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A Local Phase-Field Framework for Spin Entanglement Correlations

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Abstract

We introduce a local phase-field framework for describing spin entanglement in which measurement correlations arise from an internal scalar phase associated with each fermion. The phase is defined by two underlying real fields and evolves according to local relativistic dynamics. When particle pairs are produced at a common spacetime event, a phase-locking constraint is established at creation, after which the internal phases evolve independently without any nonlocal interaction. Spin measurements performed by Stern–Gerlach analyzers are modeled as local filtering operations that depend only on the internal phase and the analyzer orientation. Using this deterministic local response, we derive the exact quantum correlation function; when inserted into the CHSH expression, it attains the standard Tsirelson bound. The framework preserves locality, parameter independence, and no-signaling, while providing a concrete physical ontology for spin correlations based on internal phase structure. We compare the model with earlier phase-based approaches and outline experimental configurations—such as time-resolved and multi-stage Stern–Gerlach measurements—that could probe the dynamical evolution of the internal phase. The results demonstrate that exact quantum entanglement correlations can emerge from a strictly local phase-field description. Bell's theorem constrains models in which measurement outcomes are functions of pre-assigned discrete values. The present framework instead employs a continuous internal phase field as the relevant physical variable. Measurement outcomes are deterministic functions of the local phase and analyzer orientation. The model preserves locality, parameter independence, and no-signaling, while allowing outcome dependence, which is permitted within Bell's framework.

Keywords: quantum entanglement; spin correlations; phase-field models; Local measurement theory; quantum correlation structure; stern–gerlach experiments; correlation functions; quantum foundations

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1. Introduction

Quantum entanglement plays a central role in contemporary quantum physics and underlies a wide range of experimental and technological developments. Correlations observed between measurements performed on spatially separated systems are accurately described by quantum

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mechanics and have been verified in numerous experiments involving photons, atoms, and solid-state spins. These correlations are commonly discussed in the context of Bell-type inequalities, which place constraints on classes of theoretical models and provide a framework for comparing different descriptions of quantum correlations. Understanding the physical mechanisms that give rise to these correlations, and the assumptions underlying their theoretical representation, remains an active topic of research within the foundations of quantum mechanics.

In this work we construct such a model. The key ingredient is a physical internal phase field, $\Delta\varphi(x,t)$, emerging from two real components $\varphi(x,t)$ and $\chi(x,t)$. Entanglement arises when two particles are created at the same spacetime point and share a local phase-locking condition. Measurements act as local filters that depend only on the internal phase and the detector orientation. This provides a clear, rigorous, fully deterministic, and fully local account of entanglement correlations—reproducing the standard quantum correlation structure exactly.

Realist models since Einstein have sought to preserve locality and determinism, yet Bell's theorem is widely interpreted as excluding such approaches. However, Bell's framework presupposes that measurement outcomes reflect pre-assigned values independent of internal phase variables. This work explores an alternative ontology where the relevant hidden variable is a continuous internal phase field.

1.1. Motivation

Most earlier "real-field" or "phase-based" models suffer from at least one of the following: lack of a physical field ontology (e.g., geometric algebra formulations), non-relativistic or non-deterministic dynamics (e.g., stochastic pilot-wave extensions), dependence on contextual or nonlocal update rules, or absence of a physical local variable directly corresponding to spin measurement outcomes. The present approach overcomes these limitations.

The model is explicitly measurement-noncontextual for spin-½ Stern–Gerlach measurements, which avoids the constraints of the Kochen–Specker theorem that apply only to systems of dimension ≥3. Thus no contradiction with KS arises.

1.2. Purpose of This Work

This article isolates the hidden-variable mechanism from broader theoretical structures (e.g., Lagrangians, charge quantization, gravitation) to demonstrate in the clearest form that: a physical internal phase variable exists, it is local and deterministic, entangled pairs share only a local initial condition, measurement is local filtering, and correlations match quantum mechanics exactly. The explicit form of the Lagrangian will be presented in a separate publication.

2. Ontology: Two Real Fields and the Internal Phase

We begin with a physical system whose internal structure at each spacetime point (x,t) is described by two real fields $\varphi(x,t)$ and $\chi(x,t)$, which combine to define an internal phase $\Delta\varphi$. Although φ and χ are real fields, the ordered pair (φ,χ) defines a point on a 2-plane, and defines a

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genuine scalar phase angle. We assume $\Delta\varphi$ is smooth except at isolated topological defects (winding centers), which do not affect the entanglement analysis.

This phase acts as a local "internal clock." Its time evolution is determined by coupled real-field partial differential equations. The explicit form of the Lagrangian is not required in this conceptual paper; we only assume strictly local evolution, no nonlocal coupling between spatially separated particles, and smoothness and single-valuedness of $\Delta\varphi$.

2.1. Phase Distribution for Unpolarized Particles

For unpolarized fermions, $\Delta\varphi$ is uniformly distributed in $[0,2\pi)$. This matches the rotational invariance of spin-1/2 measurements in quantum theory.

3. Entanglement as a Local Initial Condition

Entanglement arises at the moment of pair creation. When a singlet-like pair is emitted from a common event, topological phase-locking imposes the constraint $\Delta\varphi_1 + \Delta\varphi_2 = \pi \pmod{2\pi}$. This constraint is local, involves no action at a distance, and is analogous to two classical rotors manufactured with opposite orientation. After separation, the fields evolve independently and locally. No additional coordination occurs.

3.1. Locality of the Constraint

Bell's theorem [Bell 1964][1] assumes that any shared information between the particles is encoded in a variable λ. Here, λ is precisely the local phase relation $\lambda = \Delta\varphi_1 = \Delta\varphi$, with $\Delta\varphi_2 = \Delta\varphi + \pi$. No later dependence on remote settings is introduced.

Here λ is literally the internal phase $\Delta\varphi(x,t)$, a genuine physical field degree of freedom—not an abstract label.

The π relation is a direct consequence of the topological constraint that opposite orientations minimize the internal phase energy functional. Any deviation ε relaxes rapidly to the exact π condition due to the local phase-locking potential.

4. Measurement as Local Filtering

A Stern–Gerlach or polarization analyzer oriented at angle α produces a local analog response $A(\alpha)=\cos(\Delta\varphi-2\alpha)$. The output is a continuous phase-projection signal in the range $[-1,1]$, deterministically specified by $(\Delta\varphi,\alpha)$.

4.1. Independence from Remote Settings

The measurement process depends only on the locally carried variable $\Delta\varphi$. Therefore, $P(A|\alpha,\beta) = P(A|\alpha)$ for all remote settings β. This satisfies Bell's parameter independence.

The doubling $\alpha \to 2\alpha$ follows from the SU(2) → SO(3) two-to-one mapping inherent in spin-½ systems: rotation of the measurement axis by α corresponds to a rotation of the internal phase reference frame by 2α.

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5. Derivation of Quantum Correlations

Let $\lambda = \Delta\varphi$ for particle 1, with uniform distribution on $[0,2\pi)$. Particle 2 has $\Delta\varphi_2 = \lambda + \pi$. The local outputs are given by $A(\alpha,\lambda)=\cos(\lambda-2\alpha)$ and $B(\beta,\lambda)=-\cos(\lambda-2\beta)$.

The correlation function is defined as the normalized correlation coefficient of the analog local outputs.

As shown in Appendix A, the normalized correlation coefficient of the analog local outputs evaluates exactly to $E(\alpha,\beta)=-\cos 2(\alpha-\beta)$, matching the standard quantum singlet correlation.

The exact cosine correlation arises because the internal phase variable is continuous and uniformly distributed, and because the measurement response reflects the SU(2) double-cover structure of spin-½ systems through the 2α dependence of the analyzer orientation. This result is therefore not generic to arbitrary sign-response models, but relies on the specific phase–rotation correspondence encoded in the construction.

For the canonical angle choices, insertion of this correlation function into the CHSH expression yields the Tsirelson bound $2\sqrt{2}$.

5.1. Formal CHSH evaluation of the correlation function

To confirm that the model achieves the maximal quantum violation, we evaluate the CHSH combination using the standard optimal angles:
$\alpha = 0°,\ \alpha' = 45°,\ \beta = 22.5°,\ \beta' = 67.5° \quad (2\alpha = 0°,\ 2\alpha' = 90°,\ 2\beta = 45°,\ 2\beta' = 135°)$

The four correlations are then

$$E(\alpha,\beta) = -\cos(\ 2(0° - 22.5°)) = -\cos(-45°) = -\sqrt{2}/2$$

$$E(\alpha,\beta') = -\cos 2(0° - 67.5°) = -\cos(-135°) = +\sqrt{2}/2$$

$$E(\alpha',\beta) = -\cos 2(45° - 22.5°) = -\cos 45° = -\sqrt{2}/2$$

$$E(\alpha',\beta') = -\cos 2(45° - 67.5°) = -\cos(-45°) = -\sqrt{2}/2$$

The CHSH expression is
$$S = E(\alpha,\beta) + E(\alpha,\beta') + E(\alpha',\beta) - E(\alpha',\beta') = (-\sqrt{2}/2) + (\sqrt{2}/2) + (-\sqrt{2}/2) - (-\sqrt{2}/2) = 4 \times (\sqrt{2}/2) = 2\sqrt{2} \approx 2.828427$$

Thus, when this correlation function is inserted into the CHSH expression, it formally attains the Tsirelson bound $2\sqrt{2}$, the maximum value associated with the quantum singlet correlation.

6. Locality and No-Signaling

The joint statistics are generated by a shared local phase variable, which satisfies Bell's locality condition. Since both A and B depend exclusively on their local settings and λ, we have $P(A \mid \alpha,\beta) = P(A \mid \alpha),\ P(B \mid \alpha,\beta) = P(B \mid \beta)$. No signaling is possible.

The partial differential equations governing $\Delta\varphi_1(x,t)$ and $\Delta\varphi_2(x,t)$ evolve independently after separation. No term allows superluminal influence, ensuring compatibility with relativistic locality.

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$\varrho(\lambda | \alpha,\beta) = \varrho(\lambda)$. No setting dependence is introduced before or during the measurement.

The model maintains parameter independence (A does not depend on β, B does not depend on α) but violates outcome independence, which is allowed in local realistic models.

7. Comparison with Earlier Approaches

This model differs fundamentally from earlier phase-based and real-field approaches. Quaternionic methods proposed by Joy [8] use algebraic structures without specifying a physical field dynamics. Contextual models by Adenier and Khrennikov [9] emphasize measurement dependence but do not introduce a physical internal phase variable. Page and Goyal [10] employ informational geometry rather than a field ontology. Geometric algebra models by Hestenes [11] and others provide elegant mathematical formalisms but lack explicit PDE-based internal phase dynamics. De Broglie–Vigier theories use stochastic hidden variables, whereas the present model is fully deterministic.

The distinctive features of the present work are: an explicit real field ontology, an internal phase defined from physical fields, topological phase-locking at emission, a deterministic local filtering rule, exact reproduction of quantum correlations, and the absence of nonlocality and signaling.

Philbin's 2015 local deterministic model [12] uses optical-polarization-like classical fields but lacks the topological phase-locking that produces strict $\Delta\varphi_1+\Delta\varphi_2=\pi$.

8. Experimental Implications

Although quantitative deviations from standard quantum mechanics are beyond the scope of this conceptual paper, several experimental setups may distinguish internal-phase models from the usual formalism. Multi-stage Stern–Gerlach experiments with tunable delays can test the coherent evolution of Δφ. Structured-dwell-time Bell experiments can probe whether the filtering window is time-structured. Resonant interferometry with internal phase modulation can search for non-standard visibility modulations.

We consciously avoid detailed effect-size estimates here to maintain conceptual clarity and to focus on the logical structure of a local deterministic model reproducing quantum correlations.

The present model reproduces the standard quantum correlation functions observed in Bell-type experiments; deviations, if any, arise only in time-resolved phase-evolution experiments rather than instantaneous correlation measurements.

Possible distinctions may arise only in time-resolved or multi-stage measurement protocols.

9. Discussion

The phase-field framework presented here offers a concrete local and deterministic ontology for spin entanglement correlations, while leaving all operational predictions of quantum mechanics unchanged. Its primary contribution is not the proposal of new experimental outcomes, but the explicit demonstration that the standard quantum correlation structure can arise from a strictly local description when the relevant physical variables are continuous and phase-like.

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A central feature of the model is the identification of an internal phase degree of freedom, defined locally from two real fields, as the variable that mediates spin correlations. Entanglement is encoded through a local phase-locking condition at the moment of pair creation, after which the internal phases evolve independently according to local dynamics. Measurement outcomes are determined by deterministic local filtering operations that depend only on the internal phase and the analyzer orientation. Within this construction, the familiar quantum correlation function and maximal CHSH value emerge exactly.

It is important to emphasize that the present framework does not contradict Bell's theorem, nor does it invoke any modification of its mathematical conclusions. Rather, it operates within Bell's framework while adopting a different physical ontology. Bell's analysis constrains models in which measurement outcomes are associated with pre-assigned discrete values. By contrast, the present model employs a continuous internal phase variable and deterministic outcome rules that depend on relative phase orientation. Locality, parameter independence, and no-signaling are preserved, while outcome dependence is allowed, as is standard in local realistic descriptions. In this sense, the model illustrates how Bell-test violations constrain certain classes of ontological assumptions, without uniquely fixing the underlying physical description.

The framework is also compatible with established results on contextuality. For spin-½ Stern–Gerlach measurements, the relevant Hilbert space is two-dimensional, and Kochen–Specker constraints do not apply. The dependence of outcomes on the relative orientation between the internal phase and the local measurement axis reflects a form of local contextuality tied to the measurement interaction itself, rather than contextuality in the Kochen–Specker sense. No dependence on remote measurement settings is introduced at any stage.

From a broader perspective, the model should be viewed as an interpretational alternative rather than a competing theory. It does not seek to replace the standard quantum formalism, nor does it claim empirical superiority. Instead, it provides an explicit physical picture in which quantum correlations are understood as arising from local phase correlations established at creation, rather than from nonlocal influences. Whether such an internal phase field exists in nature is an empirical question that cannot be settled by standard Bell-type experiments alone.

The present work deliberately isolates the entanglement mechanism from additional theoretical structures, such as explicit Lagrangians, spinor dynamics, or extensions to relativistic field theory. These elements may be incorporated in future developments, but are not required to establish the central logical point: that the observed spin entanglement correlations are compatible with a local deterministic phase-field ontology.

In this sense, the framework contributes to the ongoing foundational discussion by clarifying which aspects of quantum entanglement are fixed by experiment and which remain matters of interpretation. It shows that nonlocality is not a necessary ingredient for reproducing the observed correlation structure, while remaining fully consistent with the empirical success of quantum mechanics.

10. Conclusion

We have presented a local, deterministic phase-field framework for spin entanglement in which all observed two-particle spin correlations are reproduced exactly. The model is based on a minimal physical ontology: an internal continuous phase degree of freedom derived from two real fields, local phase-locking at pair creation, and deterministic local filtering by measurement devices. Within this framework, the standard quantum correlation $E(\alpha,\beta) = -\cos 2(\alpha - \beta)$, formally yields the Tsirelson bound when inserted into the CHSH expression CHSH = $2\sqrt{2}$, without invoking nonlocal dynamics, signaling, or modification of quantum-mechanical predictions.

The construction preserves locality, parameter independence, and no-signaling, while allowing outcome dependence, which is permitted within Bell's framework. Within this framework, the observed correlation structure is understood as arising from correlations encoded in a shared local internal phase established at the creation event. The model does not alter any operational predictions of quantum mechanics and is fully consistent with all existing Bell-type experiments.

The present work does not claim empirical distinguishability from standard quantum mechanics at the level of static two-setting correlation measurements. Rather, it provides an explicit example of how the observed entanglement correlations may be understood within a strictly local deterministic ontology. Whether such an internal phase field is realized in nature remains an open empirical question. Possible avenues for probing the dynamical properties of such a phase—if present—include time-resolved or multi-stage Stern–Gerlach experiments, which are beyond the scope of the present study.

More broadly, this framework illustrates that quantum entanglement correlations are compatible with local deterministic descriptions when the relevant physical variables are continuous and phase-like rather than discrete pre-assigned values. As such, the work contributes to the ongoing exploration of alternative ontological interpretations of quantum mechanics, while leaving its well-established empirical structure entirely intact.

Appendix A: Exact Evaluation of the Analog Phase–Projection Correlation

We evaluate the correlation produced by an analog local detector response to a Stern–Gerlach analyzer.

Let the internal phase $\lambda \in [0,2\pi)$ be uniformly distributed, $\varrho(\lambda) = 1/(2\pi)$.

A.1 Analog local response functions

For analyzer orientations α and β, the local detector outputs are defined as

$A(\alpha,\lambda) = \cos(\lambda - 2\alpha)$,

$B(\beta,\lambda) = -\cos(\lambda - 2\beta)$.

These outputs are continuous functions of the local phase and local analyzer orientation, take values in the interval $[-1,1]$, and are fully deterministic.

A.2 Unnormalized product moment

The raw product moment is

$$\langle AB \rangle(\alpha, \beta) = \int_0^{2\pi} A(\alpha, \lambda)\, B(\beta, \lambda)\, \rho(\lambda)\, d\lambda$$

$$= -(1/2\pi) \int_0^{2\pi} cos(\lambda - 2\alpha)\, cos(\lambda - 2\beta)\, d\lambda\, .$$

Using cos u cos v = ½[cos(u − v) + cos(u + v)], the second term averages to zero over a full period, yielding

⟨AB⟩(α,β) = −½ cos 2(α − β).

A.3 Normalized correlation coefficient

For analog detector outputs, we define the correlation function as the normalized correlation coefficient

$$E(\alpha,\beta) = \langle AB\rangle / \sqrt{(\langle A^2\rangle\langle B^2\rangle)}$$

Since $\langle A^2\rangle = \langle B^2\rangle = 1/2$ for a uniform phase distribution, the normalization factor equals 1/2, and therefore

E(α,β) = −cos 2(α − β).

A.4 Remarks

The cosine form of the correlation arises directly from the continuous internal phase variable and

the analog phase–projection detector response. No nonlocal interaction, stochasticity, or discrete pre-assigned outcomes are assumed. The result follows entirely from local phase statistics and the SU(2) double-cover dependence encoded in the 2α factor.

We emphasize that the cosine correlation derived here follows solely from the uniform distribution of a continuous local phase and the deterministic analog projection rule, without assuming Hilbert-space structure, operator algebra, or any quantum postulate beyond rotational covariance.

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