On the Appearance of Action at a Distance

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Article

Keywords: EPR correlations, Bell Inequalities, Relativistic Causality, Retarded Interaction, Nonlinear Classical Fields, de Broglie Waves.

Posted Date: August 1st, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3166914/v1

Additional Declarations: No competing interests reported.

On the Appearance of Action at a Distance

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After forty years of EPR experiments, it appears on the face of the experimental facts that one of the oldest ideas in Physics has been falsified, namely the retarded interaction paradigm, the notion that long range interactions between quanta, or equivalently causal influences between point events, are mediated by physical entities - fields, particles or "causal influences" in general - that travel through space from one point to the other at or below the characteristic velocity, *c*. A critical examination of this basic idea shows it to be unsatisfactory in all respects. An alternative is then proposed that satisfies both causality and local action, "distributed action", which is germane to local realist field models of the quanta, where matter and energy extend in space and interact locally and causally at all locations where they overlap. Bell Inequalities cannot be derived in this context because, with distributed field-field interactions, spacelike separation of events does not guarantee the fundamental "no influence" assumption from which all the various Bell Inequalities are derived. Distributed action thus explains what appears to us as instantaneous action at a distance.

Keywords: EPR correlations, Bell Inequalities, Relativistic Causality, Retarded Interaction, Nonlinear Classical Fields, de Broglie Waves. PACS: 03.65.Ud 03.75.-b

1 Introduction

Of all the quantum mysteries, perhaps the most confronting is the existence of Bell spacelike causal correlations, as found in the various modern, loophole free EPR experiments, [1–3], that have secured the evidence dating back decades [4–6]. Many arguments have been constructed, *eg* [7–10], to avoid the unpalatable conclusion that nonlocal relations between observables exist in nature, which Norsen [11–13] and others have refuted, isolating the problem to locality. Some form of instant action at a distance must be involved. Since this has long been regarded as unintelligible, an uneasy "consensus" has emerged: "Either locality or reality must fail", amounting to a choice between *prima facie* incomprehensible positions. Intensive scrutiny of Bell's Theorem has provided invaluable precision, but it has thus reached an impasse.

Seldom discussed is the well known finding by Redhead that nonlocal relations at the level of observables, "Epistemological nonlocality", are not necessarily incompatible with "Ontological locality" [14]. Several authors, including [15–17], have pursued "subquantum" fields, where the idea is that Bell correlations might be explained by physical local realist fields but no conclusive results have been shown. 't Hooft has, however, shown that instant correlations at a distance can evolve under local (nearest neighbour) interaction in cellular automata [18]. Such *ontological* correlations will be essential for constructing spacelike *causal* correlations between *observables* in local realist field models. This paper moves beyond the present impasse by considering spacelike causal correlations in a class of local realist, physical field models that emerged from quantum theory in 1980 [19]. A plausible distributed action model of Bell Inequality violations is specified in [20]. The focus here will be on the new insight such models provide, not only into Bell violations but also the workings of our quantum formalisms.

Underlying the Bell Inequalities is the basic assumption that spacelike separation of events guarantees that a measurement intervention in one arm of the apparatus cannot influence (spacelike separated) events in the other arm. This is the "no influence" assumption. This physical assumption translates mathematically into factorisability of probabilities, which is the core assumption in the derivation of all Bell Inequalities. The EPR dilemma [21] and the various Bell Inequalities [22,23] are the inevitable mathematical consequence of this core assumption [12]. Since nature violates the Bell Inequalities, it follows that spacelike separation of events does not in fact guarantee "no influence". In this paper, we shall simply take the decades of experimental evidence at face value, put aside the detailed discussions on every *other* assumption, and show why the "no influence" assumption is unsafe in (at least some) local realist field models of the quanta.

We shall thus take it as given that, when Alice measures some spin component of her electron in [1], there is an immediate influence on the physical state of affairs of Bob's electron. This is simply what Quantum Mechanics says: Alice's spin measurement along axis "a" projects both members of the entangled pair, such that each of them is now in a well defined spin state, one aligned along a, the other counteraligned. The question this paper addresses is "How can that be so?" No new formalism is required, only the removal of a longstanding, unjustified *Metaphysical* prejudice concerning action at a distance. Not only do the (relativistic and non-relativistic) quantum formalisms we already have function appropriately but also, as we shall see, they already reflect the revision to our concept of interaction at a distance that is proposed in Section 3.

Behind the no influence assumption is the idea that, for being a causal influence, any long range interaction must have propagated from Alice's electron's pointlike vicinity to Bob's with a velocity at or below *c*. This is simply the modern rendition of Classical Physics' retarded interaction paradigm, where interactions between charged particles travel from the source particle to the target particle at or below *c*. Section 2 examines and dismisses this ancient idea, the roots of which trace back at least as far as Newton. Logical deficiencies were identified long ago but never resolved. It never did work in practice under genuinely dynamic conditions. There is nothing resembling a retarded interaction in Modern Physics and it has failed every available experimental test. We therefore begin by rejecting this incompetent explanation for long range interactions.

But then the same question comes back: "How can we explain EPR without violating causality and local action?" Rejecting retarded interaction enables it to be seen that Modern Physics already contains the answer. Subsection 3.1 considers how relativistic quantum theory deals with interaction at a distance, specifically how "virtual particle" interactions work in Quantum Electrodynamics (QED), where interactions do not propagate from source to target, and could never be understood within the retarded paradigm. A proper, local realist, explanation for long range Electromagnetic interactions, "distributed action", suggests itself. Subsection 3.2 first discusses two important constraints that the quantum phenomena impose on field models then identifies an existing class of physical models, [19], that meets the constraints and also generates the Dirac Equation. Distributed interactions between such, *suitably correlated*, distributed quanta can have distributed impacts that happen in distant places at the same time. We thus arrive at an explanation for the experimentally observed facts.

In Section 4, we shall focus on a unique aspect of this proposal, testability. Unlike every other "explanation" that has been put forward, this one makes a testable, new prediction that can be falsified in experiments we can do today. Finally, Section 5 discusses the significance of this approach and the central lesson to be learned from EPR.

2 The Failure of the Retarded Interaction Paradigm

The retarded interaction paradigm has a long history in Physics, dating back at least as far as Newton, who first gave prominence to it as part of his response to Leibniz's criticism that Newtonian Gravity introduced instantaneous action at a distance. His early response is famous in its own right:

> *"I frame no hypotheses; for whatever is not deduced from the phenomena is to be called an hypothesis; and hypotheses.... have no place in experimental philosophy."* — Isaac Newton [24].

Those words secured the future of Physics as a scientific discipline focussed on experimentally falsifiable relations between observable facts. They did not, however, constitute an answer to the criticism, and history shows that Newton himself understood this because, fifteen years later, he finally framed an artful Hypothesis, in the negative:

> *"That one body may act upon another at a distance thro' a Vacuum, without the Mediation of any thing else, by and through which their Action and Force may be conveyed from one to another, is to me so great an Absurdity that I believe no Man who has in philosophical Matters a competent Faculty of thinking can ever fall into it."* — Isaac Newton [25].

This remark has also left an indelible mark on every physicist who ever lived. The father of Physics gave the one and only true path for any theory of interaction mechanisms. Anything else but interaction as a thing that travels between primary participants must be the product of incompetence. This *Metaphysics*, only forced upon us by the point particle concept, is the root of the EPR dilemma.

When Maxwell's Laws and the Electromagnetic wave equation were found, Newton had long ago put the possibility that interactions do not travel between point particles beyond consideration so it was immediately recognised that the speed of interactions as they travel between massive particles would have to be constrained by the speed of light. The retarded interaction paradigm thus crystallised in Classical Physics.

However, it has been recognised since the outset that this interaction mechanism is unsatisfactory and the role of this Section is to recall just how unsatisfactory it is in four key respects: Logical coherence; Mathematical clarity; Fruitfulness in practical applications; Consistency with experimental facts.

2.1 Logical Coherence

Newton's two famous 17^{th} century remarks above were made in the context of instantaneous action at a distance in Newtonian gravity, however the modern curved space theory of Gravity does not interpret the observed motions of celestial bodies in terms of "any thing else" that conveys "Action and Force" from one to another. Today, the principle archetype of the idea Newton expressed over 300 years ago is Classical Electrodynamics. Therefore, let us first consider the Classical model of the electron, where the far field was thought of as an Electromagnetic field that propagates away from the body of the electron.

The core problem with this was conservation of energy-momentum because, in order to transfer momentum from the source to the target, the source must forever be radiating power in every direction. This problem was well known at the time, but it was never resolved in the Classical Theory. (Advanced waves were never considered satisfactory, but this approach has been ruled out recently [20]: Inward and outward radial propagating waves are incompatible with the experimental facts on matter beam interference because identical wavelets from neighbouring slits do not exhibit the usual interference pattern while neighbouring slits are, in any event, not identically illuminated).

A second difficulty is that the linear momentum of a radiated field points away from the source, but interactions between oppositely charged particles transfer momentum in the opposite direction.

Thirdly, retarded interaction leaves unresolved the question how the source knows where and when interaction mediating agents are absorbed, and consequently is unable appropriately to account for the reaction momentum.

2.2 Mathematical clarity

One result of this logical incoherence is that, to this day, there is no satisfactory theory of Classical Electrodynamics under dynamic conditions [26,27]. These textbook references to early paradoxes with the Abraham-Lorentz self force represent only the tip of an iceberg. Retarded interaction induces Mathematical contortions at every turn. Indeed, Classical Electrodynamics can be seen as a fine Theory in many respects, but not under actual dynamic conditions. As Feynman put it in a discussion of point models: "... this tremendous edifice [classical electrodynamics], which is such a beautiful success in explaining so many phenomena, ultimately falls on its face." [28].

It is not that Physics did not try to resolve the difficulties. These rather simple issues led many of the greatest physicists of the 20^{th} century into great mathematical depth. [29] represents the state of affairs in 1972, which the editor, E.H. Kerner, characterises as "but a sketch". For Kerner, despite a host of unresolved issues, progress was being made but fifty years later the fact remains that arguably the first problem in Classical Physics, the two body problem, still cannot be formulated.

2.3 Practical Applications

Paradoxes aside, the Liénard-Wiechert retarded potential produced a variety of *useable* early results, but Special Relativity shows, in particular, that the velocity field of the electron follows directly from purely kinematical coordinate transformations, without using retardation. Since the velocity field comoves with a charged body in a uniform condition of motion, the *"cleanest"* result from retarded time analysis is that the velocity field is not retarded. As discussed in subsection 2.2, it broke down in the general case of long range, dynamic interactions between classical charged bodies.

Of most relevance here, (with one stark exception) the retarded interaction paradigm is conspicuous by its absence in Modern Physics: It is not used in Gravity, Quantum Mechanics, QED nor any of the Quantum Field Theories. As for the Special Theory, Einstein's derivation of Lorentz Transformations was fully kinematical, and the *original* Theory was thus independent of any model of causality. Retarded interaction was subsequently "grafted on", in the form of light cone causal analysis, as an integral part of the traditional concept of relativistic causality. Of course, the definition of relativistic causality has now been revised in the light of EPR experiments, with signalling replacing causation. This change entirely removes retarded interaction from Modern Physics and restores to Special Relativity its original generality regarding causality. The reason for the failure of light cone causal analysis will be discussed in Section 5.

The one stark exception to the absence of retarded interaction in Modern Physics is, of course, the EPR literature, where it remains as the basis for Bell's concept of local causality [12], for the "no influence" assumption, for the factorisability of probabilities and the derivation of every known Bell Inequality.

2.4 Consistency with Experimental Facts

To test the retarded paradigm experimentally is nontrivial because the characteristic velocity is high. To our knowledge there have, however, been at least two distinct forms of experimental evidence obtained.

The first of these is, of course, EPR experiments, and there is no need to dwell on this here since it is now so widely accepted that the facts cannot be explained by causal influences that propagate from Alice's lab to Bob's at or below c. It is the fact that the retarded paradigm cannot explain the observations that motivates the present article.

Less well known are precision measurements in Gravity which show that the Earth accelerates towards the *instantaneous* position of the Sun, and not the *retarded* position as would be expected under retarded interaction [30]. This result is not entirely unexpected as it corresponds to the usual practice in computational relativity – used to chart the movements of celestial bodies within the solar system – where the metric is calculated based on instantaneous positions.

In summary, while initially appealing, this retarded notion of interaction is unsatisfactory on every criterion: It makes no sense; It doesn't work; It is experimentally falsified; And it is not even used in Modern Physics.

In the next Section, we shall consider the alternative, "distributed action", which emerges directly from an interaction mechanism that actually is used in Modern Physics, specifically in QED.

3 Distributed Action and the Bell Inequalities

3.1 The Interaction Mechanism in Quantum Electrodynamics

The Electromagnetic interaction between charged quanta in Quantum Electrodynamics (QED) is mediated by so called "virtual photons" (see for example [31]), which exist only for short periods of time, constrained by the energy-time uncertainty relation, which allows energy to be "borrowed", temporarily, from the vacuum. When Feynman originally set up QED, this term, "virtual", just referred to a possible process with nonzero probability [32]. His QED is set up on the basis of Classical Electrodynamics but, although he explicitly has the retarded paradigm in mind, the retarded potentials are not used and his key calculations are done in the momentum basis, where the issue is moot.

A virtual photon becomes permanent – in the sense of having persistent observable consequences – only if it is absorbed by the target quantum during its brief lifetime. The principal benefit of this "virtual" device was to resolve the first issue that we recalled in subsection 2.1 above, energy-momentum conservation.

The virtual photons propagate at the characteristic velocity, but they do not in general propagate from the source, A, to the target, B. Nor are they particles, in the usual atomist sense of being well-localised corpuscles. The virtual photon is instead to be thought of as a momentum eigenstate that occupies all of space, and might be propagating in any direction.

For an attractive force, as between an electron and a proton, there is a preponderance of absorbed virtual photons propagating in the direction from target to source: They approach the target from the "wrong" side. This resolved the second logic problem recalled in subsection 2.1, where the linear momentum of a retarded field could only point radially away from the source. Clearly, this QED interaction mechanism in no way resembles the retarded interaction paradigm.

Of most interest here is the resolution that distributed momentum eigenstates provide for the third issue in subsection 2.1, how to account for the reaction - the momentum change of the source which must be equal and opposite to the momentum change of the target. A momentum eigenstate that occupies the whole space cannot be thought of as generated by a pointlike source and similarly nor can it be thought of as absorbed by a pointlike target.

If we are to think of the interaction quanta as distributed fields then we must also think of the source and the target quanta as distributed fields. Each of them permeates the entire space, which is also the modern view from Quantum Field Theories. The source and the target are thus always touching, everywhere. The Principle of Local Action is automatically satisfied, our quanta are free to interact locally, everywhere in space, and the retarded interaction field is rendered redundant. (NB: While the impact of a point disturbance on remote parts of the same field would be retarded, with inherently distributed interaction quanta there are no pointlike excitations [15].)

Therefore, what the QED interaction mechanism is describing is a distributed transfer of energy-momentum from one distributed field to another. In other words, it is describing local field-field interactions that are spatially distributed, not atomist particle-particle interactions. It is describing *distributed action*.

3.2 Measurement Interactions in Local Realist Field Models of the Quanta

Any discussion of the physical structure of the quanta is usually so deprecated in the Quantum Mechanics literature that Bell himself referred to it as "Unspeakable in Quantum Mechanics" [33]. However, we have arrived above at a definitively physical picture that has already undermined the core idea in "Bell's concept of local causality" [12] that, when Alice measures the spin of her point-like electron at A, the only possible physical mechanism for influencing Bob's point-like electron at B is for the quantum located at A to generate some form of causal influence that propagates radially away from A towards B.

Instead, we can now interpret Alice's spin measurement as a spatially distributed measurement interaction between two distributed fields, her electron and her measurement field, with consequences that are distributed, not pointlike.

However, merely to weaken the logical basis for Bell's Theorem like this does not go far enough. To address the fundamental "How can that be so?" question that EPR experiments have raised, we now describe in detail how distributed action enables Alice's measurement instantly to project the spin of Bob's electron, B, onto the same measurement axis, counter-aligned with the spin of her electron, A. This necessitates considering some pertinent inferences that can be drawn from quantum physics regarding the physical structure of the quanta, in two steps.

The first step is to take matter beam interference phenomena [34] at face value: When we solve the relevant Schroedinger, Klein-Gordon or Dirac wave equations for an individual electron in an electron beam, subject to the boundary conditions imposed by a beam collimator, the result is a planar de Broglie wave that occupies the entire beam width, which is many orders of magnitude larger than the Compton radius (*i.e.* the reduced Compton wavelength) of the electron.

In order to produce observable interference phenomena, the slit system as a whole should be illuminated everywhere with the same amplitude and phase. The electron in the beam is then a distributed wave phenomenon. The implication is clear and unavoidable: The wavefield features instant correlations at a distance, at least as widespread as the slit system or the beamwidth, spanning at least tens of microns. EPR experiments just show that these correlations extend to the far field. (As for the particle side of wave-particle duality - producing tiny dots on the screen - note that we are in that case solving the same wave equation under very different, central, boundary conditions.)

In particular, an electron at rest features a "space independent phase". This is just what de Broglie [35] analysed with his "periodic phenomenon", $e^{i\omega t}$, associated to the rest particle and its Lorentz Transformation, the de Broglie wave, $e^{i(\gamma\beta kx-\gamma\omega t)}$, associated to the moving particle. Let it be emphasised that $e^{i\omega t}$ has no space dependence: It has the same phase at every space point, while with the de Broglie phase wave, the phase varies only in the x-direction, normal to the slit system, but not transverse to it, so that the slits are everywhere evenly illuminated with the same amplitude and phase.

This is the first necessary condition for both matter beam interference and EPR correlations: Quanta in the comoving system oscillate everywhere with the same phase. The second necessary condition for matter beam interference phenomena [20] is that the wavefield must evolve internally under elements of Special Relativity's little group of transformations, which retains the linear momentum of a free particle. In particular, rest particles evolve under elements of the group of ordinary rotations in 3D, SO(3). In other words, any trajectory of the wavevector exists on the surface of a sphere in the comoving system. Since the radian frequency, ω, is fixed, while the energy, $E = \hbar\omega = mc^2$, propagates at the constant characteristic speed, c, the dimension of the sphere is fixed, in the vicinity of the Compton radius, $\sim 10^{-13}$m.

Any viable local realist field model must thus provide instant correlations at macroscopic distances from fields that are constrained to evolve on microscopic spherical surfaces (in the comoving system). This implies a "field of oscillators" structure: A widely distributed system of well-localised oscillations - energy moving on the surfaces of spheres that are distributed throughout space, all coupled into a single whole, oscillating in harmony.

We shall see below how spacelike causal correlations arise from interactions between such structures, but we must first consider the essential role that the SU(2) group plays in resolving the obvious topological issues with such models, and how they reproduce the Dirac Equation. For the second step, then, a specific physical model by Battey-Pratt and Racey, [19], adds the necessary mathematical and physical insights. Closely related to the well known "Dirac's double belt trick" [38], this distributed physical model develops both de Broglie waves and the Dirac Equation in the above context. They describe the wavefield in these words:

> *"Our conclusion, then, is that the spinning continuum is surrounded by an undulating, wavelike region whose phase, ϕ , satisfies the equation*
>
> $$\nabla^2\phi - \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} = \frac{\omega^2}{c^2}\phi\,.$$
>
> *This looks very like the Klein-Gordon equation for an elementary particle. We shall therefore make the identification exact....."* — Battey-Pratt & Racey, [19] p. 450.

From this point, they proceed via the Klein-Gordon Equation to the Dirac Equation. Their (spinor) phase, ϕ, evolves along the trajectories of field movements that are confined to the surfaces of tiny spheres, satisfying the little group. The key consideration here is that it has been shown how the visualisable, physical picture under discussion - a widely distributed, undulating wavelike region characterised by a single phase, ϕ - produces the Dirac Equation. The proposed class of physical wave structures thus shares the same mathematical foundations as relativistic quantum mechanics.

It is now straightforward to understand spacelike causal correlations in terms of distributed interactions between such distributed wavefields.

If Alice's electron has the same phase everywhere then, since aligned magnetic fields form a low energy state, the direction of its field angular momentum density, which is proportional to $d\phi/dt$, will also be the same everywhere. Moreover, if this applies to one quantum it applies to all, so it applies also to the quanta that constitute her measurement field, which is aligned along the measurement axis at every space point. Each of the measured and measuring fields is thus *"suitably correlated"*.

't Hooft, [18], has shown how such instant *ontological* correlations at a distance can evolve under local interaction in cellular automata, but it is pertinent to recall here that waves are, quite generally, systems of distantly correlated movements sustained by strictly local interactions. Upon replacing 't Hooft's digital cell contents with analogue variables, cellular automata (*i.e.* one per quantum) provide the basic framework for modelling wavefields [19] and distributed measurement interactions between them that induce spacelike causal correlations [20]. The measurement interaction proceeds as follows.

Given that Alice's electron's wavefield and her measurement field each feature correlations at a distance, when her spin measurement is performed there are, in effect, innumerable copies of the same interaction happening everywhere, in parallel, at the same time. The entire electron A field angular momentum rotates as a single, distributed whole, until it aligns or counteraligns with the measurement axis, a.

As for Bob's electron, ever since preparation it has been in a special "entangled" relationship with Alice's, where the total angular momentum of the pair vanishes. These states persist for extended periods of time, in the vicinity of 10 mSec in the Delft experiment [1]. This is an aeon on the timescale of an electron oscillating at $f \sim 10^{20}$ Hz. Such long lifetimes in a noisy environment [39, 40] require an ongoing interaction between the two "distributed, undulating, wavelike regions" that are the electrons forming the entangled pair. The basis for this interaction is well understood: Counteraligned magnetic fields are also a low energy state, so there is a binding energy of the entangled state, which then displays noise immunity, enabling it to survive for such extended periods.

The two members of our entangled pair being bound together by this interaction, when Alice's electron's spin rotates during her spin measurement, Bob's electron's spin follows suit, rotating as a single, distributed whole in the opposite direction until it becomes counteraligned with her measurement result along the same axis, a, at which point the entanglement is disrupted, as the A and B angular momenta are locked onto that axis by the strong measurement interaction.

Bob's measurement is then just a case of a spin measurement along b of a particle prepared in a definite spin state along a. The well known quantum probability for this, ($P(+_b|\theta) = cos^2(\theta/2)$, where $P(+_b|\theta)$ is the probability for Bob to get the result "UP along b", given the angle θ between the preparation axis and the measurement axis) involves no hint of nonlocality. Since Alice's result is "UP along a" on 50% of trials and "DOWN along a" on the other 50%, this leads trivially [20] to the familiar correlation function, $C(a, b) = -\mathbf{a} \cdot \mathbf{b}$, which violates Bell Inequalities.

Two obstacles to implementing the above relation in distributed action models were identified and resolved in [20]. The first of these is the "synchronisation" problem: How do colocated cells of the measured and measuring systems near Alice (on the one hand) and near spacelike separated Bob (on the other) know when to interact? It was shown that local realist mechanisms are available in principle but what is notable here is that the problem does not arise with QED's distributed interaction quanta: The part of Alice's measurement in her own lab is automatically sychronised with the part in Bob's lab.

The second issue is the "voting" problem. If the cell level decision were random, per the usual quantum probability above, then upon measurement different interim decisions would be reached in different cells all over the space. The system level result would then be resolved by local cell-cell interactions in the sense of the Ising model, but this is not satisfactory: Once the cell level "UP" probability exceeds 0.5, the whole quantum is forced into the "UP" state with probability 1. That does not reproduce the quantum predictions. However, this "voting" problem presents no problems for deterministic but time dependent models of the interaction. To illustrate this, a local, realist but distributed variation of a toy model by Bell was found to replicate the usual quantum prediction: $A_i = SGN[sin\,(\omega_{\sigma_i} t_{mA}) - f(\theta_{Ai})]$, where A_i is the cell-level decision, $f(\theta_{Ai}) = sin(-\frac{\pi}{2} cos\,\theta_{Ai})$, t_{mA} is the measurement time, and ω_{σ_i} is a frequency associated with the time evolution of the spin.

In this Section, we have shown how distributed action, already familiar from QED, can reproduce all the usual quantum predictions for EPR experiments, without appealing to superluminal movements, violations of local action [41], retrocausality

[42], counterfactual indefiniteness [43], many worlds [44], conspiracy / contextuality [45], nor any of the other "disgusting" extravagances, to use 't Hooft's word [18], that characterise the literature in this field.

We shall now emphasise, in Section 4, a supposedly core consideration in Physics, all but forgotten in the literature, namely the fact that the present proposal makes an experimentally falsifiable prediction.

4 Experimental Tests

Consider the list of alternative resolutions to the EPR paradox that has been proposed in the literature: "Reality fails" (counterfactual indefiniteness), retrocausality, superdeterminism, many worlds, ("spooky") violations of local action, conspiracy / contextuality etc. Although the last one seems highly unlikely in view of the experiment [45], the common hallmark is that there are never any testable, new predictions that can be falsified experimentally. Even the notion of superluminal causal influences, which substantially undermines Lorentz Invariance, can never be falsified by tightening timing windows.

In stark contrast, the present resolution is readily falsifiable, as follows.

The total energy of any given quantum is finite. In local realist field models, this is just the integral over all space of its field energy density. In order for this integral not to diverge as $r \to \infty$, the far field energy density asymptote cannot exceed $1/r^4$. This corresponds to a $1/r^2$ force field asymptote, just as the energy density of the Electromagnetic field is proportional to either $\mathbf{E}^2$ or $\mathbf{H}^2$. The binding energy of the entangled state referred to in subsection 3.2 is therefore range dependent and it follows that the noise immunity and the lifetime of the entangled state are also range dependent.

Photon experiments are relatively insensitive to noise, but experiments with electrons, such as [1], are not [39, 40]. No effort is spared to maximise the state lifetime, both with cryogenic cooling and fine tuning of the Nitrogen Valence (NV) electron sites. These efforts have been so successful that the lifetime of the entangled state is five to six orders of magnitude greater than the time delay between preparation with the Barrett-Kok entanglement swapping protocol [46] and the Bell measurements, while, notably, the change in the protocol success rate between [47] and [1] is sufficiently explained by the additional fibre optic cable losses in the latter, loophole free, experiment. The result of these remarkable technical achievements is that the experiments do not test for the anticipated range dependence of the lifetime of the singlet state.

However, this experiment can easily be degraded, for example by increasing the temperature, injecting a controllable magnetic noise level, slightly detuning the NV centres and / or delaying the Bell measurements, so that at a given close range - say on the order of 5 metres from Alice to Bob - the fringe visibilities begin to degrade because we are now including trials where the entanglement has already been broken. The CHSH inequality, [23], is still violated, but the violation is significantly reduced. If we now repeat the experiment with exactly the same degradation, but at a longer range - say 50 metres - the prediction is that the state lifetime should now be reduced to the point where the CHSH inequality is no longer violated. (Note that spacelike separation of events is not required for this test so Bell measurements can be delayed and, to save time, only need to be performed on trials where the Barrett-Kok protocol succeeds.)

No doubt, in the event that this prediction is confirmed, it will be shown within the quantum formalism, but to our knowledge no such calculation has been performed at the time of writing. The proposed resolution is thus unique in that the entire class of local realist field models described in subsection 3.2 can be experimentally excluded.

5 Discussion

While the far fields of Alice's electron may seem too weak to exert a sufficient influence on the near fields of Bob's, this is an empirical question about *coherent* binding interactions versus *incoherent* noise. The fact is that Bell's assumption is called the "no influence" assumption. It is not called the "very little influence" assumption and, if EPR experiments were performed at the same distances, measured in kilometres, but without spacelike separation, no one would question that the (supposedly retarded) far fields were responsible for the observed influence. Judging by the lifetime of the singlet state in [1], we are still not close to the maximum range that might be achievable in the future.

A final issue illustrates the general nature and scope of the proposal in this paper. Alice's measurement axis choice is also spacelike separated from Bob's measurement, and it is the part of her measurement field in Bob's lab that influences, locally, the part of her electron in his lab. The instant preparation of Alice's measurement field in Bob's lab is already addressed by the argument in Section 3: Any physical process that implements Alice's choice, to set up her measurement axis, proceeds in parallel at all space points at the same time, same as the spin measurement she then performs.

EPR correlations defied explanation for so long mainly because the usual light cone causal analysis is based on an idea that is actually irrelevant: "Any effect of a point event must lie in its future light cone". In EPR experiments, the effects of pointlike observable events - *eg* "Alice's UP detector clicks" - are simply irrelevant. Only the effects of the measurement interaction between Alice's electron and her measurement field are relevant and the pointlike nature of her observable result in no way implies that the measurement interaction itself is pointlike. It is essential to recognise that the pointlike observable is caused by the measurement interaction, not *vice versa*. Light cones emanating from pointlike observable events invert this relation, with the result that any part of the measurement interaction that is not collocated with the event is excluded from the causal analysis. In particular, the interaction between those parts of Alice's electron and measurement field that were already in Bob's lab before her measurement is excluded, rendering the phenomena unintelligible.

By contrast, in this paper, the experimental fact of instant correlations at a distance in de Broglie waves and the QED interaction mechanism were seen to imply, first, that the quanta are widely distributed, correlated wave systems and, second, that interactions between these spatially distributed, correlated systems are similarly distributed. The physical state of affairs in Bob's lab simply coevolves with that in Alice's lab, without any "causal influence" that travels from her lab to his.

6 Conclusions

This paper has shown Bell spacelike causal correlations as a local realist wave phenomenon. Like looking behind the scene of magicians, there turns out to be no magic involved. As with magicians, we were simply deceived by appearances. The objects we observe in the world appear well localised in space and we naturally presumed the same about elementary particles (although we could no longer see them directly). If it were really so, particles would truly be separated and could only interact through retardation, which we have seen leads to problems in all respects, not just the EPR paradox.

Instead of particles, the quanta were treated here as wavefields that extend indefinitely in space, comoving with the pointlike phenomena of our experience. What looks like "action at a distance" - from a point particle perspective - can then be understood coherently in terms of local field-field interactions distributed throughout regions of space where the involved quanta overlap. The EPR experiments were explained in this way, without requiring a single "disgusting extravagance".

Data Statement

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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