Entanglement, Common-Origin Correlations, and the Interpretation of Bell Violations

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Abstract

Bell's theorem demonstrates that no local deterministic theory can reproduce the complete set of correlations predicted by standard quantum mechanics. The present work accepts Bell's theorem as mathematically correct but questions the physical interpretation of the quantum correlation function used in Bell analyses. It is argued that entangled particles inherit a complete common physical state at their creation and that subsequent measurements reveal selected observables of this state rather than generating new information or requiring superluminal communication. The paper further proposes that the standard quantum correlation function, ($E(\theta) = -\cos\theta$), incorporates additional angular dependence beyond the information physically established at the source. Under this interpretation, the observed violation of Bell inequalities arises from the mathematical structure of the correlation function rather than from nonlocal information transfer between distant particles. An explicit local common-source model is presented, leading to a piecewise linear correlation function and motivating a decomposition of the standard quantum prediction into a local component and a supplementary angular term.

1. Introduction

Quantum entanglement is frequently presented as implying instantaneous communication between spatially separated particles. This interpretation has contributed to the widespread perception that measuring one particle somehow influences another particle located arbitrarily far away.

The central argument of this paper is different. When two particles originate from a common physical process, they inherit a common physical state established at their creation. Later measurements reveal aspects of that shared state but do not necessarily imply that new information is exchanged between the particles at the moment of measurement. This interpretation accepts Bell's theorem as mathematically correct. Bell rigorously demonstrated that local deterministic models cannot reproduce the full set of correlations represented by the standard quantum prediction. However, Bell's theorem does not require one to conclude that the quantum correlation function is the only possible physical representation of common-origin correlations. The incompatibility between local hidden-variable theories and the statistical predictions of quantum mechanics was formalised by Bell in his celebrated theorem [1].

The question addressed here is therefore not whether Bell's theorem is valid, but whether the quantum correlation function represents only the information established at the source or whether it incorporates additional angular structure arising from the mathematical treatment of the measurement process.

2. Correlations Established at the Source

Consider an initial physical system (P) that separates into two correlated subsystems (P') and (P''). The separation process establishes a common physical state shared by both particles before they travel toward distant observers. When Alice measures one particle and Bob measures the other, neither measurement creates the correlation. The correlation already exists because both particles originate from the same physical event. Consequently, if Alice determines one observable of her particle, she acquires information about the corresponding observable of Bob's particle without requiring any physical signal to propagate between them (Figure 1).

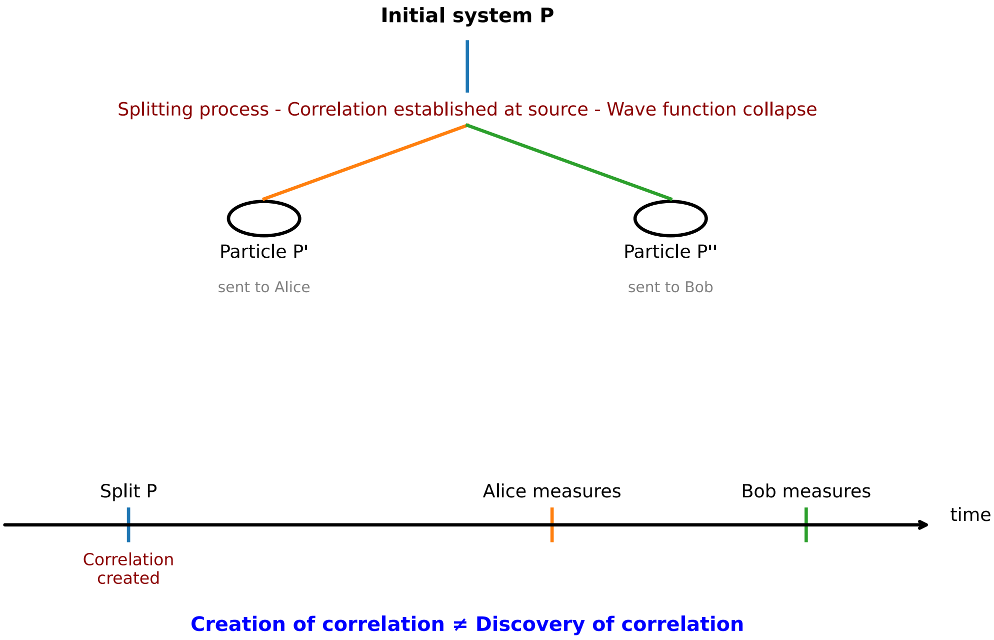

Figure 1. Creation of a correlation should not be conflated with the later measurement (discovery) of that correlation.

In the interpretation proposed here, the complete physical state of the entangled pair is established during the splitting process. Consequently, the conventional notion of wave function collapse at the moment of measurement is replaced by the view that measurements merely reveal observables associated with a pre-existing common state established during the pair's creation. The distinction between creating a correlation and discovering a correlation is fundamental.

3. The Complete Shared State

In the interpretation proposed here, the two particles inherit the complete physical state generated during their common preparation. The measurements performed by Alice and Bob reveal only selected observables extracted from this underlying state.

An analogy may be drawn with identical twins. Their complete genetic information is determined at conception, although any particular experiment may examine only a small fraction of their DNA. The measurement does not create the similarity; it merely reveals part of an already existing common structure.

Similarly, entangled particles may share substantially more information than is accessed in any individual measurement.

4. Bell's Theorem and Local Correlations

Bell's theorem proves that no local deterministic model based solely on predetermined measurement outcomes can reproduce the complete statistical predictions of quantum mechanics. The present work fully accepts this mathematical result.

However, Bell's theorem does not itself identify the physical origin of the quantum correlation function. Rather, it demonstrates that this function violates inequalities satisfied by local deterministic correlations. Therefore, one may legitimately ask whether the cosine dependence represents only the information inherited from the common source or whether it incorporates additional mathematical structure associated with the measurement geometry.

Appendix A compares these two descriptions through a self-contained numerical simulation summary included in the present PDF. [6]

To make this proposal more explicit, the following section derives a simple deterministic common-source model and the corresponding local correlation function.

The following derivation presents one explicit realisation of the proposed local common-source model and is intended as a constructive mathematical example rather than a uniqueness proof.

5. Derivation of the Proposed Local Correlation Function

To formalise the proposed interpretation, consider an entangled pair created by the splitting of an initial particle into two daughter particles, (P') and (P''). At the moment of creation, both particles are assumed to inherit a complete common hidden state

$$\lambda = (\phi, \mu_1, \mu_2, \ldots),$$

where (ϕ) denotes a shared orientation established at the source and (μ_i) represent any additional internal variables that may characterise the pair. The essential assumption of the model is that all relevant physical information is fixed at the moment of separation and that no further information is exchanged between the particles thereafter.

Suppose that measurements are performed by two observers using analyser orientations (a) and (b). The corresponding deterministic outcomes are defined by

$$A(a, \lambda) = \operatorname{sign}\big(\cos(a - \phi)\big),$$

and

$$B(b, \lambda) = -\operatorname{sign}\big(\cos(b - \phi)\big),$$

where the minus sign reflects the perfect anti-correlation expected for the singlet state when both analysers are aligned.

Assuming that the shared orientation (ϕ) is uniformly distributed over the interval $(\phi \sim Uniform(0{,}2\pi))$, the expected correlation is obtained by averaging over all possible source orientations,

$$E(a,b) = \int A(a,\lambda), B(b,\lambda), \rho(\lambda), d\lambda.$$

Since only the common orientation (ϕ) contributes to the integral, the correlation depends solely on the relative analyser angle

$$\theta = |a - b|,$$

yielding

$$E_{\text{local}}(\theta) = -\frac{1}{2\pi}\int_0^{2\pi} \text{sign}(\cos x)\ \ \text{sign}(\cos(x-\theta))\,dx\,.$$

The regions where the signs agree occupy $2\pi - 2\theta$, while opposite signs occupy 2θ. Therefore

$$E(\theta) = -\frac{(2\pi - 2\theta) - 2\theta}{2\pi}\,.$$

Simplifying, the integral gives the linear expression

$$E_{\text{local}}(\theta) = -1 + \frac{2\theta}{\pi} \quad \text{for} \quad 0 \le \theta \le \pi\,.$$

which corresponds to the (red) straight-line correlation illustrated in Figure 2.

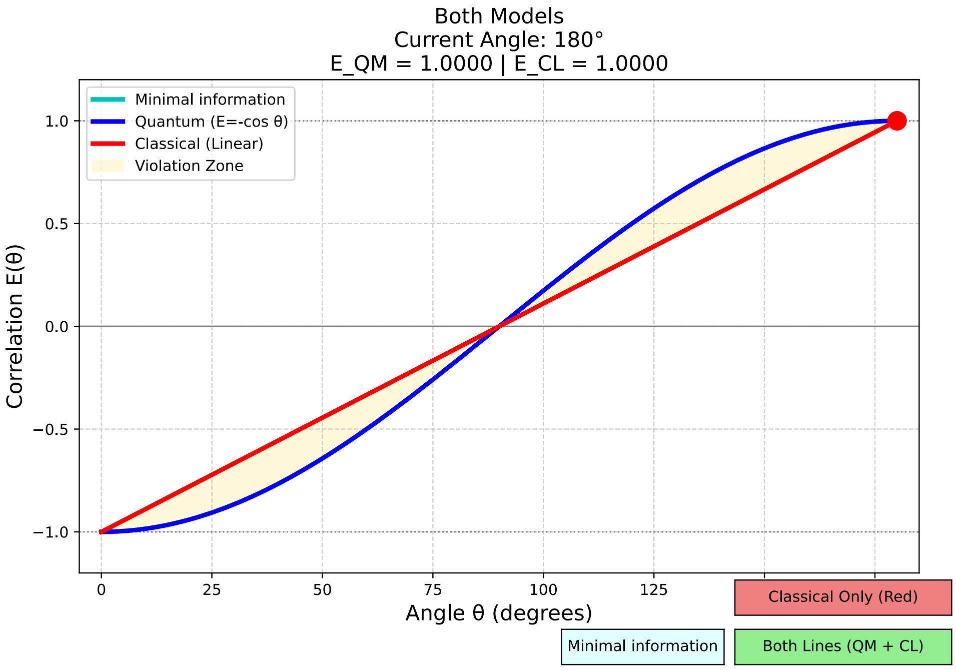

Figure 2. Comparison between the proposed common-source correlation (red) and the quantum correlation function E(θ) = − cos θ (blue). The shaded yellow region highlights the angular difference between the two descriptions.

Within the interpretation proposed here, the shaded region corresponds to the supplementary angular term

$$F(\theta) = E_{\text{quantum}}(\theta) - E_{\text{local}}(\theta),$$

representing the difference between the standard quantum correlation and the proposed common-source correlation.

For comparison, the standard quantum prediction for the singlet state is

$$E_{\text{quantum}}(\theta) = -\cos\theta .$$

The difference between the two descriptions may therefore be expressed as

$$F(\theta) = E_{\text{quantum}}(\theta) \; - \; E_{\text{local}}(\theta) = -\cos\theta + 1 \; - \; \frac{2\theta}{\pi} .$$

Within the interpretation proposed in this work, (F(θ)) represents a supplementary angular contribution contained in the standard quantum correlation function beyond the minimal common-source correlation obtained from the local hidden state (λ). Correspondingly, the difference

$$\Delta S = S_{\text{quantum}} - S_{\text{local}}$$

may be interpreted as the net contribution of this supplementary angular term to the CHSH parameter. The central hypothesis advanced here is therefore not that Bell's theorem or its experimental verification are incorrect, but rather that the quantum correlation function may encode a richer statistical structure than is strictly required to describe the information established at the common source of the entangled pair.

Simple local deterministic constructions naturally produce piecewise linear correlation functions satisfying $|S| \leq 2$, consistent with Bell's inequality, whereas the quantum prediction $E(\theta) = -\cos\theta$ yields $|S| = 2\sqrt{2}$, exceeding the local bound. The experimentally accessible CHSH inequality provides a practical formulation of Bell's theorem for four measurement settings [2].

The interpretation proposed here is that the quantum prediction should not be viewed solely as a direct representation of the information established when the entangled pair is created. Instead, the function incorporates an additional angular dependence associated with the measurement geometry. Consequently, the quantity entering the Bell analysis reflects not only the common-source information shared by the particles but also the mathematical structure of the quantum correlation function itself.

This idea can be illustrated by the following example, where the cyan line represents the actual angle (θ), the red line represents the local hidden-variable prediction, and the blue line represents the quantum correlation function ($E(\theta) = -\cos\theta$).

a. Linear dependence

If the question posed by the measurement is simply, "*Does the angle increase uniformly?*", then the relevant information is represented by the cyan line, which varies linearly as (θ) increases from (0°) to (180°). Any additional functional structure is unnecessary for answering this particular question (Figure 3).

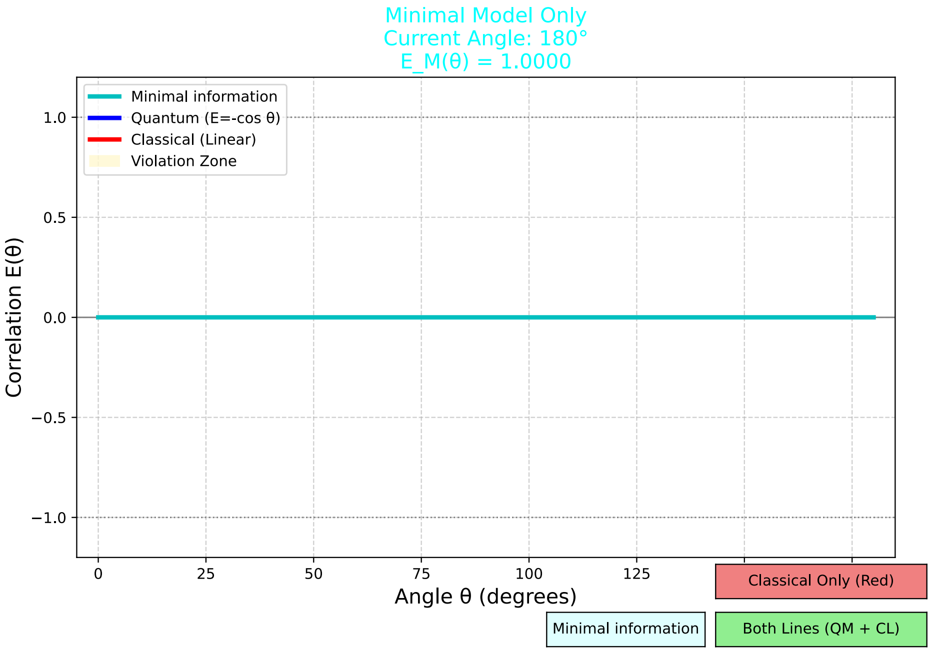

Figure 3. Classical local hidden-variable model using only the minimal information required for correlation prediction.

b. Local deterministic description

If one wishes to characterise the complete local correlation established at the source, the red line provides a deterministic description that remains within the Bell bound. Estimating this correlation

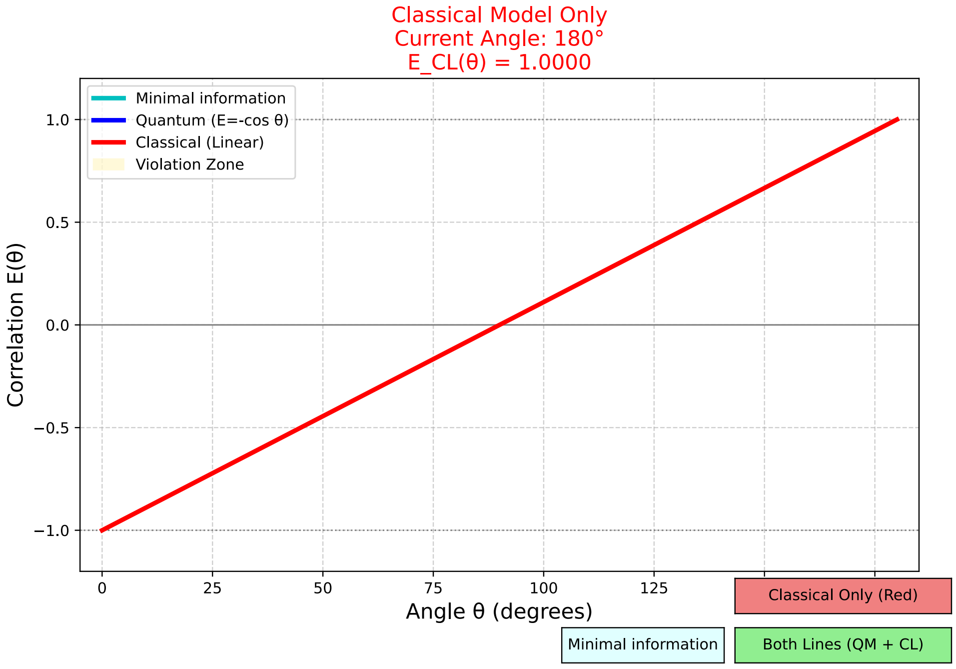

Figure 4. Comparison between the proposed common-source correlation (red) and the quantum correlation function $E(\theta) = -\cos\theta$ (blue). The shaded yellow region represents the supplementary angular term $F(\theta) = E\_quantum\ (\theta) - E\_local\ (\theta)$.

experimentally requires repeated measurements in order to reduce ordinary statistical sampling fluctuations (Figure 4).

c. Quantum correlation function

The quantum correlation function ($E(\theta) = -\cos\theta$), represented by the blue line, introduces a nonlinear angular dependence F(θ) beyond the linear relationship associated with the common-source correlation (Figure 2).

An analogy may be drawn with everyday communication. Sometimes a simple "yes" or "no" completely answers the question being asked. A longer explanation may provide useful additional context, but it also incorporates information that was not required to answer the original question.

Similarly, the present interpretation suggests that the quantum correlation function incorporates angular structure beyond the information physically established during the creation of the entangled pair.

6. Discussion

The interpretation proposed here should not be understood as a criticism of Bell's mathematical theorem. Instead, it represents a distinction between two conceptually different objects:

1. the physical information established when the entangled pair is created; and
2. the mathematical function used to describe the observed measurement correlations.

If the particles inherit a complete common physical state at their source, then later measurements merely reveal different aspects of that state. The nonlinear cosine dependence may therefore reflect not only the original shared information but also the mathematical framework used to project that information onto different measurement settings.

An intuitive analogy may help clarify the interpretation proposed in this work. The following analogy is intended only as an intuitive illustration and should not be interpreted as a literal physical correspondence.

Consider two identical twins who inherit effectively identical DNA from a common origin. A local description concerned only with the inherited genetic information predicts complete agreement between them. A more comprehensive statistical model ($E_{\text{quantum}}(\theta) = -\cos\theta$), however, may also account for extremely rare future mutations, even when no such mutation is relevant to the observation being made. By analogy, the local common-source correlation $E_{\text{local}}(\theta)$ represents the inherited shared information, whereas the supplementary angular term

$$F(\theta) = E_{\text{quantum}}(\theta) - E_{\text{local}}(\theta)$$

represents the additional statistical structure contained in the quantum description. Under this interpretation, the difference

$$\Delta S = S_{\text{quantum}} - S_{\text{local}}$$

represents the net contribution of this supplementary angular term to the CHSH parameter. The central hypothesis of this paper is therefore not that Bell's theorem or its experimental verification are incorrect, but rather that the quantum correlation function may encode a richer statistical structure than is strictly required to represent the information established at the common source of the entangled particles.

Numerous experiments, beginning with the pioneering work of Aspect and co-workers and continuing through modern loophole-free Bell tests, have consistently confirmed the statistical predictions of quantum mechanics [3, 4, 5]. The present proposal instead concerns the physical interpretation of these correlations and suggests that the quantum correlation function may incorporate additional angular dependence beyond the information established during the common preparation of the entangled pair.

Whether this interpretation can be developed into a complete predictive model remains an open question requiring further theoretical and experimental investigation.

7. Conclusion

The principal claim of this work is not that Bell's theorem or its experimental tests are incorrect, but that the physical interpretation of the quantum correlation function deserves further examination.

Entangled particles may inherit a complete common physical state established during their joint preparation, with subsequent measurements revealing only selected observables of that state. Under this interpretation, no superluminal communication is required to account for the observed correlations.

The paper further proposes that the standard quantum correlation function introduces additional nonlinear angular dependence beyond the information physically established at the source. If so, Bell inequality violations may arise from the mathematical representation of the correlations rather than from the necessity of instantaneous information transfer between distant particles.

Within the framework proposed here,

$$E_{\text{quantum}}(\theta) = E_{\text{local}}(\theta) + F(\theta),$$

where F(θ) represents the supplementary angular contribution relative to the proposed common-source correlation.

The local deterministic and quantum correlation functions should not necessarily be viewed as competing descriptions. Rather, they may represent complementary aspects of the same physical process: the former reflecting the common-source correlation established during particle creation, and the latter describing how that correlation is manifested through the measurement geometry.

References:

[1] J. S. Bell, On the Einstein Podolsky Rosen Paradox, Physics Physique Fizika 1, 195–200 (1964). ← Return to the main text

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[4] A. Aspect, J. Dalibard, and G. Roger, Experimental Test of Bell's Inequalities Using Time-Varying Analyzers, Phys. Rev. Lett. 49, 1804–1807 (1982). ← Return to the main text

[5] Giustina, M., Versteegh, M. A. M., Wengerowsky, S., et al., "Significant-Loophole-Free Test of Bell's Theorem with Entangled Photons," Physical Review Letters 115, 250401 (2015). ← Return to the main text

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Appendix A

Bell Local vs Quantum Simulation

Trials per setting: 100000

```
               Local Hidden Spin Model
This model uses shared hidden directions and local measurements.
It does NOT use the quantum probability rule.
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Settings A, B:
  same results     = 24986
  opposite results = 75014
  measured E       = -0.500

Settings A, B':
  same results     = 25057
  opposite results = 74943
  measured E       = -0.499

Settings A', B:
  same results     = 24955
  opposite results = 75045
  measured E       = -0.501

Settings A', B':
  same results     = 75065
  opposite results = 24935
  measured E       = 0.501

S = -2.001
|S| = 2.001 - A finite simulation may introduce random sampling
noise while increasing the number of trials will slow down the
script.

             Quantum Singlet Probability Model
This model uses the quantum spin-singlet probability rule:
E = -cos(θ).
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Settings A, B:
  same results     = 14678
  opposite results = 85322
  measured E       = -0.706

Settings A, B':
  same results     = 14719
  opposite results = 85281
  measured E       = -0.706

Settings A', B:
  same results     = 14898
  opposite results = 85102
  measured E       = -0.702

Settings A', B':
  same results     = 85590
  opposite results = 14410
  measured E       = 0.712

S = -2.826
|S| = 2.826 - Within the interpretation proposed in this work,
this reflects the angular dependence of the quantum correlation
function E(θ)=-cosθ.
```

← Return to Section 4