9\%$. Likewise for $R \to 0$ if using the NB-detector. It seems like the click of any detector could be an excellent indicator of the existence of the bomb without (mostly) ever exploding it. It can be proven [25] that if the Milieu is GI-NB, the B-detector mostly never clicks (ideal yellow line in Figure 5) or, alternatively, the NB-detector almost always clicks (ideal purple upper line in Figure 5). The labels 'B' and 'NB' for the detectors were chosen based on which one clicks with the bomb present, i.e. R was chosen close to unity.

In [25] we also proved that in the high-intensity monochromatic lossless case with ***no*** bomb, upon reaching steady-state ($t \to \infty$), the fraction of the incident intensity that reaches the 'B' detector at the resonance frequency is zero, while that of the 'NB' detector is unity. Its relationship with the single-photon case points to another oddity of quantic behavior beyond the mere 'how can it detect the presence of the bomb sans interacting with it'. Assuming, to simplify matters, a perfect reflection for PTI-3 and PTI-4 ($R_3 = R_4 = 1$) and also $R_1 = R_2 = R$, we have $|C|^2/|I|^2 = R/(1-R)$ and $|BP|^2/|I|^2 = 1/(1-R)$, where C and BP are respectively the steady-state wave-amplitudes for the beam into the liquid Cavity and the Bottom Path between the two prisms. So at resonance, for say $R_1 = R_2 = R = 0.99$, if the input intensity is unity, the intensity in the liquid cavity is 99, the one in the bottom path 100, and the input reappears at the NB detector.

The high-energy storage in the block due to resonance is apparent. But… what does this mean when we dim the input intensity down to a single-photon at a time? Could this huge steady-state intensity ratio inside the block be interpreted as the probability for a single photon to circulate around the block until such steady-state is reached? No, because this ratio is higher than unity so… what is the meaning of 'steady-state' for a single photon? Steady-state requires a transient we do know exists for high-intensity light. Thus, is there a transient for the single-photon regime upon a Milieu-Event (bomb in or out) taking place? Perhaps the transient-state is a phenomenon inherent in the m**a**croworld – non-existent in the m**i**croworld? A tenet of QR/TOPI is precisely that a Milieu-Event and its ***non**-evincing* effects (State-Events) are absolutely *simultaneous* [25].

Pursuing the analysis for the single-quanton regime, when entering GI-NB, the actual State $|s\rangle$ of the photon undergoes PTI-1 jointly with its own State $|s_4\rangle$ inside the block after having successfully undergone PTI-2, 3, and 4. Notice that -per QR/TOPI- ***no*** two or more actual states of a quanton can be co-extant, from which $|s_4\rangle$ can only be ontically probable. Ergo, because the quanton only undergoes PTIs inside the crystal block, $|s_1\rangle$, $|s_2\rangle$, and $|s_3\rangle$ must be ontically probable as well. From Figure 4, in contrast to PTI-B, PTI-NB has one input ($|s\rangle$) and only two output channels, one entering detector 'B' and one entering detector 'NB'. The photon's states in the monolith and before the detectors are all ontically probable; its states after the two detectors are actual, ergo mutually exclusive (black dotted-encircled 'a'). The relevant Milieu Bases are: MB-1 $= \{|b\rangle, |s_1\rangle\}$; MB-2 $= \{|nb\rangle, |s_2\rangle\}$; MB-3 $= \{|s_3\rangle\}$; MB-4 $= \{|s_4\rangle\}$; and MB-NB $= \{|b\rangle, |nb\rangle\}$. In [25] we showed that expressing the photon's State $|s\rangle$ in MB-NB -due to the feedback loop- led to an endless iterative process (a geometric series) whose limit delivers the probabilities:

$$Pr\left(|b\rangle/\overline{BOMB}\right) = \left|\frac{\sqrt{R}\left(e^{i\delta} - 1\right)}{1 - Re^{i\delta}}\right|^2 \quad ; \quad Pr\left(|nb\rangle/\overline{BOMB}\right) = \left|\frac{(1 - R)}{1 - Re^{i\delta}}\right|^2$$

From which $\delta = 0 \Rightarrow \left\{Pr\left(|b\rangle/\overline{BOMB}\right) = 0\right\} \wedge \left\{Pr\left(|nb\rangle/\overline{BOMB}\right) = 1\right\}$. And we already know that $R \to 1 \Rightarrow \{Pr(|b\rangle/BOMB) \to 1\} \wedge \{Pr(|nb\rangle/BOMB) \to 0\}$. Therefore, the B-detector clicks with high probability when there is a bomb in the cavity, practically does not click when there is no bomb, and the probability of exploding ($[1 - R]R$) when there is a bomb is negligible.

As said, one of QR/TOPI's basic tenets is that the *simultaneity* between changes of a quanton's Milieu and the effect on its state-transition PD is absolute. Hence, the relationship between m**i**cro and m**a**cro-worlds is subtler than a mere straightforward correspondence between high-intensity ratios and probabilities. In fact, Paul and Pavĭcić in [48] were clearly puzzled by the relation between the *resonance* established for high-intensity light only time-after reaching steady-state on one side and the one-at-a-time photon situation on the other. Using a Pockels cell to simulate the bomb rapidly being inserted/removed in/from the cavity, they proposed an experiment "which would decide whether sudden changing of boundary conditions" would redirect each photon to register in detector NB (instead of in detector B) "instantaneously (classically untenable) or after a delay which would allow for sufficiently many round trips to build up the interference". As we saw in [25], there is solid experimental evidence for the *simultaneity* between changes on the photon's Milieu and the effect on its state-transition PD. The high-intensity *transient* before reaching *steady-state* seems to disappear for the single-photon regime – making the *transient* an emergent phenomenon associated with the legion of photons.

Going back again to Bruce's defense of Oxford's MWI, he says: "…The importance of the monolithic reflector is that it delays a photon by trapping it, unmeasured, for a significant period—thus preserving communication with that other world…. You might be making use of information from worlds where, if a real bomb had been present, you would already have been dead." [6]

Uncanny indeed. As we saw, under QR/TOPI, when there is ***no*** bomb, there is ***no*** direct relation between the resonant steady-state intensity inside the block if fed with high-intensity light on one side, and the probability of a single photon to circle the block on the other. In the ideal lossless case, upon the photon entering the MOTIRR, its probability to be reflected into the B-detector is nil and its probability to go out into the NB-detector is unity – tout court. The MOTIRR does ***not*** delay the photon "by trapping it, unmeasured, for a significant period—thus preserving communication with that other world". And, when there is a bomb, there is ***no*** optical circuit.

No wonder Bruce (striving to convince us that MWI is verisimilar) repeatedly resorts to statements from the non-believer Zeilinger (now Nobel laureate) and to the fact that Deutsch made foundational contributions to quantum computing [50] – based on his conviction that the only way to understand the colossal parallelism displayed by a quantic computer is via the existence of parallel universes. Deutsch claims in [38] that factorizing a 250-digit number with the Shor's algorithm involves about 10^{500} "interfering universes", despite the algorithm requiring "only a few thousand arithmetic operations". With Zeilinger and Nicolas Gisin, I am puzzled that there are outstanding scientists and philosophers who genuinely believe in such a vision of Reality.

3.6 Tri-Quanton Phenomena: Anthropic Teleportation/Cloning

Zeilinger claims his Information Principle explains the security of entanglement-based cryptosystems, teleportation, and hyperdense coding, while reinstating the equivalence between his *Total Information* and the quantic State. Nonetheless, he chooses the former (a derivative of the latter) as the reason why "No action at a distance or other mysterious processes happen" and why in a maximally entangled State "if the eavesdropper extracts any information, this can only be at the expense of the two non-local bits, thus reducing the entanglement." [13]

Let us understand Nature's and anthropic teleportation/cloning per QR/TOPI. In Figure 6, qubits A and B are entangled after a PEI created them in one of the four Bell States, each qubit (in an ontically probable state) respectively sent to Alice's and Bob's stations. Being entangled, they endure an ITI. Quanton T (whose ***unknown*** actual State $|s_T\rangle$ we wish to teleport to quanton B) undergoes a Bell Interaction (BI) with quanton A. This latter PI entangles quantons T and A randomly delivering them in a Bell State and, because A is entangled with B, all three quantons are now entangled so that each one of the probable four Bell States is uniquely paired with one of four probable states of quanton B. One of the latter is a clone of the *pure* State in which T originally was ($|\boldsymbol{ds_B}\rangle$ in Figure 6); the other **u**ndesirable three are rotations of $|s_T\rangle$. When the PDI in the BI occurs, quanton B (while traveling to Bob's Station in a tri-co-State) adopts the actual pure State associated with the actual bi-composite Bell State delivered by the BI. Note that the Bell State and quanton B's State are actual, but A and T are in ontically probable states and remain so until a PDI on one of them occurs. Being the Bell State random, Alice needs to determine which one it was and let Bob know. To do so, she includes in the BI's PDI the electronics to detect, amplify, codify, and transmit the information to Bob's station via an RT-signal.

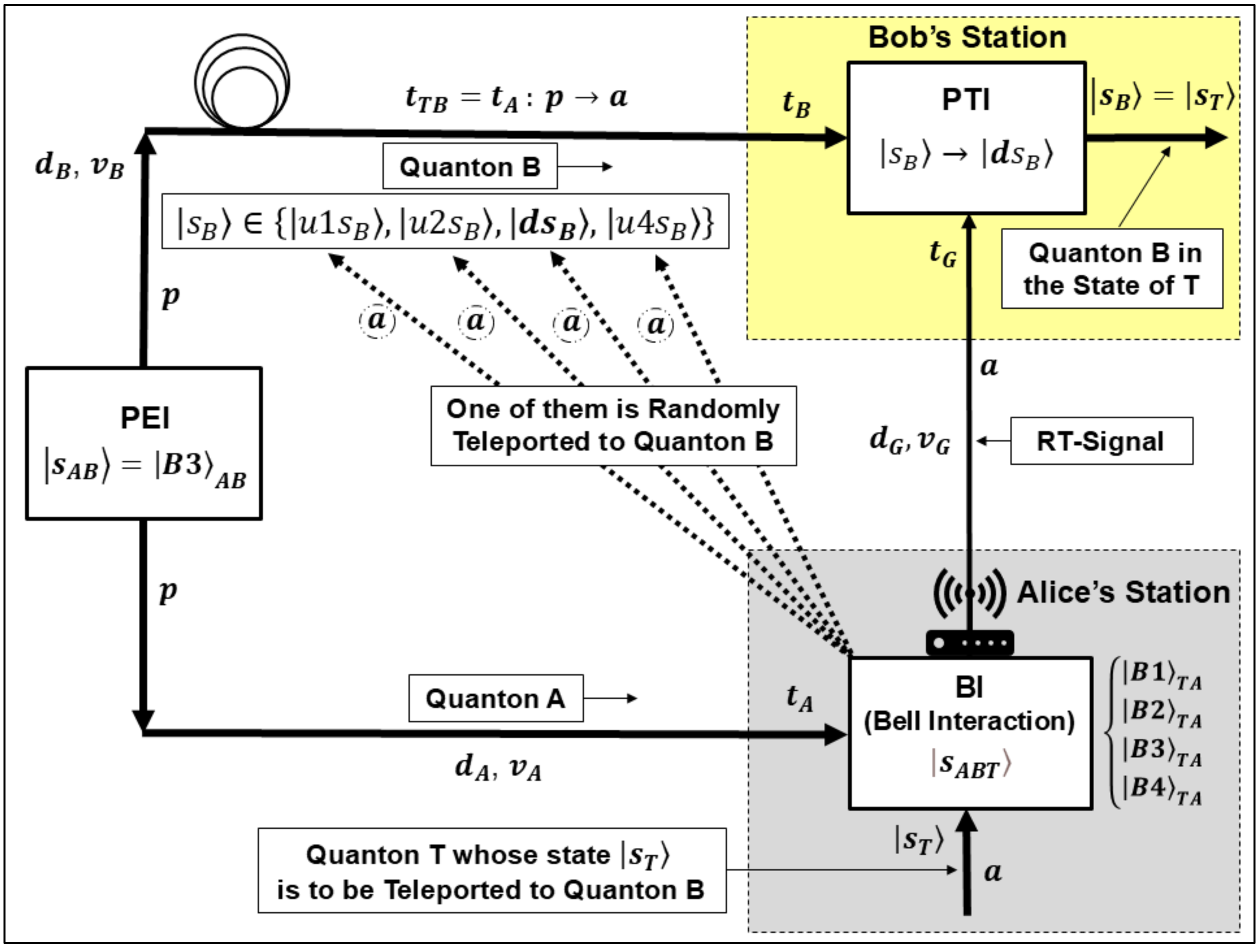

Figure 6: Anthropic State Teleportation of Quanton T onto Quanton B (Graphics from [25])

Using two bits to codify the four possible results of the BI, if the resulting Bell State is the one associated with $|s_T\rangle$, the received signal at Bob's station sets the PTI to do nothing; otherwise, the received code sets the PTI (with e.g. an electro-optical modulator or a rotatable half-wave plate) to duly rotate the State of the upcoming qubit-B. With the appropriate R-Timing, the PTI receives quanton B in the actual *teleported* State and (time-before it) the necessary RT-signal to properly transform the latter into a clone of quanton T. Note that the information RT-transmitted does not uncover the State of quanton T to be teleported but its composite State with quanton A and that is why merely two bits are subluminally transmitted, which is enough for the at-will teleportation of quanton $T's$ ***unknown*** State onto quanton B. Fully transmitting the State (a continuous complex variable) via a light-limited genidentical chain [25] would have required an infinite number of bits – proving again that, even though you can experimentally extract no more than 1 bit out of single isolated qubit, its State carries much more than 1 bit of information.

We proved in [25] that upon *teleportation*, despite not being able to observe/measure it per se, we are able to experimentally time-confine its occurrence between two R-Times (t_A and t_B), which can be made virtually *equal* in any IF by adjusting the delay line. Therefore, the very (***non-evincing***) adoption by quanton B of the *teleported* State must be considered *simultaneous* with the PDI-Event in the BI ($t_{TB} = t_A$) irrespective of how far the PTI still is (if there is one). Despite the *teleportation* QR-Event being recordless per se, its QR-Time is well-defined as a limit – via inference based on experimental data. Besides, it is objectively absolute. This absolute *simultaneity* exists betwixt three events: one PDI-Event (part of the BI); one State-Event (A and T randomly adopting a bi-composite State); and another distant State-Event (B adopting a teleported State). Because only one of the three actual events is *evincing*, no conflict with RT exists [25].

Interestingly, QR/TOPI's analysis in [25] also showed that, for a non-destructive PDI at the output (not shown), regardless of the time-order between t_A and t_B (either due to the Milieu or a change of IF) and assuming the coherence requisites remain valid throughout the network of GIs, we have: (1) for $t_B < t_G$ the datapoints can always be sorted out into four groups of roughly equal cardinality, one for each of the four possible bi-composite results in the BI and its corresponding State for quanton B – in short, ***no*** *cloning*; and (2) for $t_B > t_G$ all datapoints belong to a single group containing the quanton B in the original State of quanton T – i.e. anthropic *cloning* took place. Furthermore, even if quanton B is 'measured' destructively before the BI but its results are registered, the above sorting in four groups is still valid and provides the same (cloning/no-cloning) data – despite neither tri-quanton *entanglement* nor *teleportation* having occurred. Under QR/TOPI, there is a big difference between *entanglement*/*teleportation* between quantons and their data correlations on the other. In his charming book 'Dance of the Photons' [17], Zeilinger was deeply concerned because he thought those two *phenomena* were still taking place between ***non***-existent quantons (Section 3.7.1).

3.7 Tetra-Quanton Phenomena: Teleportation/Cloning of Entanglement

A composite State can also be teleported by Nature, and by us if we use a modicum of signaling as we showed we must for a single-quanton State. It was proposed by Zukowski et al in 1993 under "entanglement swapping" and experimentally realized by Pan et al in 1998 [9] and Jennewein et al in 2001 [14]. All those authors were members of Zeilinger's team in Innsbruck [17]. Figure 7 shows two independent PEIs, PEI-1 and PEI-2, producing respectively two pairs of entangled photons $(iX, iY), i = 1,2$, with each pair encircled in solid green indicating the sub-quantons are in co-states of one Bell State $|s\rangle_i$ in $MB_i = \{|B1\rangle_i, |B2\rangle_i, |B3\rangle_i, |B4\rangle_i\}$, $i = 1,2$. Two Milieus for the four photons are possible. In the first (black-dotted lines), the two quantons in each pair go through two GIs, each of the four probable states morphing into actual states. The two GIs for each pair are assumed to be simultaneous so that their input states are drawn both as probable; otherwise, the input State for the time-second GI would be actual. Recall that, if their corresponding PDI-Events are spacelike, their time-order could be due to a change in IF and that, regardless, upon numerous repetition, statistical analysis of the whole dataset confirms that the quantons in each pair were entangled upon creation (dotted-encircled) but quantons in different pairs were ***not***.

In the second Milieu (in red): two photons, one from each pair (the 'inner quantons' $1Y$, $2X$) undergo a Bell Interaction (BI) and the other two (the 'outer quantons') go straight to their respective GIs with their arrival R-Times arranged to occur time-after the BI. This is similar to the BI in the anthropic teleportation setup in Figure 6 except that the then-to-be-teleported quanton T is now not a quanton in an isolated pure State but a sub-quanton in a co-State, i.e. entangled with another quanton: $1Y$ (entangled with $1X$) undergoes a BI with $2X$ (entangled with $2Y$).

The BI is a GI whose PTI has the Milieu Basis $MB_I = \{|B1\rangle_I, |B2\rangle_I, |B3\rangle_I, |B4\rangle_I\}$, where the sub-index '$I$' stands for '**I**nner quantons'. Ergo, upon the PDI in the BI, one of those four probable bi-composite states comprising $1Y$ and $2X$ (encircled in solid red) becomes actual like one bi-composite of quantons A and T did in Figure 6 (making quanton B's probable State also actual by *teleportation*). But now -before the PDI in the BI occurs- by virtue of the prior external entanglement with two other quantons, instead of a tri-composite State (A, B, T), a tetra-composite State $(1X, 1Y, 2X, 2Y)$ is formed – involving the outer photons. Hence, upon the BI's PDI, one bi-composite State in MB_I becomes actual at random while the outer photons ($1X$ and $2Y$ encircled in solid red) adopt by *teleportation* corresponding co-states of an actual bi-composite State in $MB_O = \{|B1\rangle_O, |B2\rangle_O, |B3\rangle_O, |B4\rangle_O\}$, where the subindex '$O$' stands for '**O**uter'. Note these two bi-composite states are actual, while the co-states for their respective sub-quantons ($1Y$ with $2X$ and $1X$ with $2Y$) are probable: what is *teleported* is not a State of a single-quanton as in Figure 6 but a composite entangler State comprising the outer quantons.

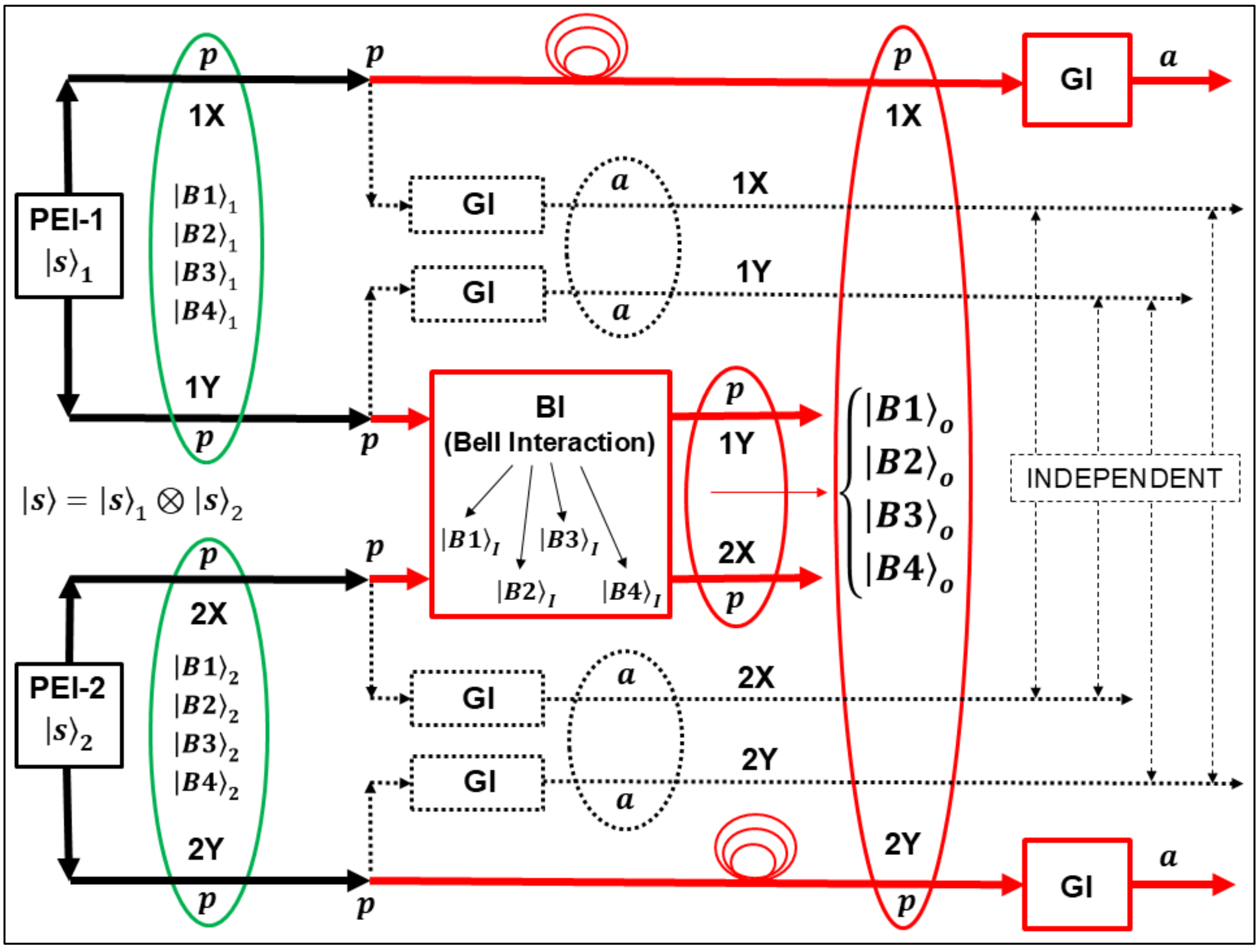

Figure 7: Nature's Teleportation/Cloning of Entanglement (Milieu in Red) (Graphics from [25])

Triggered by the PDI in the BI, the entangler State randomly formed in the BI and the one teleported onto the outer photons are the result of State-Events, ergo actual, ***non**-evincing*, though pinpointable in our RT-spacetime [25]. By submitting the outer photons to GIs, upon repetition, the statistical analysis proves they were indeed entangled – even though they were created by fully independent sources and never directly interacted one with another: their entanglement is the result of *teleportation*. However (as in Figure 6), for a human being to avail of the latter entanglement resource, it would require that two bits (codifying which one of the four Bell States was randomly created in the BI) be transmitted via an RT-signal to the required place, from which the receiver (knowing also which Bell States were delivered by PEI-1 and PEI-2) could determine which is the particular Bell State the *outer* quantons are in. As in Figure 6, a new PTI receiving the RT-signal could automate such a determination and, if cloning is the goal, transform it accordingly.

This *entanglement* teleportation/cloning is formally studied in Appendix B of [25] where, if the Bell States for the two input pairs are equal, the Bell State adopted by the inner quantons is directly *teleported* onto the outer quantons, viz: the outer composite State is a clone of the inner composite State. If the input Bell States are different, the bi-composite State *teleported* to the outer quantons is different from the one adopted by the inner quantons [25]. Regarding entanglement swapping, Zeilinger [13] stated: "This, more than any experiment before, underlines that Bell's theorem is not about properties particles carry, but about the information concerning possible measurement results." Bell's theorem under QR/TOPI is fully treated in [25].

3.7.1 Zeilinger asks: How can two non-existent Photons become Entangled?

In his book [17], Zeilinger mentions an Asher Peres' idea as "ghostly… rather strange, surprising, and elegant": Figure 8 shows basically the same topology as in Figure 7 –with minor changes to achieve a different R-Timing between PDI-Events. The two GIs undergone by the *outer* photons are made destructive (D-GI) and performed immediately after their creation by the two PEIs at Bob's Station. Being the outer photons absorbed, only the results of the D-GIs can be sent to Alice's Station so -for the Milieu in black-dotted lines- the *inner* photons (already disentangled!) undergo their own GIs and Alice, upon repetition and comparison of her data with Bob's data, finds that (as in Figure 7) each of them were random by itself but entangled with its corresponding (random by itself) *outer* photon. This is shown by the black-dotted encirclement of their records. Note the input states to the dotted GIs are both actual while before they could have been probable sans any experimental consequences: the GIs in Alice's Station being delayed with respect to their respective D-GIs in Bob's Station makes no difference (if coherence requisites [25] are met). Again, for spacelike separation, such time-order could be merely the result of a change in IF.

In the Milieu in solid red, the BI occurs time-after the two *outer* photons ceased to exist, leaving only their records (sent to Alice via RT-signaling). Zeilinger's team in Viena realized it with glass fibers in 2001 and later (in 2009) Xiaosong Ma et al made the choice betwixt the two Milieus via a quantum random number generator (QRNG) spacelike-separated from Bob's Station. They found the same results as in Figure 7. What they found "ghostly" was that because the BI entangles its two input quantons, each one of which is supposedly entangled with another quanton, the four of them would become entangled only if -and after- the BI occurred. But by the time the BI occurs, the two *outer* photons do not exist any longer so… how can they become entangled with the *inner* photons, adopting a specific tetra-composite entangler State? This is one more embodiment of Zeilinger's "very fundamental question", which he attempts to answer in his book/publications [17] [11] [16] [15] [21] and seems to be still unanswered in 2025. In his book, Zeilinger says:

> "So Alice can decide at a point in time when Bob's photons Y and B [1X and 2Y] no longer exist, when their polarizations have already long ago been measured and the results written down somewhere, whether these photons are entangled or not. How can that be? How is this possible? Certainly, Alice's measurement [BI] cannot act back into the past and influence the earlier measurement [D-GIs] results on Bob's photons Y and B… Changes of written-down measurements records certainly do not happen… How can the measurement results now reflect that B and Y are entangled, just because Alice decided to perform a Bell-State measurement on A and X [1Y and 2X]? Even though before, when Alice measured her photons separately

[dotted-black Milieu], Bob's photons B and Y were not entangled, their measurement results were completely uncorrelated? How is that possible?" [17]

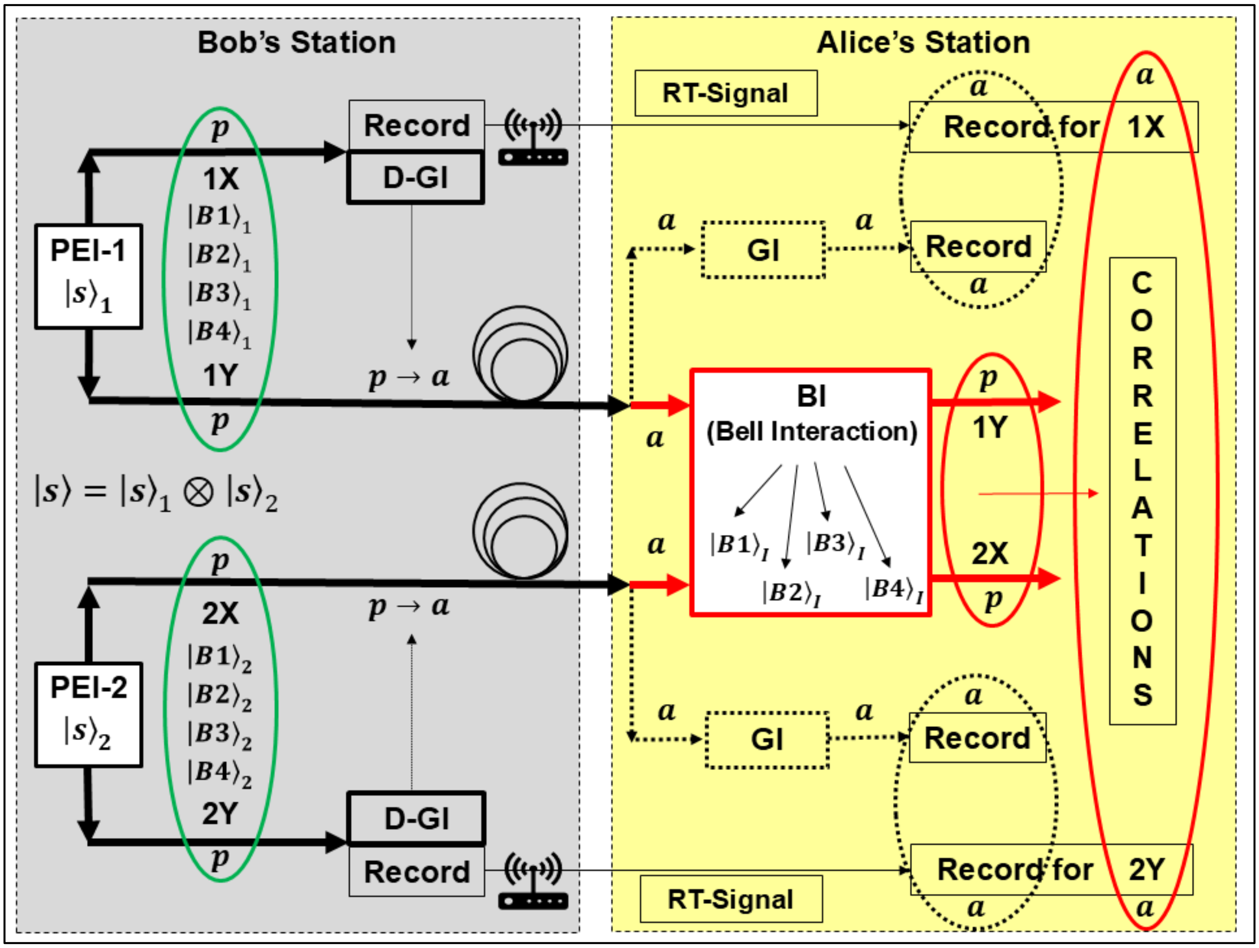

Figure 8: Delay Choice of Milieu (Graphics from [25])

No wonder Zeilinger calls the situation "ghostly": he finds out that two ***non***-existing photons "become entangled". He is conflating *entanglement* with *data correlation*, and continues:

"Philosophically speaking, we have a very interesting situation. The data obtained by Bob long before Alice decided what kind of measurement to perform can be part of two completely different physical stories… the data have no story to tell before Alice makes her decision and does her measurement accordingly and this decides the meaning of Bob's data. One might very well say that Bob's data are a primary reality in no need of explanation. If we wish to have an explanation, we need to complete the experiment. This completion of the experiment requires Alice to make a decision that defines the meaning of the data already obtained." [17]

Brukner, Aspelmeyer, and Zeilinger resort to *Information* to explain the situation as follows:

"… This does not arise as a paradox if the quantum state is viewed as just a representative of information… Because the quantum state is no more than the most compact representative of [Schrödinger's] such lists [51], it is conceptually allowed to say that particles can become entangled even after they already have been registered." [21]

We fully explained in [25] why, per QR/TOPI, those statements are wrong. Alice does ***not*** decide if the *outer* photons are entangled or not: when Bob's *outer* quantons undergo D-GIs prior to the BI, not only they cease to be entangled with their corresponding *inner* quantons but they decease, while the *inner* ones adopt actual states resulting from the actualization of each PEI's characteristic ITI. The eigenvalues associated with these teleported eigenstates are related to the eigenvalues already recorded and sent to Alice. Even if the GIs were not destructive, the two entanglements would cease to exist, but -upon repetition- their datasets would be correlated. Because of the GIs, Figure 8 shows that the two quantons entering the BI have actual states. Only had the GIs occurred time-after the BI (Figure 7), the entanglement of the pairs $(1X, 1Y)$ and $(2X, 2Y)$ would have persisted, with $1Y$ and $2X$ entering the BI as probable, the ITI for the tetra-composite quanton preserved, and the *outer* quantons becoming entangled. But the GIs did occur time-before the BI: *entanglement* and *correlation* must not be conflated: the former occurs among quantons (no "ghosts" allowed); the latter between corresponding datasets obtained upon copious repetition of a given quanton/Milieu setup. Viewing the State of an object as "just a representative of information" does not entitle us to let such inexistent object entangle with another object.

As for the data: datasets are sets of datapoints, all of which -for a proper assessment of their correlation- are to correspond to the same State and Milieu. Alice's (or her QRNG's) decision to suddenly include a BI on the *inner* photons entails submitting state-related photons to a different Milieu, so the new datapoints cannot be intermingled with those of the Milieu experienced by the *inner* quantons when ***no*** BI existed. In the first case there is a correlation between properly partitioned *outer* photons' datasets (whether in each run the *outer* photons exist or not when the BI occurs); in the second case there is no correlation. Specifically, to confirm the entanglement of the *outer* photons via its inherent correlation (Figure 7) or the same correlation without their entanglement (Figure 8), datapoints corresponding to each one of the four possible Bell States delivered by the BI are to be distinguished. The sudden change of Milieu instantly produces a change of probabilities for subsequent events – like taking a m**a**croscopic pin off in Galton's quincunx right before being hit by the ball instantly alters it probability to eventually fall into a given bin [24]. For a given State and Milieu, the PD is ontic, reciprocal, **a**spatial, and **a**temporal.

The outer-photons dataset for the Milieu without the BI has a "physical story" and meaning per se – without a purported "completion" of the experiment. The inclusion of the BI by Alice simply provides a new dataset that, when contrasted and adequately sorted together with Bob's data, allows them to discover a correlation which they knew did ***not*** exist when the BI was not part of the Milieu. The BI sub-dataset tells Bob and Alice the adequate partitions of the *outer* quantons sub-datasets (one partition for each of the four Bell States randomly provided by the BI) within which four correlations betwixt them are exposed. Without such partitioning, the *outer* datasets still show the dull 50/50 PD each, with ***no*** correlation between the two sets. And these data correlation within each subset are the same whether, for each run, the BI between the *inner* photons occurs R-Time after (Figure 7) or R-Time before (Figure 8) the GIs undergone by the *outer* photons. In the latter case, the *inner* photons entering the BI are in *co-states* (ergo ontically probable) and the expression 'the four photons become entangled' is valid; in the former case, they are in *pure* actual states but related to the record left by their corresponding deceased *outer* quantons – so the expression is meaningless but their datasets reveal the same PDs in both cases.

Once more: the referred time-orders could be simply the result of a change in IF, proving once again that the probability distribution for the state-transition is the ontic IF-Invariant attribute of a (single or composite) quanton in a given (ontic) State experiencing a given Milieu.

3.8 The Delayed-Choice 'Quantum Eraser' via Entanglement

In Figure 2 we saw how the alleged "marking/erasing" of "which-slit information" can be attained by subjecting the quanton to the appropriate local PTIs. But then, as proposed by Scully and Drühl in 1982, were the quanton entangled with another, the 'marking/erasing' could be the result of PTIs undergone by its entangled twin – which could be arbitrarily spacetime-separated (if coherence requisites [25] were met). In 2000 Kim et al conducted such an *entanglement* variant of the "Delayed-Choice Quantum Eraser". The language used in their paper's Abstract says it all:

> "… The experimental results demonstrated the possibility of simultaneously observing both particle-like and wave-like behavior of a quantum via quantum entanglement. The which-path or both-path information of a quantum can be erased or marked by its entangled twin even after the registration of the quantum." [52]

In 2001, Walborn et al confidently spoused the same philosophical stance:

> "Therefore, it is enough that the which-path information is available to destroy interference. Moreover…, one can erase the which-path information and recover interference by correlating the particle detection with an appropriate measurement on the which-path markers. Such a measurement is known as quantum erasure. In addition, if the which-path marker is capable of storing information, the erasure can be performed even after the detection of the particle." [53]

Figure 9 outlines in green a double-slit setup via a beam splitter $\mathrm{BS_{DS}}$ representing the Double-Slit screen and a detector D_{PP} representing a detection spot on the Photographic Plate. Clicks on different spots of the plate are equivalently obtained by changing the path-length (relative phase) on one of the arms (implied by the green coiled optic fiber). A unique feature in this setup is that the two inputs for D_{PP} do ***not*** come from the two outputs of $\mathrm{BS_{DS}}$ but from two Spontaneous Parametric Down Converters (SPDCs), each of which can transform a photon of a given frequency into two entangled photons of half the frequency. Even more unique: each SPDC's input is ***not*** an actual photon but one of the two probable states of the single photon entering $\mathrm{BS_{DS}}$ with actual State $|s\rangle$. Recall that the photon is in general not abstractable to a point-object in RT-spacetime.

To ease the discussion of Brian Greene's excerpts, we replace the heralding/heralded photon vocabulary we used in [25] for SPDCs with his idler/signal terminology. In Figure 9 we can talk about two pairs of idler (red)/signal (green) ontically probable *photons*, each pair created from each one of the two probable states (green) of the referred actual input *photon*. Only upon the two probable states $|s_1\rangle$ and $|s_2\rangle$ morphing into one actual State, can we talk about one signal actual photon and one idler actual photon. Otherwise, there are two probable signal photons with states $|s_{A1}\rangle, |s_{B2}\rangle$ and two probable idler photons with states $|s_{A2}\rangle,|s_{B1}\rangle$. Hence -due to *entanglement*- the interference pattern (if any) on the double-input green detector $\mathrm{D_{PP}}$ can be affected not only by the relative phase between $|s_{A1}\rangle$ and $|s_{B2}\rangle$ (as in regular double-slit or MZI setups) but by the GIs to which their respective *entangled* idler states $|s_{A2}\rangle$ and $|s_{B1}\rangle$ are subjected. In the which-path information/marking/erasing/wave-particle philosophical stance, Brian Greene "shapes the past":

> "Before you have the results of the idler photon measurements, you really can't say anything about the which-path history of any given signal photon. However, once you have the results,

you conclude that signal photons whose idler partners were successfully used to ascertain which-path information can be described as having—years earlier—traveled either left [upper] or right [lower]. You also conclude that signal photons whose idler partners had the which-path information erased cannot be described as having—years earlier—definitely gone one way or the other… We thus see that the future helps shape the story you tell of the past." [46]

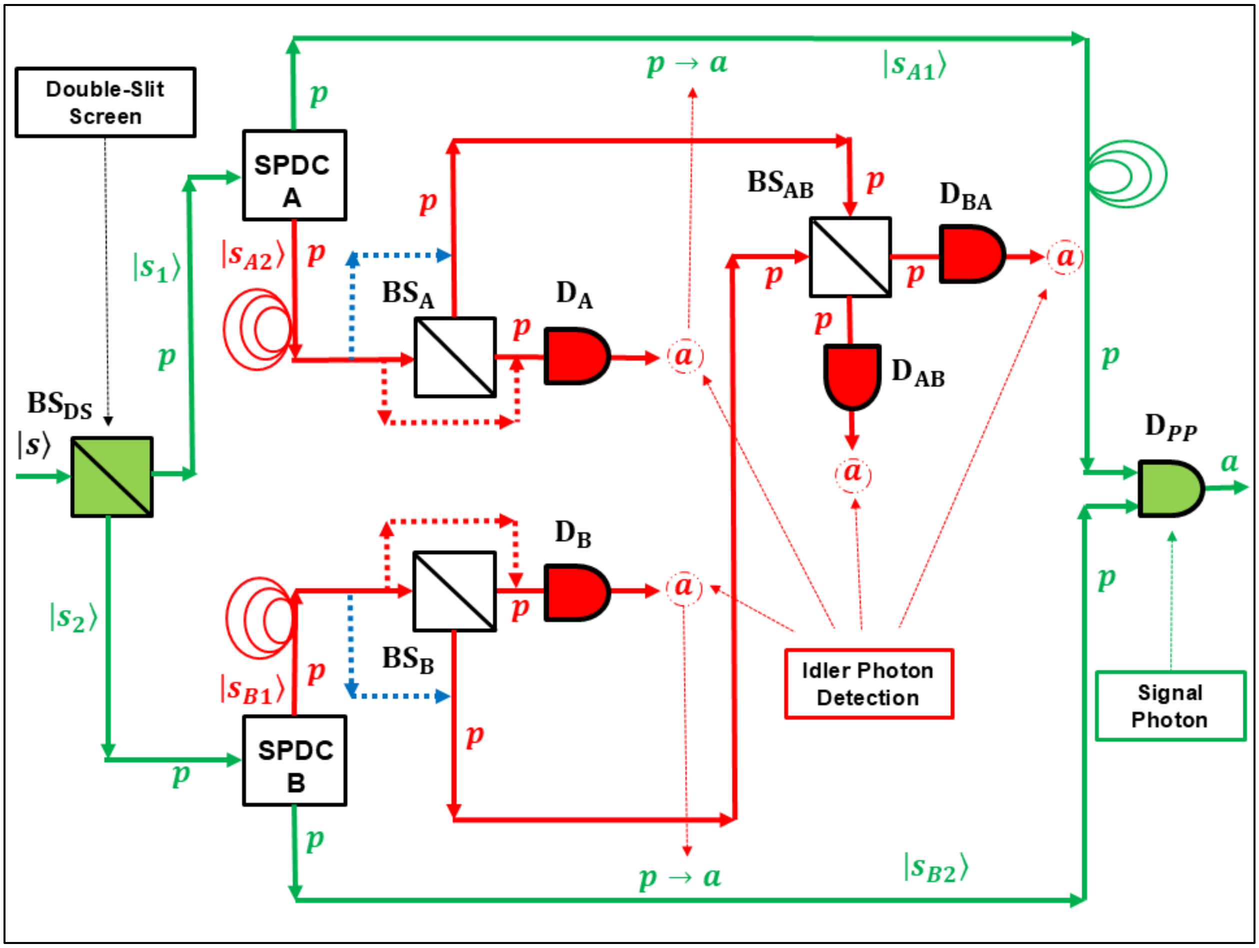

Figure 9: Delayed Choice of Milieu via Entanglement (Graphics from [25])

I can see Greene attempts to make the phenomena mysterious albeit intelligible. I repeat: "under the very same theory, the physical interpretation of what actually happens just now and here cannot depend on our future experimental caprice". I likewise reckon why Kim et al say that "The experimental results demonstrated the possibility of simultaneously observing both particle-like and wave-like behavior of a quantum via quantum entanglement", by which I believe they mean that some of the quantons allegedly passed through only one slit (no interference) and some through both slits (interference). It is also apparent what they mean when they say that the which-path information is 'erased' when there is interference. However, our understanding of what they mean is not the same as their providing a coherent physical meaning free of anthropic references.

Obviously, QR/TOPI rejects those contrived narratives: the quanton's current State plus its current Milieu determine the PD for the next State, full stop. The analysis, description, and prediction for the setups in Figure 9 could of course be achieved using the same *formalism* we extensively used in [25] for previous setups but, as the last century has amply proved, *formalisms* are efficient for *prediction* but useless for *answering* Zeilinger's fundamental question. The best of the two worlds, a specialized AI-tool is under design – merging the *conceptual* with the *formal* so as to explain/predict quantum systems of arbitrary complexity. For now, to further demonstrate QR/TOPI's power, we present a *conceptual* explanation of this quantic system.

Referring to Figure 9, the idler probable states $|s_{A2}\rangle$ and $|s_{B1}\rangle$ (in red) may be submitted to three different Milieus so they can undergo six different GIs: GI-1 consisting in their straight detection, indicated by red-dotted lines going to $\mathrm{D_A}$ and $\mathrm{D_B}$; GI-2 indicated by blue-dotted lines, with the idler states going straight to $\mathrm{BS_{AB}}$ and detected by $\mathrm{D_{AB}}$ and $\mathrm{D_{BA}}$; and GI-3 (red-solid) in which idler probable State $|s_{A2}\rangle(|s_{B1}\rangle)$ enters $\mathrm{BS_A}(\mathrm{BS_B})$ with one output going to detector $\mathrm{D_A}(\mathrm{D_B})$ and the other to a third common BS ($\mathrm{BS_{AB}}$) and then detected by $\mathrm{D_{AB}}$ and $\mathrm{D_{BA}}$. The R-Timing for the three GIs is such that all processing occurs time-before $\mathrm{D_{PP}}$. By delaying such processing (via the red coiled fibers) so that it occurs after $\mathrm{D_{PP}}$, we have three more GIs: GI-1D, GI-2D, and GI-3D. Note that the Delayed version of a GI changes neither its topology nor its sub-GIs, only its R-Timing vis à vis $\mathrm{D_{PP}}$; hence it does ***not*** change the Milieu (the MB is the same).

In GI-1 (red-dotted line), $\mathrm{D_A}(\mathrm{D_B})$ fires time-before $\mathrm{D_{PP}}$ so, being State $|s_{A2}\rangle(|s_{B1}\rangle)$ entangled with State $|s_{A1}\rangle(|s_{B2}\rangle)$, the latter State as well as State $|s_1\rangle(|s_2\rangle)$ morph from probable to actual, and State $|s_2\rangle(|s_1\rangle)$ dissociates from the input photon [25]. Note that $|s_{A1}\rangle$ and $|s_{A2}\rangle$ as well as $|s_{B1}\rangle$ and $|s_{B2}\rangle$ can be both actual because they correspond to different quantons but $|s_1\rangle$ and $|s_2\rangle$ ***cannot*** because they belong to the same quanton. Thus, $\mathrm{D_A}$ and $\mathrm{D_B}$ cannot click together because that would make $|s_1\rangle$ and $|s_2\rangle$ actual. Firing/not firing time-before $\mathrm{D_{PP}}$, a destructive $\mathrm{D_A}(\mathrm{D_B})$ on $|s_{A2}\rangle(|s_{B1}\rangle)$ acts as a ***non***-destructive PDI on $|s_{A1}\rangle(|s_{B2}\rangle)$ and $\mathrm{D_{PP}}$ receives only one actual State per run. Ergo, the probability for $\mathrm{D_{PP}}$ to click is simply the sum of the two probabilities for $|s_{A1}\rangle$ and $|s_{B2}\rangle$ so that, varying the green coiled-fiber's length (the spot on the photographic plate), those two probabilities vary per the two red-dotted curves in Figure 2 – whose summation varies as the red-solid curve: there is ***no*** interference. In the long run, the number of clicks by $\mathrm{D_{PP}}$ is equal to the number of clicks by $\mathrm{D_A}$ plus the number of clicks by $\mathrm{D_B}$. In Walborn's language for GI-1: the idler photons are the "which-path markers" for the signal photons.

However, not acting on a signal but on an idler State, $\mathrm{D_A}$ and $\mathrm{D_B}$ can now be arranged to click long time-after $\mathrm{D_{PP}}$ does (by the red coiled fibers or by changing the IF), creating the GI-1D (same Milieu, different R-Timing). But then, by the R-Time the two idler detectors have a chance to click/no-click, the signal photon has been absorbed by $\mathrm{D_{PP}}$, which, given that it presumably had received two probable states, we could conclude that now interference would have occurred and there is nothing we can do about it, correct? NO: once again, the ITI associated with the common PTI for GI-1 and GI-1D comprises a set of reciprocal probabilistic relations between probable states which evolve in QR-Sync with R-Time. When $\mathrm{D_{PP}}$'s PDI-Event occurs, the click/no-click could take place under one of three combinations of state categories:

Combination (a): $|s_{A1}\rangle, |s_{A2}\rangle$, and $|s_1\rangle$ actual; or

Combination (b): $|s_{B1}\rangle, |s_{B2}\rangle$, and $|s_2\rangle$ actual; or

Combination (c): $|s_{A1}\rangle, |s_{A2}\rangle, |s_1\rangle, |s_{B1}\rangle, |s_{B2}\rangle$, and $|s_2\rangle$ all ontically probable.

But Combination (c) cannot stand because the same argument we used for GI-1 will be valid when one of the two idler photons hits one of the detectors. Under QR/TOPI, upon $\mathrm{D_{PP}}$, only one of the states $|s_{A2}\rangle$ or $|s_{B1}\rangle$ (both probable states of probable quantons) becomes actual (i.e. either

(a) or (b) occurs) by teleportation – guaranteeing a click when the photon reaches its detector. Anything else would be inconsistent with the common Milieu for GI-1 and GI-1D, which together with the input photon's State $|s\rangle$ define a common state-transition equation. Sharing the Milieu, if the coherence requisites [25] remain valid, the ITI is independent of the R-Timing between events – leaving all PDs invariant. Remember the difference between quantons and their registered data.

In sum: for GI-1 and GI-1D, whether we delay the firing of the idler detectors or not, if looking at all their datapoints without any sorting, we would find for the signal datapoints the red-solid curve in Figure 2 (varying the green coiled-fiber length); and when grouping the datapoints based on whether D_A or D_B clicked, we would find for the signal dataset the two red-dotted curves. In the anthropic/informational language, by erroneously concluding that because $D_A(D_B)$ clicked the input photon did actually create the signal photon that traveled the upper(lower) arm of the green BS_{DS}, they would say that the availability of the which-path information destroyed *interference.*

But GI-2 and GI-2D (blue dotted-line) send both idler probable photons into BS_{AB} so that states $|s_{A2}\rangle$ and $|s_{B1}\rangle$ are combined in a fashion that such 'availability' of the "which-path information" is lost – opening the door to the misguided notions of "erasing" such "marked" information "even after" D_{PP} has fired/not fired (falsely implying *retrocausality*). In Walborn/Kim/Greene lexis, the PTI imposed by the BS_{AB} to the idler photons is the "which-path eraser" for the signal photons creating *interference*. Per QR/TOPI, in GI-2, D_{AB} or D_{BA} occurs time-before D_{PP} but induces neither $|s_{A1}\rangle$ nor $|s_{B2}\rangle$ to change from probable to actual, validating Combination (c) and, ergo, *interference* does occur. And, again, because GI-2 and GI-2D share a common Milieu, as long as the coherence requisites remain valid [25], the ITI remains the same – leaving all PDs invariant. In GI-2D ***no*** adoption of any actual State by teleportation occurs when D_{PP} occurs. The input photon undergoing GI-2 or GI-2D behaves as in a regular MZI (viz: without the two SPDCs); a curve like the black solid one in Figure 2 would result from a statistically sound dataset.

Now to GI-3, i.e. with both dotted-lines off and one of the four idler detectors firing time-before D_{PP}. If it is $D_A(D_B)$, we conclude again that only $|s_{A1}\rangle(|s_{B2}\rangle)$ becomes actual time-before reaching D_{PP} and there is ***no*** interference. Sorting their datapoints based on which detector clicked, we have the red-dotted curves; not doing so we have the red-solid curve in Figure 2. But any statistically sound dataset will also contain the cases when D_{AB} fired and those when D_{BA} fired, with states $|s_{A1}\rangle, |s_{A2}\rangle, |s_1\rangle, |s_{B1}\rangle, |s_{B2}\rangle$, and $|s_2\rangle$ remaining ontically probable (Combination c) – opening the door for interference when D_{PP} occurs. But full (alleged) "erasure" of the "which-path information" would require for BS_A, D_A, BS_B, D_B not to exist: because anyone of the four idler detectors may randomly fire in any run, *interference* only is present within some data subsets so, to identify it, we need to organize the large set of datapoints by grouping them according to which detector fired. The data signal subsets corresponding to the idler subsets in which D_{AB} or D_{BA} clicked will display *interference*; those corresponding to D_A or D_B will not. In general, the complete dataset will ***not*** show *interference*. Nothing to erase.

Regarding GI-3D, namely when D_A, D_B, D_{AB}, and D_{BA} can only click long time-after D_{PP} does, by the R-Time they have a chance to click/no-click, the signal photon has been registered and absorbed by D_{PP}, and given that it presumably had received two probable states, we could conclude that now interference would have occurred regardless of which one will eventually click. Not true again: the ITI associated with the common PTI for GI-3 and GI-3D constitutes a set of reciprocal probabilistic relations between probable states which evolve in QR-Sync with R-Time. As explained before, D_{PP}'s click/no-click could have occurred under circumstances (a), (b), or (c) but, now, all of them are consistent with GI-3D – which one was the case will be revealed by which idler detector clicks: (a) if $\mathrm{D_A}$, (b) if $\mathrm{D_B}$, and (c) if $\mathrm{D_{AB}}$ or $\mathrm{D_{BA}}$. Because GI-3 and GI-3D share the Milieu, as long as the coherence requisites remain valid [25], the ITI remains the same irrespective of the R-Timing between events – leaving all PDs invariant. Nothing to erase.

In sum, for GI-3 and GI-3D, whether we delay the firing of the idler detectors or not, if looking at all datapoints <u>without</u> any partitioning, we would find (varying the green coiled-fiber's length) a curve similar to the red-solid one in Figure 2 (***no** interference*); when grouping the datapoints based on whether D_A or D_B fired, we would find the two red-dotted curves; and when grouping the datapoints based on whether D_{AB} or D_{BA} clicked, we would find a pattern like the black curve, i.e. *interference*. Interference/no interference is revealed when the full dataset is appropriately <u>sorted</u>.

Greene in [46] imagines that in GI-3D the processing of all idler photons is ten years later than for all signal photons. He collects a statistically sound dataset from the signal photons hitting $\mathrm{D_{PP}}$, finds ***no*** interference, stores the datapoints, and waits ten years to collect data from the traveling idler photons. He knows which idler photon corresponds to which signal photon. Then, despite not having found any *interference* ten years ago, he partitions the whole idler dataset according to the detectors where they showed up and finds that for the subsets related to $\mathrm{D_{AB}}$ and $\mathrm{D_{BA}}$, the signal data (collected ten years ago) display *interference* while those subsets for D_A and D_B do not. He says the signal photons corresponding to the idler ones arriving at the former two detectors "should be described as having traveled both paths" (*interference*) and those associated with the latter two detectors "went along either the left [upper] or right (lower) path" (***no** interference*). Still, the whole idler dataset implies ***no** interference* – agreeing with the 10-year-old signal dataset.

Greene does a final twist to GI-3D and imagines that just one day before the legion of idler photons are to hit the detectors after traveling for almost ten years, a "practical joker sabotages the experiment" by switching to our GI-1D, i.e. installing the red dotted-lines (a Milieu Event [25]), only allowing for the idler photons to hit either D_A or D_B. He then concludes:

> "Every signal photon went along either the left path or the right path and there will be no interference pattern to extract from the signal photon data. Thus, as this discussion forcefully highlights, the story you'd tell to explain the signal photon data depends significantly on measurements conducted ten years after data were collected." [46]

We already explained why different explications of the past have no place within a single theory. Greene instead claims that with this variant of his thought experiment all signal photons went one path or the other, while sans the sabotage, he would have concluded <u>some</u> of them had gone through both. Nonetheless, the ***no***-interference he had observed ten years before, still registered and accessible, agrees with the ***no***-interference inferred from the idler <u>whole</u> dataset – with the different explanations being just that: alternative stories with the purpose to explain something utterly mysterious. But Greene did not think about suddenly sabotaging from GI-2D to GI-1D. In such a case, while GI-2D shows at the moment of $\mathrm{D_{PP}}$ a signal *interference* pattern which -of course- agrees with the pattern inferred by the delayed idler dataset without sabotage, the idler dataset with sabotage implies ***no*** interference – either as a whole or after any possible partition. Greene's stories to explain the signal photon data based on the 10-year later idler data seem to be more than alternative "stories" about the past because the past dataset was recorded and showed *interference*, while the conclusion extracted from the idler dataset with sabotage contradicts what we know happened and was recorded ten years before.

QR/TOPI explains: the PD for a D_{PP} click depends on the quanton's initial State $|s\rangle$ and its global Milieu, which is supposed to remain the same throughout the quanton's evolution. Upon a Milieu-Event for the idler photons, there is an instantaneous change for the PD, so any conclusion based on the idler dataset ***cannot*** be used to coherently infer what already happened to the signal photon. In Greene's sabotaged experiment (GI-3D → GI-1D), the ***no***-interference inference ten years later agreed with the recorded ***no***-interference signal data in the past; in our sabotaged experiment (GI-2D → GI-1D), the ***no**-interference* inference ten years later disagrees with the *interference* recorded signal data in the past. This shows that all explanations based on *information* of which-path, marking, erasing, particle-wave duality, etc. are not just different-albeit-valid explanations of the past: they are simply wrong.

Conclusions

Zeilinger associates only the results of experiments with *Reality* and "what can be said about reality" with *information* – declaring by fiat that (as opposed to classical physics) they are "on an equal footing" and necessary for "a complete understanding of the world". I disagree: the relation between *Reality* and *Information* is the same in classical and quantum worldviews. The positing of *Reality* must be ab initio and primordial. *Information* is anthropic.

Zeilinger's *Principle* is not self-evident, unless we argue it is implicit in QT *Structure*, in which case it becomes a *theorem*. Bruckner and Zeilinger admit they use the prior concept of State to find out how to make their measure of *Information* complete, conservative, and unitary; and, after doing so, they speciously claim *Information* is fundamental. Having replaced the notion of State with *Total Information*, its general application is a sequitur, while presuming it is "the most basic notion" is not. Per QR/TOPI, there is no need for the epistemic notion of *Information*: the concept of State is enough, the Quanton is the object, the State is its fundamental *ontic* attribute – with its events being all actual albeit non-evincing. And being so, the so-called measurement problem is not such, and entanglement and nonlocality require no physical transmission of *Information*.

Against Zeilinger's 'Foundational Principle', per QR/TOPI, an elementary system 'carries' much more than the answer to one question. If the only *information* carried by a quanton with a spin along the z-axis is about the 'definite' result of a 'measurement' along the z-basis, why is its Probability Distribution (PD) 'definitely' different for other directions? A PD is also *information*. There is nothing to 'erase': the sudden change of Milieu instantly changes the ontic PD for the Quanton – like taking a m**a**croscopic pin off in Galton's quincunx right before being hit by the little ball instantly alters its probability to eventually fall into a given bin.

Entanglement and correlation must not be conflated: the former occurs among *quantons*; the latter between datasets obtained upon copious repetition of a given quanton/Milieu setup. Viewing the State as "just a representative of information" does not entitle an inexistent object to *entangle* with other objects. Actual and (ontically) probable quantons are real; ghosts are not.

Under the very same theory, what actually happens just now and here cannot depend on our future experimental caprice or, equivalently, cannot change what happened in the past. By reviewing several experimental epitomes of quantum 'quirkiness', it is shown that all explanations based on *Information* of which-path, marking, erasing, particle-wave duality, etc. are not just different-albeit-valid explanations of the past: they are simply wrong. Under QR/TOPI, quantons are neither *waves* nor *particles*: any physical explanation in terms of wave-particle duality is doomed to failure by deceiving us into mistakenly accepting *retrocausality*.

Statements and Declarations

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References

[1] A. Einstein, B. Podolsky and N. Rosen, "Can Quantum-Mechanical Description of Physical Reality be Considered Complete?," *Physical Review,* vol. 47, pp. 777-780, 1935.

[2] F. Alba-Juez, "The Ontic Probability Interpretation of Quantum Theory - Part I: The Meaning of Einstein's Incompleteness Claim," 5 February 2020. [Online]. Available: https://philpapers.org/rec/ALBTOP-2.

[3] F. Alba-Juez, "The Ontic Probability Interpretation of Quantum Theory - Part II: Einstein's Incompleteness/Nonlocality Dilemma," 5 February 2020. [Online]. Available: https://philpapers.org/rec/ALBTOP.

[4] J. S. Bell, Speakable and unspeakable in quantum mechanics, Cambridge: Cambridge University Press, 1987.

[5] T. Maudlin, Quantum Non-Locality & Relativity, Cambridge, MA: Blackwell Publishers, Inc., 1994.

[6] C. Bruce, Schrödinger's rabbits - the many worlds of quantum, Washington, DC: Joseph Henry Press, 2004.

[7] R. Landauer, "The Physical Nature of Information," *Physics Letters,* vol. A 217, pp. 188-193, 1996.

[8] R. Alicki, "Information is not Physical," 11 February 2014. [Online]. Available: arXiv:1402.2414v1 [quant-ph].

[9] J.-W. Pan, D. Bouwmeester, H. Weinfurter and A. Zeilinger, "Experimental Entanglement Swapping: Entangling Photons That Never Interacted," *Physical Review Letters,* vol. 80, no. 18, pp. 3891-3894, 4 May 1998.

[10] A. Zeilinger, "A foundational principle for quantum mechanics," *Found. Phys.,* vol. 29, pp. 631-643, 1999.

[11] A. Zeilinger, "Experiment and the foundations of quantum physics," *Reviews of Modern Physics,* vol. 71, no. 2, pp. S288-S297, 1999.

[12] C. Brukner and A. A. Zeilinger, "Malus' Law and Quantum Information," *acta physica slovaca vol. 49 No. 4, 647 – 652,* vol. 49, no. 4, pp. 647-652, 1999.

[13] A. Zeilinger, "Bell's Theorem, Information, and Quantum Physics," 2002. [Online]. Available: https://www.oeaw.ac.at/fileadmin/Institute/IQOQI-Vienna/PDF/publications-zeilinger/2002_-_Quantum_Unspeakables_-_Bells_Theorem_Information_and_Quantum_Physics.pdf.

[14] T. Jennewein, G. Weihs, J.-W. Pan and A. Zeilinger, "Experimental Nonlocality Proof of Quantum Teleportation and Entanglement Swapping," 29 January 2002. [Online]. Available: http://arxiv.org/abs/quant-ph/0201134v1.

[15] A. Zeilinger, "Why the quantum? "It" from "bit"? A participatory universe? Three far-reaching challenges from John Archibald Wheeler and their relation to experiment," in *Science and Ultimate Reality: Quantum Theory, Cosmology, and Complexity. Barrow, J., Davies, P., Harper, C. (eds.)* , Cambridge, Cambridge University Press, 2004, p. 201–220.

[16] A. Zeilinger, "On the interpretation and philosophical foundation of quantum mechanics," in *Vastakohtien todellisuus (Festschrift for K. V. Laurikainen), U. Ketvel et al., eds.*, Helsinki, Helsinki University Press, 1996.

[17] A. Zeilinger, Dance of the Photons - From Einstein to Quantum Teleportation, New York: Farrar, Strauss and Giroux, 2010.

[18] C. Brukner and A. Zeilinger, "Conceptual Inadequacy of the Shannon Information in Quantum Measurements," 25 October 2002/2018. [Online]. Available: http://arxiv.org/abs/quant-ph/0006087v3.

[19] C. Brukner and A. Zeilinger, "Information and fundamental elements of the structure of quantum theory," 23 October 2002/2018. [Online]. Available: http://arxiv.org/abs/quant-ph/0212084v1.

[20] C. Brukner and A. Zeilinger, "Young's experiment and the finiteness of information," 22 October 2002/2018. [Online]. Available: http://arxiv.org/abs/quant-ph/0201026v2.

[21] C. Brukner, M. Aspelmeyer and A. Zeilinger, "Complementarity and Information in ”Delayed-choice for entanglement swapping"," 25 October 2004/2018. [Online]. Available: http://arxiv.org/abs/quant-ph/0405036v1.

[22] C. Z. A. Brukner, "Operationally Invariant Information in Quantum Measurements," 19 May 2000. [Online]. Available: http://arxiv.org/abs/quant-ph/0005084v1.

[23] C. Brukner, M. Zukowski and A. Zeilinger, "The essence of entanglement," 20 June 2001. [Online]. Available: http://arxiv.org/abs/quant-ph/0106119v1.

[24] F. Alba-Juez, "The Ontic Probability Interpretation of Quantum Theory - Part III: Schrödinger's Cat and the 'Basis' and 'Measurement' Pseudo-Problems," 4 April 2021. [Online]. Available: https://philpapers.org/rec/ALBTOP-3.

[25] F. Alba-Juez, "The Ontic Probability Interpretation of Quantum Theory, Part IV: How to Complete Special Relativity and Merge it with Quantum Theory," 9 September 2024. [Online]. Available: https://philpapers.org/rec/ALBTOP-4 .

[26] F. Alba-Juez, Galloping with Light - Einstein, Relativity, and Folklore, Salt Lake City, USA: Felix Alba-Juez, Publisher, 2011.

[27] F. Alba-Juez, Records of the Future - Classical Entropy, Memory, and the 'Arrow of Time', Salt Lake City: Felix Alba-Juez, Publisher, 2013.

[28] F. Alba-Juez, Aiming at REALITY - Statistical Entropy, Disorder, and the Quantum, Salt Lake City: Felix Alba-Juez, Publisher, 2017.

[29] F. Alba-Juez, Nighing REALITY: Quantum Fusion after 25 Years of Confusion, Saint George, Utah, USA: Felix Alba-Juez, Publisher, 2018.

[30] F. Alba-Juez, Elements of REALITY - 1925-1935: The Onset of an Unfinished Philosophical Struggle, Saint George, Utah: Felix Alba-Juez, Publisher, 2019.

[31] O. Lombardi, "About the Nature of Quantum Information," in *Conference on Theoretical and Foundational Problems in Information Studies, IS4SI Summit*, 2022.

[32] C. Brukner and A. Zeilinger, "Conceptual inadequacy of the Shannon information in quantum measurements. 63, 022113," *Physical Review A,* vol. 63, p. 022113, 2001.

[33] C. Timpson, "On a Supposed Conceptual Inadequacy of the Shannon Information in Quantum Mechanics," 18 December 2002. [Online]. Available: http://arxiv.org/abs/quant-ph/0112178v3.

[34] C. G. Timpson, "The applicability of the Shannon information in quantum mechanics and Zeilinger's Foundational Principle," in *PSA 2002, PITT-PHIL-SCI-00000710.*, Pittsburgh, 2002.

[35] A. Shafiee, F. Safinejad and F. Naqsh, "Information and The Brukner-Zeilinger Interpretation of Quantum Mechanics: A Critical Investigation," 27 March 2022. [Online]. Available: http://arxiv.org/abs/quant-ph/0407198v2.

[36] M. J. W. Hall, "Comment on “Conceptual Inadequacy of Shannon Information ...” by C. Brukner and A. Zeilinger," 31 July 2000. [Online]. Available: http://arxiv.org/abs/quant-ph/0007116v1.

[37] A. Duwell, "Quantum Information Does Not Exist," *Stud. Hist. Philos. Mod. Phys.,* vol. 34, pp. 479-499, 2003.

[38] D. Deutsch, The Fabric of Reality - The Science of Parallel Universes and Its Implications, New York: Penguin Books, 1997.

[39] A. Elitzur and L. Vaidman, "Quantum Mechanical Interaction-Free Measurements," 5 May 1993. [Online]. Available: http://arxiv.org/abs/hep-th/9305002v2.

[40] S. Carroll, Something Deeply Hidden - Quantum Worlds and the Emergence of Spacetime, Penguin Random House LLC, 2019.

[41] D. Wallace, The Emergent Multiverse: Quantum Theory According to the Everett Interpretation, Oxford: Oxford University Press, 2012.

[42] M. Tegmark, Our Mathematical Universe - My Quest for the Ultimate Nature of Reality, New York: Alfred A. Knopf, 2014.

[43] A. Ananthaswamy, Through Two Doos at Once - The Elegant Experiment that Captures the Enigma of our Quantum Reality, New York: Dutton, Pinguiin Ramdom House, 2018.

[44] M. Arndt and Others, "Wave-particle duality of C60 molecules," *Nature,* vol. 401, 14 October 1999.

[45] J. Wheeler, "The “past” and the “delayed-choice” double-slit experiment," in *Mathematical Foundations of Quantum Theory, Marlow, A.R. (ed.)* , New York, Academic Press, 1978, pp. 9-48.

[46] B. Greene, The Fabric of the Cosmos - Space, Time, and the Texture of Reality, New York: Vintage Books, 2004.

[47] P. G. Kwiat and Others, "High-efficiency quantum interrogation measurements via the quantum Zeno effect," 27 September 1999. [Online]. Available: http://arxiv.org/abs/quant-ph/9909083v1.

[48] H. Paul and M. Pavĭcić, "Nonclassical interaction-free detection of objects in a monolithic total-internal-reflection resonator," *Journal of the Optical Society of America,* vol. B 14, pp. 1273-1277, 1997.

[49] H. Paul and M. Pavĭcić, "Realistic Interaction-Free Detection of Objects in a Resonator," *Foundations of Physics,* vol. 28, p. 959–970, 1998.

[50] D. Deutsch, "Quantum Theory, the Church-Turing Principle and the Universal Quantum Computer," *Proc. Roy. Soc. Lond.,* vol. A 400, pp. 97-117, 1985.

[51] E. Schrödinger, "Quantum Theory and Measurement," *Naturwissenschaften,* vol. 23, pp. 807-812,823- 828, 844-849, 1935.

[52] Y. Kim, R. Yu, S. Kulik and M. Scully, *Phys. Rev. Lett.,* vol. 84, no. 1, pp. 1-5, 2000.

[53] S. P. Walborn and Others, "A double-slit quantum eraser," 13 June 2001. [Online]. Available: http://arxiv.org/abs/quant-ph/0106078v1.