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Rhetoric, logic, and experiment in the quantum nonlocality debate

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Abstract: Quantum nonlocality (QNL) has not been rigorously proven, despite recent Einstein-Podolsky-Rosen-Bohm (EPRB) experiments claimed to be 'loophole-free'. First, readers are alerted to rhetorical arguments, which are unfortunately often appealed to in the QNL debate, to empower readers to identify and reject such arguments. Second, logical problems in QNL proofs are described and exemplified by a discussion of the projection postulate problem. Third, experimental issues are described and exemplified by a discussion of the postselection problem. The paper concludes that QNL has not been proven and that locality cannot be excluded.

Keywords: quantum nonlocality, Bell/CH/CHSH inequalities, projection postulate, postselection, rhetoric

1 How to prove quantum nonlocality

Quantum nonlocality (QNL) is a big deal. Large research groups have sprouted up to investigate quantum information and its applications in computation, security, and communications. Billions of dollars are spent worldwide in an attempt to make these promising technologies real (with little to show for the investment thus far). We should be convinced beyond doubt of the reality of QNL before investing large amounts of money and other resources into its realization. The proof of its existence must be rock solid.

What would a proof of QNL look like? Just like any experimental proof. Raw experimental data is analyzed using a theory and assumptions to deliver a verdict on a proposition, in this case, the proposition that 'QNL exists in nature'. The analysis is a deductive process working on the raw data, and can include statistical arguments. To accept the truth of QNL, we can reasonably expect to receive the full raw data and the full deductive analysis applied to reach the verdict. Usually, the analysis is done by a computer program, so the full deduction is contained in the computer source code. With the data and the analysis we are in a position to look for problems in the data, the data gathering (the experimental design), and the analysis. Only if no disqualifying problems are found can the experiment be considered to bear upon the truth of QNL. We need to be confident that an offered proof is not wrong because of problems in the proof.

Often we hear the argument that quantum mechanics (QM) is already thoroughly experimentally proved, and because QM theoretically predicts QNL, QNL is also thoroughly proved. Experiments designed to test QNL are considered pointless. However, I show in Section 3.2 that QNL is only one of several possible theoretical predictions for an EPRB experiment, the choice of which is determined by the experimental arrangement. QM can still be true while QNL is false. It is a misconception to assume that QM necessarily predicts QNL. We do need dedicated experiments to test QNL.

The goal of this paper is to guide readers in assessing the reported experiments bearing on QNL, and to instil an appropriate degree of skepticism, so that readers can reach an informed conclusion. I divide the main discussion into two sections: 'Logic' and 'Experiment and data analysis' (the dividing line is not always clear). I focus on one potentially disqualifying and underappreciated problem in proofs of QNL for each of these two categories that readers should know about. Other interesting papers in this special edition address additional problems.

While surely all of us welcome data and analysis as important components of a proof, we can also agree that rhetorical arguments (in the broadest sense) are not valid components of the proof. They distort the process of truth seeking. An example: the peremptory dismissal of reasoned arguments as 'crackpot', while giving no reasoned arguments in rebuttal. Name calling cannot be taken as a valid part of a proof.

Unfortunately, rhetorical arguments figure prominently in the current QNL debate. Another goal of this paper is to alert and warn readers about rhetoric so its harmful effects can be avoided. I begin with a section

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about rhetoric in the QNL debate, after which I try to set a desirable example by presenting my following arguments without rhetoric of any kind. Data and analysis must speak the first, last, and only words.

2 Rhetoric

2.1 'Loopholes' and other dubious terminology

The term 'rhetoric' in the QNL debate refers broadly to strategy or tactics unrelated to the crucial components of a proof, data and deductive analysis. The goal of rhetoric is to influence the debate in favor of one side or the other. Rhetorical argument is seen in all aspects of human activity, so it is not surprising to see that it has a big presence in the QNL debate. A careful, rational observer suspects that a person appealing to rhetoric may be covering up for problems in their rational arguments. Their real argument might be very weak. Without concluding on that matter, we can agree that rational arguments for or against QNL should not and cannot be dismissed or defeated by rhetoric, and that we should view attempts to sway the debate with rhetoric as red flags.

Ideally, our advancement and consideration of arguments in QNL should exclude any rhetorical influences. To support this goal I present in this section a short survey of rhetoric in science to help readers better identify rhetorical arguments in the QNL debate. Then in the following section I make some arguments in the QNL debate in a manner avoiding all rhetoric, hoping to serve as a meritorious example of scientific argument without rhetoric. My arguments challenge the existence of QNL, and they should be assessed and judged without rhetorical considerations.

Consider the term 'loophole' in the context of the QNL debate [1–3]. The term implies or assumes there is a strong, decisive argument in favor of QNL that is thwarted only by nitpicking quibbles. QNL is assumed true and the loopholes are considered inconsequential details. It's just a matter of closing all the loopholes in experiments and then QNL will be proved. We notice, however, that the term 'loophole' is pejorative rhetoric and should therefore be banished. Instead, we should use the term 'problem'. We should talk about problems in our data and analyses, and how we might resolve these problems. When we cannot identify any significant problems in a proof of QNL, only then can we say that the proof supports QNL.

What are some of the problems we might find in a proof of QNL? Here are some:

1. flaws in logic (incorrect analysis),
2. false and unchallenged assumptions (conventional wisdom, 'unspeakables', etc.),
3. incomplete analysis,
4. insufficient statistics,
5. incorrect statistical analyses,
6. incomplete data (data discarding, postselection, etc.),
7. spurious data (noise, dark counts, accidental counts, etc.),
8. corrupted data,
9. fabricated data.

These things are not quibbles and they cannot be resolved by dismissing them with rhetorical labels like 'loophole'.

Another rhetorical strategy in the QNL debate related to 'loopholes' that borders on dishonesty and insults our intelligence goes like this: "loophole A was closed in experiment P, loophole B was closed in experiment Q, loophole C was closed in experiment R, so all the loopholes are closed." But a given experimental proof of QNL must be without any problems, that is, all the 'loopholes' must be closed in any given experiment if it is to weigh in favor of QNL. Fable: A magician likes to prove that things can be made to disappear by performing some tricks. Each trick uses a different sleight-of-hand for each performance. If one trick is exposed, the magician says it doesn't matter because the other performances succeeded without that sleight. Or different magicians perform using different sleights. Here we see that 'magic trick' plays the role of a 'loophole'.

For QNL adherents, 'loopholes' refer to tricks or obscure expedients that allow a local mechanism to produce the quantum correlation. But a local realist may prefer to talk about 'magic tricks' in the proof of QNL. If the consensus view was against QNL, the approved terminology would be 'magic tricks' rather than 'loopholes'. The rhetorical discussion may be deadlocked but fortunately it is irrelevant. To avoid rhetorical bias either way, as suggested, we should talk about problems in the proof, i.e., in logic, experimental design, interpretation of data, etc. Any unresolved problems in the proof must disqualify it. The proof breaks into a logical argument, experimental data collection, and analysis. Any of these components can have problems that disqualify the purported proof of QNL.

An amusing new rhetorical phrase in the QNL debate is 'loophole-free' [4–6]. Here the authors of experimental papers include the phrase 'loophole-free' in their arguments (and even in their paper titles!) as an imprimatur or certificate of authenticity. It is amusing because 'loophole-free' simply means without problems. Can we imagine writing a paper with a title like this: "Problem-free demonstration of relativistic dynamics"? As if we might otherwise publish a paper that we know is undermined by significant problems. Therefore, the term 'loophole-free' is a red flag signaling that rhetoric is being employed.

Other rhetorical terminology appears in debate. Scientists are referred to as 'crackpots' [7] or 'dissidents'. We hear that 'no sensible physicist can doubt' and that 'the majority of physicists believes'. We hear emotional, indignant, and pejorative terminology. This noise in the debate is a given of human behavior and it should not surprise us. The sword cuts both ways. A local realist might talk like this: 'Behold the colossal lie of quantum nonlocality! A lie so colossal that nobody can doubt it." To reach truth, however, we have to identify rhetoric from all sides and leave it out of our considerations.

2.2 More troublesome rhetorical strategies

While the rhetorical aspects just described may be relatively benign because they can simply be ignored when recognized, other more egregious practices present obstacles that are difficult if not impossible to evade. For example, though the debate on QNL has yet to be resolved definitively either way (a proof of QNL would be Nobel prize material but one has not been awarded), several important and high-impact physics journals enforce a policy that declares that papers challenging QNL will not be considered or sent for review. One well-known example of this is [8] and I have also received such communications from the American Physical Society. Papers challenging QNL receive immediate desk rejections. This type of 'gatekeeping' is seen not just in publishing but also in employment and the awarding of research grants. Local realists are systematically excluded. Advocacy of local realism can be a suicidal career move.

Another interesting aspect of QNL rhetoric affects the literature. We see collections of invited articles that amount to hagiography (paying homage for example to John Bell and other stalwarts of QNL). These collections neither invite nor include critical views, thereby misleadingly giving the erroneous impression that there is no valid challenge to QNL. Conversely, Albert Einstein is derided for his critical views; some have gone so far as to imply that his objections were due to the onset of senility. This is rhetoric of the highest order. The popular science press underscores this rhetoric with gee-whiz articles and personality cultism, while rarely giving voice to critical views. This represents a genre of science journalism that might be thought of as 'fake news'. Meanwhile, discredited experiments continue to be regularly cited as proof of QNL.

In my view, for a matter of such fundamental importance, if the real goal is to establish the truth, research and experimental teams should include both nonlocalists and local realists. In several fields of endeavor this is standard practice. The concept is referred to as 'red and blue teams'. I offered to assist one research group in identifying possible problems before their research was published, but the offer was rejected with an accompanying dose of ridicule. The failure to include diverse views is a giant red flag suggesting that the group may be more concerned with fame and fortune (grants and positions) than with establishing truth.

2.3 Rhetoric-free communication

Naturally we expect those seeking the truth of the matter of QNL to be unpersuaded by rhetoric and disinclined to pollute the debate with rhetoric of their own. I hope in this section to have helped readers to identify rhetoric in the current debate. As an exercise in correct science that follows these precepts and excludes rhetorical arguments, I now present rhetoric-free consideration of several problems in the modern proofs of QNL. While I refrain from using rhetoric in the following material, I must not hestitate to point out its use by others when necessary, and to alert readers to attempts to illegitimately influence their thinking.

3 Logic

In this section I consider a potentially disqualifying logical problem in purported proofs of QNL. By logical problems I mean those affecting the deductive component of the proof. Obviously there is not room to discuss all such problems that have been identified and discussed, so I choose to discuss one that seems important and underappreciated to me. Others are discussed by the other authors in this special edition. To make the discussion concrete I consider problems in a specific proof of QNL based on Bell-like inequality violation (either the CH or the CHSH inequalities) [9].

3.1 Basic proof of quantum nonlocality

Purported proofs of QNL based on inequality violation beginning with the work of John Bell [9] are well covered in the literature and therefore it is not necessary to include here a detailed account of the arguments. Nevertheless, it is helpful to provide an executive summary.

Consider an Einstein-Podolsky-Rosen-Bohm (EPRB) experiment using photons (spin 1 particles). A source generates a pair of photons in a quantum (anticorrelated) singlet state and sends one photon of the pair to two separated detection stations, each of which can set its orientation freely and independently. The stations record photon detections together with their arrival times.

In the context of the CH inequality [10], the joint prediction for EPRB states that the probability of both sides detecting the photon on a given source emission event is $1/2cos^2(theta)$, where $theta$ is the angle between the detector orientation settings of the two sides. In the context of the CHSH inequality [11], where a detection is assigned result $+1$ and nondetection as -1 (for single-channel experiments), the expectation value of the product of the two results is $-cos(2 * theta)$.

The EPRB experiment consists of four runs, consisting of the four combinations of two possible orientation settings at the two sides. The CH metric is:

$$CH = P(AB)_{ab} + P(AB)_{ab'} + P(AB)_{a'b} - P(AB)_{a'b'} - P(A)_{ab} - P(B)_{ab} \quad (1)$$

where $P(AB)_{ab}$ is the probability of a coincident photon detection at sides A and B when the orientation settings are a and b, etc., and $P(A)_{ab}$ is the probability of photon detection at side A when the orientation settings are a and b, etc. Clauser and Horne showed that for a local realistic theory the following inequality must be satisfied [10], while the quantum joint prediction allows for its violation.

$$CH <= 0 \quad (2)$$

The CHSH metric is:

$$S = E(AB)_{ab} + E(AB)_{ab'} + E(AB)_{a'b} - E(AB)_{a'b'} \quad (3)$$

where $E(AB)_{ab}$ is the expectation of the product of the results at sides A and B when the orientation settings are a and b, etc. Bell showed that for a local realistic theory the following inequality must be satisfied [9], while the quantum joint prediction allows for its violation.

$$S <= 2 \quad (4)$$

The experiment is designed with sufficient detection efficiency and with a sufficient number of source emission events to allow for accurate estimates of the probabilities and expectations based on the per-emission results. If the relevant inequality is violated, it is claimed that QNL is proved.

In the early history of EPRB experiments, several disqualifying problems were present, including the variable detection problem (detection efficiency depends on the orientation setting), the coincidence problem (establishment of coincident detections based on the detection times was affected by the orientation settings), the locality problem (sufficient separation was not enforced or leakage was present). Without going into details here, I acknowledge that these problems are or can be overcome in the modern generation of experiments. For example, if a device known as an electro-optic modulator is used to implement the measurement settings, the difference in detection delays across settings is orders of magnitude smaller than that needed to produce unfair sampling large enough to significantly violate the CH/CHSH inequality. Also, modern experiments are now implementing heralding, which avoids the coincidence problem entirely. Note, however, that a somewhat different view is offered in [12] of this special issue.

The next section considers a logical problem in such proofs of QNL: the projection postulate problem. I claim that the projection postulate problem remains unresolved in reported experiments and remains a potentially disqualifying issue.

It is also worth notifying readers about another prominent logical problem: the contextuality problem. Some considerations of probability theory and the conditions for existence of a joint PDF have inspired a view held in some circles that violation of the Bell inequality shows only that incompatible (noncommutative) observables have been illegitimately combined and that the inequality can tell us nothing about locality. Alternative statements of this position often heard are a) that derivation of a Bell-like inequality requires the existence of a single sample space for all the experiments, or that a joint PDF for all the experiments must exist, and b) that the Bell-like inequality cannot be derived because each run of the experiment acts upon a different subensemble of source emission events (a single source emission cannot be tested twice, once with each setting). Violations are attributed simply to the fact that a single sample space or ensemble does not exist, due to incompatibility of observables. This important problem is addressed by other authors in this special edition. The reader may also refer to the literature for further discussion and analysis.

3.2 The projection postulate problem

A succinct executive summary of the proof of QNL given in Section 3.1 contains two assertions: 1) QM predicts quantum correlations and consequent violation of the CH/CHSH inequality, implying QNL, and 2) the experiments verify that the inequality is violated in nature. It sounds convincing, but what if contrary to common belief QM does not in fact predict quantum correlations and thus does not predict inequality violation for an EPRB experiment? The proof falls apart and then an observed violation proves only that the experiments are incorrectly designed, implemented, or analyzed, and we would be motivated to identify the experimental problem(s). Indeed, I argue that both of these assertions are false and that the proof of QNL is invalid.

In this section, I develop the argument against the commonly accepted view that QM predicts quantum correlations and consequent violation of the CH/CHSH inequality. In Section 4 I develop the argument that the experiments conducted to date are invalid. Before proceeding it is important to give an overview of the projection postulate (also known as 'collapse of the wavefunction') to ensure full appreciation of my argument.

The projection postulate was first proposed by Dirac [14]. He claimed that when a measurement yields an eigenvalue of an operator, the system is left in the corresponding eigenstate. This idea was endorsed by von Neuman [15], and in modern textbooks of quantum mechanics it has since taken on the status of a postulate, the so-called Dirac-von Neumann projection postulate. For example, Rae [16] gives as his postulate 4.2: "Every dynamical variable may be represented by a Hermitian operator whose eigenvalues represent the possible results of carrying out a measurement of the value of the dynamical variable. Immediately after such a measurement, the wavefunction of the system will be identical to the eigenfunction corresponding to the eigenvalue obtained as a result of the measurement."

When the eigenvalues are degenerate, the Dirac-von Neumann projection postulate gives the resulting state as an evenly weighted mixture of the eigenfunctions singled out by the measurement. Formally, Dirac-von Neumann projection tranforms the pre-measurement density matrix to the post-measurement density matrix as follows:

$$\rho_{post} = A/Tr(A) \tag{5}$$

where A is the density operator corresponding to the measurement. The resulting state contains no trace of the original state and is therefore considered to be maximally disturbing.

Lüders extended the Dirac-von Neumann projection postulate to revise the treatment of degeneracy [17], proposing the so-called Lüders rule, which has become generally accepted as the correct projection postulate. Formally, Lüders' rule tranforms the pre-measurement density matrix to the post-measurement density matrix as follows:

$$\rho_{post} = (A\rho_{pre}A)/Tr(A\rho_{pre}) \tag{6}$$

The resulting state preserves the weightings in the original state and is therefore considered to be minimally disturbing (although I argue later that the truly minimally disturbing measurement is one without any form of projection). Note that in the absence of degeneracy the Lüders rule reduces to Dirac-von Neumann projection.

Supporters of QNL sometimes argue that projection is irrelevant to the QNL debate because (they claim) quantum correlations can be derived without appealing to the projection postulate. This is incorrect, as I show elsewhere [18]. It is true that the quantum correlations can be derived assuming a *joint measurement*, consisting of a single sampling that includes the orientation settings at both sides. However, in EPRB experiments, there are two separated independent samplings at the two sides, each of which can include only its orientation setting, and one side must project the other side in conformance with Lüders' rule if the quantum correlations are to be derived. It is very important to properly distinguish joint sampling from the separated sampling that occurs in a real EPRB experiment. I explain this very clearly in the above-cited paper.

The projection postulate appears to be satisfying in that it seems reasonable to assume that if we measure a given eigenvalue then the system must be in the corresponding eigenstate (e.g., Polkinghorne writes that the two "must obviously correspond" [19]), and in that its use leads to repeated measurements on the same system always giving the same result. Nevertheless, the projection postulate has been strongly challenged from its first introduction and it remains highly controversial [20–27]. I now briefly list some of the arguments that have been directed against the general idea of projection after which I challenge in more detail the application of Lüders' rule to EPRB. Refer to the cited references for further details on the following arguments.

1. Projection is a violation of unitary dynamic evolution, i.e., Schrodinger's equation. QM provides no guidance about what constitutes a measurement and when projection is to be applied. QM also provides no guidance about how symmetry is to be broken

for simultaneous measurements. For example, if the two sides in an EPRB experiment measure simultaneously, which one projects the other?
2. Several interpretations of QM dispense entirely with the projection postulate, e.g., the many-worlds and modal interpretations.
3. Projection is arguably not actually needed or used in any significant quantum calculations. Projection is not present in quantum field theory.
4. Projection is simply false for many real physical scenarios. Some measurements do not give the same result upon repetition, e.g., because the system is annihilated (photons disappear upon detection), or because the measurement involves an unpredictable violent disturbance.
5. In the Copenhagen interpretation a state refers to an ensemble, so it is incongruent that a measurement on a single member of an ensemble can define the distribution for the entire ensemble. In other words, QM is statistical but projection is deterministic.
6. Postulating projection in effect simply postulates QNL, obviating any need for experiments and rendering the proof of QNL tautological.

While these considerations are enough to throw the projection postulate into serious doubt, an objection more directly germane to EPRB can be given: Lüders projection cannot be valid for EPRB because it requires superluminal transmission of information. Without Lüders projection one can fall back to von Neumann projection (the projected state is a mixture) or to null projection (no projection at all), both of which fail to predict quantum correlations. The argument goes as follows (refer to [18] for full details).

Consider a spin 1/2 singlet state. The input singlet state is rotationally invariant, so it can be expressed in the a measurement basis as follows:

$$\psi_{singlet} = \frac{1}{\sqrt{2}}(|-1_a, 1_a\rangle - |1_a, -1_a\rangle) \tag{7}$$

The a subscripts denote the a measurement basis. If the measurement at A produces a value of -1_a, then Lüders' rule gives the renormalized projected state as:

$$\psi_L = |-1_a, 1_a\rangle \tag{8}$$

This is separable so the projected B state is $|1_a\rangle$, and the corresponding $2x2$ density matrix is $|1_a\rangle\langle 1_a|$. Therefore, the projected $2x2$ density matrix in the Z basis for the case of $O_A = -1$ is given by:

$$O_A = -1: \quad \rho_B^{2x2} = |1_a\rangle\langle 1_a| = \begin{bmatrix} cos^2(a/2) & sin(a/2)cos(a/2) \\ sin(a/2)cos(a/2) & sin^2(a/2) \end{bmatrix} \tag{9}$$

Similarly, the projected density matrix in the Z basis for the case of $O_A = 1$ is given by:

$$O_A = 1: \quad \rho_B^{2x2} = |-1_a\rangle\langle -1_a| = \begin{bmatrix} sin^2(a/2) & -sin(a/2)cos(a/2) \\ -sin(a/2)cos(a/2) & cos^2(a/2) \end{bmatrix} \tag{10}$$

These projections result from straightforward application of orthodox Lüders projection and are fully derived in [18]. Calculation of the expectation value $\langle AB\rangle$ now proceeds straighforwardly using the projected state and yields quantum correlation. However, all is not well because it is easily shown (see below) that this projection requires superluminal transmission of information. While a debate rages over whether superluminal influences actually violate special relativity and how, for my purposes it is sufficient to note that no satisfactory covariant account of state reduction has been proposed to date, despite intense efforts to find one [28].

Orthodox quantum theory employing Lüders projection, as shown, entails that the measurement at side A produces a projected state at side B. The projected state is one of the two states given in equations (9) and (10). The projected state must be locally present at side B, to be available for the local measurement at side B. It is obvious from equations (9) and (10) that the projected state contains information about both the measurement angle a at side A (a appears directly in the density matrices) and information about the outcome (the outcome determines which of the two states is projected). It is clear, not only from the demonstration here, but from other analyses [13, 18, 30], that both parameter and outcome independence must be violated to account for EPR correlations.

Transmission of information is not problematic as long as the transmission is not required to occur at superluminal speeds, because special relativity would be violated, and that is something that theorists must reject to maintain a consistent axiom set for physics. However, it is easy to see that the quantum separated solution using Lüders' rule requires superluminal transmission in the paradigmatic EPRB experiment with a large separation between the measurement sides. The experiment can be set up such that the measurement at side B occurs before enough time elapses to allow subluminal transmission of information. If EPR correlations are to be obtained in such a scenario, then parameter and outcome information become available in the projected state localized to side B within the arbitrarily small inter-measurement time, which is much shorter than the time required to physically transmit the information. Therefore, the general separated solution using Lüders' rule requires superluminal transmission of information, violating special relativity.

One could argue that, although the information is indeed present at side B superluminally, there is no way for side B to extract it (per the no-signaling theorem), and so there is a 'peaceful coexistence' with special relativity. This notion supposes that information that cannot be extracted is not really information, and that superluminal transfer of such "information" therefore does not violate special relativity. However, this view is easily refuted, and I emphasize that the information must have been present at side B superluminally.

Consider two separated stations A and B. Station A possesses a real variable a, and a second randomly selected real variable r. Station A generates $b = a + r$ and sends b to station B. Station B cannot extract a from b, however, b nevertheless contains information about a. This is simply proven because station B can pass b to a third station C, which also receives r from station A. Station C can access a by subtracting r from b. It is clear that information about a existed at station B and that the information was passed through station B to station C, despite station B's inability to extract that information. A more intuitive case showing the irrelevance of inability to access the information runs as follows. I write a message and lock it in a box. I send the key to my friend Charlie. I give the box to my friend Bob. Bob possesses the information of the message but cannot access it. We know the information is there from common sense but also because Bob can give the box to Charlie who can open the box and access the information.

Special relativity therefore prevents Lüders projection from validly applying to EPRB. Alternative calculation with von Neumann projection or null projection does not yield quantum correlation [18]. Although von Neumann projection does not yield quantum correlation, it does still require superluminal transmission of at least one bit of information to signal projection of the singlet state to a mixture at side B, as required. Theoretically, however, even one bit of information transferred superluminally forces us to reject von Neumann projection for EPRB.

The correct form of projection must be chosen based on the specific arrangement of an experiment. Hegerfeldt and Sala Mayato [31] correctly argue that different forms of projection "may appear naturally, depending on the realization of a particular measurement apparatus" and "Their applicability depends on the circumstances, i.e., the details of the measurement apparatus." The only correct solution for EPRB must exclude all information transfer, that is, it must exclude projection completely. In the absence of projection, quantum correlation is not possible. QNL is a mistake, and the misapplication of the Lüders projection postulate is the source of apparent nonlocality. I agree with Isham when he states that Lüders projection "is best regarded as a definition of what is meant by an 'ideal measurement' in the case of a degenerate eigenvalue" [29], rather than as an obligatory physical process.

4 Experiment and data analysis

This section considers a problem in experimental design and data analysis: the postselection problem. I claim that the postselection problem remains unresolved in several of the reported experiments and remains a potentially disqualifying issue in experimental analysis.

Again, it is also worth notifying readers here about another prominent experimental analysis problem: the coincidence or pairing problem. We need to know how detection events are related to the source events. Is a given pair of detections (one per side) in the experimental data linked, i.e., do the two detections result from a single source pair of photons, or do they represent two single detections from two source pair emissions? This is the pairing problem. A common approach to solve this problem is to use a coincidence window. After adjustment for possible differences in detection delays at the two sides due to different distances of the detection stations from the source, detection events at the two sides are considered to be paired (generated from a single source emission) if their arrival times are close enough in time to each other (the coincidence widow).

There are valid methods to avoid the pairing problem. For example, I have shown elsewhere [32] that it can be avoided by designing the experiment such that the detection times are not significantly affected by the settings (and the analysis must show that there is no such modulation), and that a sufficiently low emission rate is used. Another modern approach is to use source event heralding, in which detection events can be claimed to be reliably associated with source events. Valid heralding can also avoid the normalization problem. Estimation of probabilities or expectations requires forming ratios of detection counts to the number of source events, but without heralding, the number of source events cannot be known. With valid heralding the number of source events can be known exactly. Fully reliably heralding is the ideal way to avoid the pairing problem and Hensen et al. [4] arguably achieved it, but in my view their proof is disqualified by the postselection problem (data discarding), as we see in the next section.

4.1 The postselection problem

4.1.1 What is postselection

The postselection problem requires (in the general case), through a mechanism not specified, that some fraction of the full data of the experiment is absent from or not considered in the data analysis, producing only an artifactual violation of the applicable Bell-like inequality. Experimental physicists conducting an experiment must prove that postselection is not present in the experiment, or that any postselection that is present is harmless. Here I discuss the postselection problem in the context of two oft-cited EPRB experiments: the Christensen et al. [33] and Hensen et al. [4] experiments, and I argue that Christensen et al. and Hensen et al. have not succeeded in discharging their responsibilities to prove the absence of harmful postselection.

Throughout the paper, the term 'postselected' means postselected *out*, i.e., deleted. In some other contexts, the term might be used to denote selective inclusion, but here the meaning is selective exclusion.

Other known problems, such as the variable detection problem, can be considered to be examples of the postselection problem, as data is lost. In the variable detection case lost data is never in fact collected, although it could have been, had the variable detection mechanism not been in operation. Here I focus on cases where collected experimental data is intentionally or unintentionally discarded in the data analysis. To make this idea concrete, consider the EPRB experiment of Christensen et al. I address it only briefly as [13] covers it in detail. Subsequently I consider in detail the Hensen et al. experiment, which presents us with another paradigmatic case of postselection, although some detective work is required to uncover it.

The lesson to be learned from these two cases of postselection is that data discarding is never justified in a data analysis and that all of the raw experimental data must be included in the analysis on an equal basis.

Christensen at al. chose to implement a clocked emission source for avoiding the pairing problem. At fixed time intervals a Pockels cell is opened to allow source emissions to pass to the detection stations. The source emission rate is then set low enough so that most of the openings pass only zero or one emission events. Then in the data analysis only the first detections in an opening are considered; any others are discarded. This strategy may be referred to as pseudo-heralding.

While this strategy would not be a problem if there were indeed a maximum of only one source event per trial, analysis of the event histograms shows that there is a Poissonian distribution of detections per trial, with as many as 13 detections seen per opening at a given side. Therefore, the data analysis leads to a serious and unjustified postselection of the data (data discarding) that produces a false, artifactual violation of the CH inequality. Christensen et al. provide no argument to justify their postselection beyond the pragmatic one of avoiding the pairing problem.

In the experiment, all of the detections are recorded and a subset of them is discarded only in the analysis. Therefore, it is possible to perform alternative analyses that include all of the detections on an equal basis. I have applied two alternative analyses: full counting and windowed coincidence pairing [13]. The latter is valid when the emission rate is low enough and fortunately that is the case in the Christensen et al. experiment. Both of these alternative analyses show no violation of the CH inequality, indicating that the pseudo-heralding had produced only an artifactual violation. In the case of full counting the calculated CH metric is -0.00000344 (the negative value indicates that the CH inequality is not violated) whereas the pseudo-heralded counting yields a value of 0.0000587 (the positive value indicates that the CH value is violated).

All valid counting methods should yield equivalent results. In view of the consistent results provided by the alternative analyses I believe that realists may reasonably reject the pseudo-heralding analysis and consider the experiment to have confirmed locality and disconfirmed QNL. Another view of the matter is that one goes too far in claiming that the experiment confirms locality, even if one accepts that it does not support QNL. Space here does not permit me to address this question in the needed detail.

4.1.2 The Hensen et al. experiment

It has been a longstanding quest of experimental physicists to "close all the loopholes", or in non-rhetorical phrasing, avoid all of the potential problems and present a rigorous proof, thereby decisively confirming the existence of QNL. The experiment of Hensen et al. is the most prominent and arguably most convincing of the recent experiments claimed to be problem-free. If the experiment was to be accepted as fully valid and decisive, the foundations of physics would be shaken (and a Nobel prize could be warranted). Despite the claim by Hensen et al. that their experiment is problem-free, at least one important problem, the postselection problem described above, remains unresolved.

In the following material I show that postselection occurs in the Hensen et al. experiment. I show how similar postselection for a classical local model can produce results indistinguishable from the results of the experiment, including a significant violation of the CHSH inequality. I show how apparent violation of no-signaling in the experimental data further strengthens the argument that postselection is responsible for the claimed violation. I conclude that the Hensen et al. experiment does not succeed in rejecting local realism.

4.1.3 Demonstration of postselection in the Hensen et al. Bell test data

To test for postselection in the Hensen et al. experiment, I modified the publicly available Hensen et al. analysis code to print extra information that shows the fairness and uniformity of the random number generators (RNGs) used in the experiment. I replaced the appropriate lines in the Hensen et al. analysis code to display additional counts of the random measurement selections.

This instrumentation allows one to assess the fairness of the list of random setting choices for each side individually and the distribution of the four joint setting combinations. When the instrumented analysis code is run on the data of the experiment, the following results are obtained (the published Hensen et al. results are, of course, reproduced):

```
number of random 0's for A = 2340
number of random 1's for A = 2406
number of random 0's for B = 2345
number of random 1's for B = 2401
number of random 00 events = 1143
number of random 01 events = 1197
number of random 10 events = 1202
number of random 11 events = 1204
----------------------------------------
k/n: 196.0/245
p-value : 0.039

xy     ++,+-,-+,--
ab 00 [23  3  4 23]   (0,    -3pi/4)
ab 01 [33 11  5 30]   (0,    +3pi/4)
ab 10 [22 10  6 24]   (pi/2, -3pi/4)
ab 11 [ 4 20 21  6]   (pi/2, +3pi/4)

 E (RND00  RND01  RND10  RND11 )
   (+0.736, +0.595, +0.484, -0.608) measured
+/-( 0.093,  0.090,  0.111,  0.111 )
CHSH S : 2.422 +- 0.204
```

The additional code instrumentation shows a large excess of 1's at both A and B, and a large deficit of events for the {00} experiment. Let us now estimate the probability that the joint counts distribution we see in the experiment could be obtained by chance. We see that the {00} experiment has a low count at 1143 while the other three experiments all have counts that exceed the expected mean value of 1186. I wrote and executed a numerical simulation that estimates the probability that the {00} count is less than or equal to 1143. The resulting p-value is 0.07. While this value is slightly above the commonly used but arbitrary 0.05 level, it shows that it is unlikely that the observed distribution could be produced by chance. The code for the numerical simulation is available on-line [34].

My argument here does not depend on an exact significance level, but rather on a demonstration that it is unlikely that the observed distribution could be obtained by accident, together with consideration of a local model violating CHSH using postselection and the presence of a no-signaling violation in the experimental data (see Section 4.1.5). Taken together, I argue that the Hensen et al. data for the {00} experiment was postselected. The 'look-elsewhere effect' is not included because I test the specific null hypothesis that the {00} experiment is postselected.

It is still possible to claim that this unlikely distribution of counts could have occurred by chance. However, one must wonder why it is that with so much at stake the experiment could not have been re-run several times to obtain a distribution that does not arouse such doubts. Of course, if the distribution is in fact a result of postselection that would not be possible and the data would necessarily show this anomalous distribution.

4.1.4 Effect of anomalous postselection on Bell test results

Let us suppose that the {00} postselection loses only mismatch events (events with opposite outcomes). Failure of this supposition does not weaken the conclusions of Section 4.1.3. To investigate the effect of this postselection I created a local numerical simulation model saturating the CHSH inequality close to the classical limit of 2, together with variable postselection of {00} mismatch events (the number of lost events can be selected via user input when running the simulation). The number of events per run (after postselection) is set to 245 to mimic the Hensen et al. experiment (there are no entanglement failure events in a simulation), and 100000 runs are performed to obtain estimates for the mean CHSH metrics S and k, and the mean counts characterizing the distribution of settings. For example, I give below the result of running the simulation with 15 lost {00} mismatch events. It can be seen that the postselection artifactually increases S and k beyond the classical limits. The closeness of the simulated S and k values to the Hensen et al. reported values of $S = 2.42$ and $k = 196$, as well as the similarity of the patterns of counts characterizing the distribution of settings, are striking.

```
Enter ab mismatches to lose (q to exit): 15
mean number of 0's for A = 115.53
mean number of 1's for A = 130.01
mean number of 0's for B = 115.51
mean number of 1's for B = 130.02
mean number of 00 events = 50.54
mean number of 01 events = 64.99
mean number of 10 events = 64.97
mean number of 11 events = 65.03
---------------------------------------------
mean S = 2.419942
mean k = 195.010310
```

Figure 1 shows the relationship between the number of lost events and S. Loss of 15 or more events will reproduce or exceed the reported Hensen et al. results. The code for the numerical simulation model is available online [35].

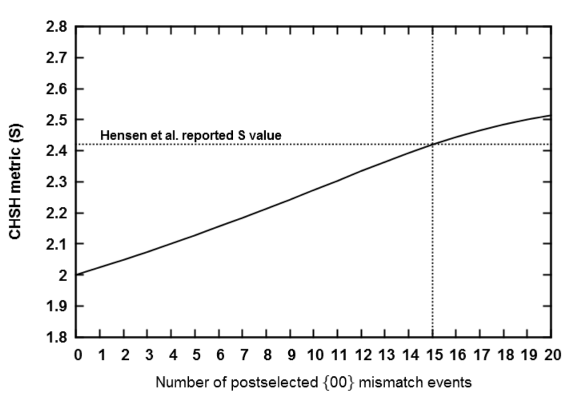

Fig. 1. Effect of postselected {00} mismatch events on S for a local realist model operating at the classical limit.

4.1.5 Violation of no-signaling provides further evidence of postselection

Bednorz [36] and Adenier and Khrennikov [37] demonstrated statistically significant violation of the no-signaling criterion in the data of the Hensen et al. experiment. Postselection of {00} events produces an asymmetry that results in an artifactual violation of no-signaling. It is not difficult to see how this works. Consider side A's counts of 1's for the {00} and {01} experiments. If side B's setting is not affecting the counts, as required by no-signaling, then these two side A counts should be close to each other. However, postselection of {00} events will selectively reduce the first side A count, thereby biasing the results and producing an artifactual violation of no-signaling. This effect is confirmed by numerical simulation showing that, in addition to the anomalous distribution previously described, CHSH violation due to postselection comes at the expense of a no-signaling violation.

The finding of apparent no-signaling violation in the Hensen et al. data therefore strengthens the analysis of this paper. Note that neither Bednorz nor Adenier and Khrennikov discussed postselection, and they did not report the anomalous postselection in the Hensen et al. data that I report here.

4.1.6 Discussion

In an interesting thread at PubPeer [38] discussing the Hensen et al. experiment, 'Peer 6' notices the missing events in the public release of data by Hensen et al. With my own grammatical corrections and paraphrasing I give the main points made by 'Peer 6':

1. The published data does not contain raw data. Instead, it contains preprocessed data, because the raw data from stations A, B, and C have already been brought together into a single file, and the file contains only 4746 events, whereas the paper reports orders of magnitude more events.
2. In the supplementary information [39], Hensen et al. say: "Every few hundred milliseconds, the recorded events are transferred to the PC. During the experiment, about 2 megabytes of data is generated every second. To keep the size of the generated data-set manageable, blocks of about 100000 events are saved to the hard drive only if an entanglement heralding event is present in that block." Therefore, what is published (4746 events, approximately 420 kilobytes) is only about 5% of a single block.

While elimination of blocks without valid events is legitimate (although it reduces the precision of possible RNG tests in the analysis), the undocumented deletion process also allows for deletion of {00} mismatch events. The processing to transform the individual raw lists to the published combined list is neither documented nor published, and the individual raw lists themselves are not available for inspection. This processing is exactly the critical step where postselection can occur. The withholding of the data and processing is troubling, given the importance of the result for the foundations of physics.

Hensen et al. address the distribution of randomness for setting choices in the experimental data, arguing that it is fair and uniform [40]. However, the counts they provide are insufficient to expose the anomaly reported here. Hensen et al. write:

> "We can get further insight by looking at all the setting choices recorded during the test. Around every potential heralding event about 5000 settings are recorded, for which we find a local P-value of 0.57 (Table 1), consistent with a uniform setting distribution."

Unfortunately, the analysis code and data justifying this conclusion are not available and the claim of uniformity appears to be false for the published data, as I demonstrated in Section 4.1.3. The overall counts in the cited Table 1 apparently contain all the excluded blocks but the CHSH calculation is performed only over the published data. If the overall counts are indeed highly uniform as claimed while the published subset of the overall data is not uniform, the conclusion that the published data was postselected is further strengthened. One also wonders why great pains are taken by Hensen et al. to show uniformity for the overall data, but nothing is said about the uniformity of the published subset of the data.

Understandably, one might be expected to speculate about the specific mechanism of the postselection demonstrated here. It is theoretically possible, of course, that defective operation of the devices of the experiment, or improper design of the experiment could account for the observed postselection. However, it is very difficult to conceive of such defects, and so this possibility can be considered to be implausible. Nevertheless, if this were the case, the experiment would clearly be placed in doubt. Another possibility is that Hensen et al. somehow postselected the {00} mismatch events during the data processing. Such postselection could have been unintentional, possibly as a result of a misguided analytical assumption, or a result of unintended side effects of the analysis. However, in the absence of provision by Hensen et al. of the entire raw data set and full documentation of the analysis (Hensen et al. have thus far declined to provide access), the possibility of intentional postselection cannot be excluded, and expressions of indignity at such a charge would constitute disallowable rhetoric. Hensen et al. bear a responsibility to explain the anomalies reported here and to provide the full experimental data set and the full analysis used to move from the data to their conclusion.

The design and implementation of the Hensen et al. experiment is laudable, and experiments like it offer the prospect of deciding the debate over nonlocality. However, the experiments can be decisive only when the data and analyses are correct and transparent, and when undocumented steps are not present in the analysis and interpretation.

One could consider analyzing the second run of the Hensen et al. experiment [40] to see if similar postselection appears. However, Hensen et al. concede that an equipment failure occurred in the middle of the run, placing the previously recorded data in doubt. I choose therefore, for the purposes of this paper, to confine the discussion to the first, successfully executed run. However, I point out that a preliminary analysis of the second run also shows anomalous postselection.

5 Conclusion

No rigorous proof of QNL without disqualifying problems exists today. That includes both the logic of the argument for nonlocality and the experimental evidence. Given the failure of these arguments and experiments, and given the conflict with special relativity, we must conclude that QNL is without support and should be rejected.

What are the responsibilities of a researcher arguing for QNL? The primary responsibility is full public disclosure of the logical argument, all of the raw experimental data (there is never an acceptable reason to withhold raw data), and the full statistical and data analyses that lead to the qualitative and quantitative conclusions. The disclosure must document all prior assumptions and formally present the logic of the argument and experimental data analysis. If anything is missing or seriously problematic the conclusion is not supported, even partially. Anything other than full disclosure is antiscientific rhetoric.

My views on QNL [13, 18, 32, 41] are clear, concise, and forceful. I argue that the correct quantum prediction for EPRB cannot use Lüders' rule. Nonlocal correlations are not predicted by quantum mechanics for EPRB scenarios. The experiments, when properly designed, analyzed, and interpreted, confirm locality and disconfirm quantum nonlocality. Einstein's legacy and Lorenz invariance are safe, and physics remains consistent and coherent.

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