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An Unspeakable Mechanism

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Abstract: *Retarded interaction has forever been an incompetent attempt to explain long range interactions, and now it is falsified by EPR experiments. An appropriate alternative, distributed action, is introduced and constraints on the microstructure of Lorentz Invariant fields that produce de Broglie waves are identified leading to a toy physical model of spacelike causal correlations in the de Broglie-Bohm EPR experiment that relies only on strictly local interactions between realist classical fields.*

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

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1. Introduction

According to experimental evidence [1–3], leading theoretical analyses [4, 5], and the best discussion thereon [6], we live in a world that features causal correlations between spacelike separated point events. In particular, measuring any spin component of one member of a pair of electrons in the singlet state instantly influences the result upon measuring a spin component of the other, regardless of where it may be. These Bell measurements point to the failure of the traditional definition of relativistic causality[1], which is the basis for both the derivation of Bell Inequalities [4] and the causal analysis of EPR experiments [6].

There are three modes of response to this discovery. First is the instrumentalist view, as Sir Isaac Newton famously put it so long ago:

> *"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."* --- Sir Isaac Newton [7].

The standard, modern conclusion in relation to Bell Inequality violations is that any physical model would have to abandon either "locality" or "reality". This is not to be understood; it is simply true.

Newton was not, however, entirely above the framing of hypotheses:

> *"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."* --- Sir Isaac Newton [8].

It will be argued that it is the uncritical acceptance of this unsatisfactory hypothesis (which evolved into retarded interaction after the d'Alembert Wave equation was deduced from Maxwell's Laws) that has prevented any resolution of the EPR paradox, while this centuries old hypothesis is precisely what is falsified by EPR experiments. Furthermore, Einstein's derivation of Lorentz Transformations needs

1 *i.e.* the observer independence of the notion that causes must precede effects. Accordingly, any effect of a point event must lie in its forward light cone, any cause of a point event must lie in its backward light cone, and there can be no causal influences between spacelike separated events. The failure of this definition has led some authors to redefine relativistic causality (with "signalling" replacing "causation"), however this article retains the traditional definition.

no such hypothesis and Special Relativity does not imply relativistic causality unless retarded interaction is also presumed.

The second mode of response is denial --- the view that either the experiments are flawed or that they don't imply any real physical influence [9–11]. This often reduces to rejecting Bell's assumption that relativistic causality implies the factorisability of probabilities for measurement outcomes in Local Hidden Variables (LHV) models. In the usual notation: $P(AB|a,b,\lambda) = P(A|a,\lambda)P(B|b,\lambda)$.

The third is to explain the correlations using various alternative metaphysical ideas. Examples include superluminality, which interferes with Lorentz Invariance, superdeterminism [12], nonseparability [13], retrocausality [14], and many worlds [15]. None of these hypotheses can be falsified experimentally.

With EPR, the non-classical physics of entangled states and projection operators is not the real problem. It is simply that the result cannot be understood once Newton's 17th century Metaphysics has been presumed. Indeed, the above conclusion, that we must give up either "locality" or "reality", is based on a definition of local realism that effectively presumes an ontology of pointlike particles with retarded interactions. Section 2 compares this way of defining local realism with the approach that is routinely adopted in field theories.

In section 3 the reader will then be invited to question the unquestionable: It will be argued that retarded interaction does not make sense. While the link from relativistic causality to factorisability is sound, if retarded interaction cannot be assumed, nor can relativistic causality.

However, with no viable alternative one moves from an incompetent explanation for interaction at a distance to no explanation at all, so it will not be sufficient merely to observe that retarded interaction is fraught with difficulties. A satisfactory mechanism to replace it in field models of the massive particles, "distributed action", will be proposed. In order to explain this adequately, some consideration of the "unspeakable" [16], *i.e.* the physical structure of energy quanta, will be required, as follows:

Section 4 develops a distributed action model for the long range Coulomb interaction between charged particles. The focus is less on the old Physics and more on understanding why causal relations between pointlike observables are not subject to relativistic causality under distributed action. Section 5 shows that Lorentz Invariant field systems that produce de Broglie waves have a cellular microstructure.

In section 6, these two concepts, distributed action and the cellular field microstructure, are combined in a local realist field model for the complete set of quantum predictions in the de Broglie-Bohm version of an EPR experiment. Although this is just a toy model, it invokes only manifestly local interactions; it does not undermine Lorentz Invariance; and, unlike [12-15], it is readily testable and it requires no exotic or profligate, opaque or even genuinely new ideas.

Section 7 identifies the crucial distinction between LHV models and local realist field models. The central conclusion of the Article is that, while Bell Inequality violations exclude the former, they do not exclude the latter. This is all the more relevant because the experimental fact of de Broglie waves shows that the correlations at a distance upon which the toy model relies also exist in the real world.

Finally, a feasible experiment to falsify this model is described.

2. DEFINING LOCAL REALISM

The Principle of locality is usually formulated in the EPR literature essentially as follows:

> *An event at point A and time t_a cannot influence a result at point B and time t_b if $t_b - t_a < D/c$, where D is the distance between the two points and c is the characteristic velocity.*

Since there are two other formulations relevant for this article, let us refer to this one as "Bell locality". The model in section 6 violates Bell locality. To introduce the second formulation, consider for a moment the EPR sufficiency condition for an element of physical reality:

> *"If, without in any way disturbing a system, we can predict with certainty (i. e. with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."* [5].

One might then contemplate a second formulation:

> *An element of reality at point A, that corresponds to an event at A and t_a, cannot influence a result at B and t_b if $t_b - t_a < D/c$.*

The model in section 6 does NOT violate this formulation and the difference lies in the question whether elements of reality can exist that correspond to the event at A and t_a but which are not colocated with it. It will be shown that this is not just possible, but entirely plausible, in local realist field models of the quanta, so let us now define the term "local realist field model".

> *A realist model is one that asserts the objective (i.e. observer independent) existence of a unique physical reality (an "ontology"), from which relevant observables (the "epistemology" of the model) may be calculated;*
>
> *A field is a function on a 3-space plus time;*
>
> *A realist field model is a realist model with a field ontology and*
>
> *A local realist field model is a realist field model that satisfies "Field locality".*

As far as Field locality is concerned, there is a third formulation of the Principle of locality that pertains to field models (a similar definition is used in Quantum Field Theory):

> *Fields at different points in space do not interact with each other. Alternatively, at any given space point, the interaction between two fields depends only on the values of the fields that are present at that point.*

To complete the definition, the notion of local interactions must be supplemented by a "no superluminal movements" constraint on individual fields:

> *No field may propagate faster than the characteristic velocity.*

"Field locality" is the combination of the last two constraints.

In the EPR literature, "reality" has various definitions, which typically concern the reality of unmeasured properties. Readers unfamiliar with the literature might find such language (about the physical existence of an unobserved observable) problematic, but the mathematics to which it refers is clear and unambiguous. Suffice it to say that the proposed model satisfies counterfactual definiteness and does not violate any reasonable definition of "reality".

The model replicates the complete set of quantum predictions in the de Broglie-Bohm version of an EPR experiment, which is to say that it generates nonlocal, causal correlations between spacelike separated point events that violate Bell Inequalities. While it satisfies Field locality, it violates Bell locality, and we shall return to the distinction between these ideas in Section 7.

For many readers, the major barrier to understanding the model will be the ingrained habit of thinking of long range interaction as a thing that travels through space. The next two sections will first criticize this way of thinking on the grounds that it is ultimately unintelligible, and then replace it with a more satisfactory interaction mechanism, one that can actually be understood.

3. How Do Two Particles Interact With Each Other?

Retarded interaction may be defined as the hypothesis that:

> *In order for two well separated particles to interact with each other, an interaction mediating agent (typically a field or a particle) must travel between their respective locations.*

Let us consider that superficially self-evident idea. It will be recalled that Newton's two famous 17th century remarks above were made in the context of instantaneous action at a distance as it appears in Newtonian gravity. As far as gravity is concerned, the modern curved space theory does not interpret the observed motions of celestial bodies in terms of "any thing else" that conveys "Action and Force" from one to another so today the principle archetype of the idea Newton expressed over 300 years ago is Electrodynamics.

To fix ideas, let us first consider the classical picture 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 field 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[2]. Another related 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. Retarded interaction also leaves unresolved the question how the source knows where and when interaction mediating agents are absorbed, and consequently how to account for the reaction momentum.

One result is that, to this day, there is no satisfactory theory of Classical Electrodynamics under dynamic conditions [17, 18], while the two body problem cannot even be formulated [19].

Energy-momentum conservation is *formally* addressed in Quantum Electrodynamics (QED), where long range interactions are ostensibly mediated by virtual particles that only exist for short periods of time, δT, subject to the energy-time uncertainty relation. The virtual particle lifetime, δT, is typically many orders of magnitude less than the light time between macroscopically separated electrons so, for all intents and purposes, the particle that interacts with the target only exists at the point of interaction.

If that were the modern viewpoint, then, since it does not exist during transit, the virtual particle could not be said to have travelled from the source to the target. Of course, that is not the modern viewpoint, so what is? One comes next to the idea of the virtual particle as a momentum eigenstate that occupies all of space, which has no need to travel from A to B, and cannot be thought of as generated at the pointlike location of the source. Attractive forces are even implemented with virtual particles that propagate in the opposite direction, *i.e.* from target to source. This is definitely not a retarded interaction mechanism (although it can easily be understood as a distributed action mechanism).

While there are various other ideas about interaction in various other Quantum Field Theories, nowhere in any branch of Quantum physics is there an interaction mechanism that vaguely resembles retarded interaction. This is no criticism of Quantum Electrodynamics, but of the abiding lack of clarity interpreting it in a classical setting with point particles and retarded interactions.

What I am suggesting is that retarded interaction is fatally flawed as a mode of explanation, not just for Electrodynamics, but in general. The fact is that no *intelligible* retarded interaction mechanism has ever been proposed, neither in Classical Electrodynamics, QED, gravity, nor any other theory. Although it has forever defied explanation, retarded interaction is still the universally accepted basis for relativistic causality and LHV models. It seems beneath suspicion in the EPR literature.

The next two sections develop a satisfactory mechanism for long range interactions, where interaction is thought of as inherently distributed throughout both participants' near and far fields.

4. How do two fields interact with each other?

Efforts to express how local action constrains causality in field systems typically begin with statements more pertinent to a particle framework, such as:

> *"The impact of any pointlike disturbance introduced into a field propagates away from its source at the characteristic velocity".*

As reasonable as that may be, it is of little use here because there is no such thing as a point source in a (pure) field model - The approach to causality in this Article will be restricted to concepts that are actually available in field models.

What one does have in a local realist field model of a particle is a set of fields, specified on the entire space at time t, that propagate at or below c. Physical observables of interest (the particle's location, mass, velocity *etc*) are to be calculated from these fields. While the conduct of Physics often requires us to invert the process, by drawing inferences about the fields from the observables, it is essential to

2 Advanced waves were always considered unsatisfactory, but this picture will be excluded here anyway, in subsection 5.1.

understand that it is the fields that cause the observables in field models and not *vice versa*. Clarity on this point is crucial when considering causal relations between observable point events.

Concerning interactions between two particles, retardation from A to B, where A and B are the observed locations of the particles, presumes first that the field of particle A at the location of particle B is caused by the field at the centre of particle A at some earlier, retarded time and second that any interaction is restricted to the two points, A and B.

As for the first presumption, some basic flaws were identified in section 3 and it will be shown in subsection 5.1 that radially propagating fields are incompatible with de Broglie waves. As for the second, in a field theory the fundamental entities that are considered actually to exist are distributed in space. It seems profoundly irrational to presume that interactions between them would be so restricted. In this Article, field-field interactions will therefore be assumed to occur, not just at the particles' locations, but at every space point where both fields are nonzero, hence the term "distributed action".

As discussed in section 2, the meaning of local action in this context is simply that the interaction at a chosen space point depends only on the fields present at that point. The sole purpose of this section is to gain some initial insight into the implications this has for the causal structure of observable events. To that end, a toy model of the Electrostatic interaction between charged particles will be developed, providing a simple but quantitative illustration of how distributed action works, and why the causal structure of events is not governed by relativistic causality.

Let it be assumed that the electron has the usual 'attached' [18] field but that it does not propagate radially away from the centre[3]. Consider the first order, nonlinear interaction between the force field of one particle, the "source" and the field energy density of the other, the "target".

It will be convenient to choose coordinates with the target at the origin, so let the force field at some point, P, be written as $\boldsymbol{\Xi}(\boldsymbol{r}) = KQ\,\hat{\boldsymbol{a}}\,/a^2$, where K is a constant, Q is a parameter that represents the strength of the field source, a is the distance from the source to the point, P, and $\hat{\boldsymbol{a}}$ is a unit vector that points radially away from the source.

As for the target, let the near field be modelled, for simplicity, as a region of constant energy density, ρ_{E0}. On general grounds, the work increment to modify a force field by moving field carriers against the field is proportional to the pre-existing field strength which implies that the far field energy density is proportional to the square of the force field, as it is in Electromagnetics. On that basis, the field energy density of the target will be assumed to vary as $1/r^4$ as $r \to \infty$.

Consider, then, the following field energy density distribution:

$$\rho_E(\boldsymbol{r}) = \rho_{E0} \qquad\qquad r < r_0 \tag{1}$$

$$= \rho_{E0}\left(\frac{r_0}{r}\right)^4 \qquad\qquad r \geq r_0, \tag{2}$$

which is shown in Fig. 1. The space integral of this function does not diverge either as $r \to \infty$ or $r \to 0$, so a finite total field energy, E, is obtained:

$$E = \int_0^\infty 4\pi r^2 \rho_E(\boldsymbol{r})dr = \pi r_0^3 \rho_{E0}\left(\frac{4}{3} + 4\right) = \frac{16}{3}\pi r_0^3 \rho_{E0} \tag{3}$$

The action of the force field source, A, on the target, B, in an incremental volume element, dV, at some space point, P, is defined as[4]:

$$d\boldsymbol{F}_{AB} = \boldsymbol{\Xi}(\boldsymbol{r})\rho_{EB}(\boldsymbol{r})dV = \frac{KQ_A}{a^2}\rho_{EB}(\boldsymbol{r})dV\,\hat{\boldsymbol{a}} \quad , \tag{4}$$

See Fig. 2. While $d\boldsymbol{F}_{AB} \neq -d\boldsymbol{F}_{BA}$, local conservation is restored by (10) below. When the action, (4), is integrated over all space, components transverse to the direction from source to target, $\hat{\mathbf{R}}$, cancel due to rotational symmetry. The remaining component of the action of A on B in the incremental

3 The propagation of the field is addressed in section 5.

4 Note that the force field units are implicitly defined as force / unit energy, or Newtons/Joule, rather than the usual force / unit charge, or Newtons/Coulomb.

volume element is $d\boldsymbol{F}_{AB}\,cos\theta_A$. For the near field, or "body", of the target, $r < r_{0B}$. Assuming only that $R > r_{0A} + r_{0B}$, it is easily shown that:

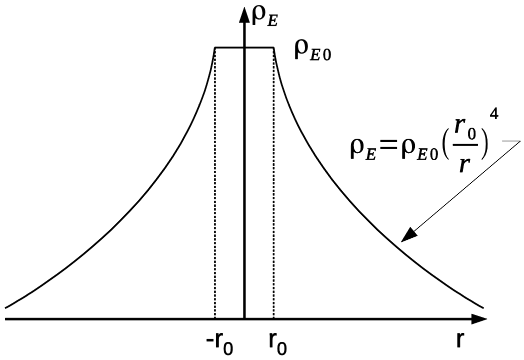

Figure1. *The modelled energy density profile, Eqns. (1, 2). (Not to scale.)*

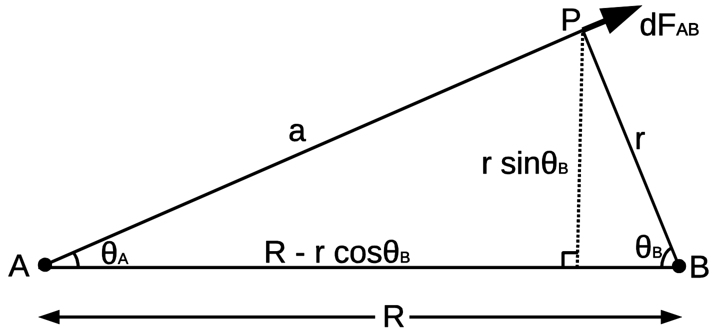

Figure2. *Shows dF_{AB} in (4), and the geometry and notation used in the space integral thereof, (7).*

$$\int_0^{r_{0B}} d\,\boldsymbol{F}_{AB} = \frac{4}{3}\pi r_{0B}^3 \rho_{EB0} \frac{KQ_A}{R^2}\ \hat{\mathbf{R}} \tag{5}$$

For the asymptotic region, $r > r_{0B}$. Using $cos\theta_A = (R - rcos\,\theta_B)/a$ gives:

$$d\boldsymbol{F}_{AB}cos\theta_A = KQ_A\rho_{EB0}r_{0B}^4 \frac{(R-rcos\,\theta_B)}{a^3r^4}dV\ \hat{\mathbf{R}}\ , \tag{6}$$

The action of the source, A, on the target, B, is given by integrating this:

$$\int_{r_{0B}}^{\infty} d\,\boldsymbol{F}_{AB} = 2\pi KQ_A\rho_{EB0}r_{0B}^4 \int_{r_{0B}}^{\infty}\int_0^{\pi} \frac{(R-rcos\ \theta_B)sin\ \theta_B}{a^3r^2}d\theta_B dr\ \hat{\mathbf{R}}. \tag{7}$$

With $a = \sqrt{R^2 + r^2 - 2Rrcos\theta_B}$, this evaluates[5] to:

$$\int_{r_{0B}}^{\infty} d\,\boldsymbol{F}_{AB} = 4\pi r_{0B}^3\,\rho_{EB0}\frac{KQ_A}{R^2}\left(1 - \frac{r_{0B}}{R}\right)\ \hat{\mathbf{R}} \tag{8}$$

Ignoring the last term in brackets because $r_{0B} \ll R$ in all situations of interest[6] and adding back (5) gives the total action of A on B:

$$\boldsymbol{F}_{AB} \simeq \frac{KQ_AE_B}{R^2}\hat{\mathbf{R}}. \tag{9}$$

Note that in this example 75% of $\boldsymbol{F}_{AB}$ corresponds to interactions between the asymptotic fields of both participants. According to Newton's third Law, the total resultant force on the target, $\boldsymbol{F}_B$, is the sum of the action of A on B plus the reaction to the action of B on A, so:

$$\boldsymbol{F}_B = \boldsymbol{F}_{AB} - \boldsymbol{F}_{BA} = \frac{K}{R^2}(E_BQ_A + E_AQ_B)\ \hat{\mathbf{R}}\ . \tag{10}$$

5 Note that it does not diverge as $a \to 0$ at the source, even if $r_{a0} \to 0$.

6 This term might be detectable in modern versions of the Cavendish null experiment [20], where $r_{0B}/R \sim 10^{-13}$, but in this case the Electric field energy of the target is arguably confined by a metal sphere of radius R, which removes the term. In any event, it can easily be removed at the expense of a slightly more complicated asymptotic behaviour.

This is actually the integral of $d\boldsymbol{F}_B = d\boldsymbol{F}_{AB} - d\boldsymbol{F}_{BA} = -d\boldsymbol{F}_A$, so the model respects local conservation laws in every incremental volume. If the field strength parameter, Q, of a charged particle is proportional to its total force field energy, E, which seems reasonable, then (10) takes the usual form of Coulomb's Law: Let $E = kQ$ for any charged particle, then:

$$\boldsymbol{F}_B = 2Kk\frac{Q_A Q_B}{R^2}\hat{\mathbf{R}} \ . \qquad (11)$$

With $2Kk = 1/4\,\pi\epsilon_0$, this is now identical to Coulomb's Law.

The above interaction mechanism models a distributed transfer of linear momentum from one field system into another. Regardless of the arbitrary field energy profile, the *ad hoc* interaction Law and the dubious empirical merit of the result this example illustrates key aspects of causality that are typically subsumed in nonlinear field theory analyses.

The transfer is instantaneous in the sense that (first) the point particle model, (11), uses instantaneous particle positions[7] and (second) if we ask "What is the linear momentum of the B particle immediately after an interaction at point P?", then, regardless of where P may be, a space integral of the field momentum density of the B fields shows an instant change in the B particle's linear momentum.

An hypothetical pointlike change like that is not however instantly observable, say by measuring the location or velocity of the peak of the energy density distribution. On the other hand, if we consider a field model from the perspectives of two observers in relative motion, there is a well defined uniform transformation that connects their respective observations on field momentum densities [21].

In order to change the particle's condition of motion from one inertial state to another, the corresponding physical changes to the fields must be implemented, not just at the particles' observed locations, but at every space point. The instantaneous, distributed, physical changes caused by distributed interactions between distributed fields are thus instantly reflected in the pointlike observables to the extent that they correspond to the uniform transformations connecting initial and final inertial states.

Although distributed action can in general produce instantaneous impacts on the observables, the example above shows that causal relations between observables are typically more complicated[8]. A distributed transfer between the field systems at some instant, t_i, must in general be followed by internal redistributions within, and radiations by, each system, until it arrives at the new inertial state.

However, with the spin measurements in section 6, local interactions simply align the target field parallel or anti-parallel to the measurement field at every space point. There is no role for any post-interaction internal redistribution of the target's angular momentum density. These spin measurements operate in parallel on the entire electron field at the same instant in time.

5. MICROSTRUCTURE OF THE ELECTRON FIELD

Although it is not relevant for this Article, the next step after the Electrostatic case above would be to include forces between charged particles in various inertial conditions of motion. The usual velocity fields *can* be developed using the Lienard-Wiechert retarded potential, but they are also routinely shown to be the direct consequence of Lorentz Transformations, which do not depend on retardation, and so nor do the velocity fields.

It has been shown previously that a field model is Lorentz Invariant if the field momentum propagates at c [21], so the discussion from here on will be limited to *luminal* field models, in which the field energy-momentum propagates at, and only at, c[9]. This necessary restriction to luminal fields raises an

7 For moving particles, the Lorentz transformed field comoves with the particle but does not propagate away from it.

8 The primary, distributed interaction above doesn't correspond perfectly to the uniform transformation between inertial states. For example, transverse components of the interaction cancel globally, but not locally. Or, consider points that are equidistant from the target on the line that joins the two particles, where the rates of momentum transfer are quite different but the transformation between inertial states is identical.

9 The usual Electromagnetic velocity field can then be reconstructed by reading (9) as the first three components of a 4-force, orthogonal to the 4-momentum in all frames [22]. As is well known, the resulting expression for the Lorentz force of one moving particle acting on another only covers the action of A on B and $\boldsymbol{F}_{AB} \neq -\boldsymbol{F}_{BA}$, so it fails to conserve momentum. Under distributed action, both action and

obvious question which turns out to be highly dispositive on the issue of the electron field microstructure: "How do *superluminal* de Broglie waves arise in *luminal* field systems?".

Investigating this question below leads to important constraints on wave propagation in Lorentz Invariant field systems that display de Broglie waves. In particular, it is shown that the fields' wave vectors cannot have any radial components, which excludes classical field models with advanced and/or retarded fields. This result is of interest, not just because it conflicts with the usual classical picture of the electron, but also it strongly suggests the alternative "classical-like" picture of the electron that will be developed in subsection 5.2, and in which context EPR correlations will finally be modelled in section 6.

5.1. De Broglie Waves and the Little Group

De Broglie waves were originally predicted by Lorentz Transforming a simple model of the particle as an infinitely distributed standing wave, $e^{-i\omega t}$, where the particle energy is $E = \hbar\omega$ [23]. It is important to notice that de Broglie's "periodic phenomenon", $e^{-i\omega t}$, has the same phase at every space point because, as shown below, without his space independent phase there are no de Broglie waves and no matter beam interference phenomena. This is also a primary concept underlying the model in section 6.

The objective here is therefore to construct, from wave energy that propagates at c, a standing wave with a space independent phase (in the comoving frame), that displays de Broglie waves (in a moving frame). Consider a wave system consisting of 2 luminal waves whose general form is the real part of:

$$\psi_n = A_n e^{i(\boldsymbol{k}_n \cdot \boldsymbol{r} - \omega t)} \tag{12}$$

Where $n = 1,2$, $\omega_n / k_n = c$ and we shall write the coordinate form of the wave vectors as $\boldsymbol{k}_n = \sum_{j=1}^{3} k_{nj}\, \hat{x}_j$. The wave amplitudes, A_n, the wave vectors, $\boldsymbol{k}_n$, and the wave frequencies, ω_n, might in general all be functions of the coordinates, but let us consider a simplified system with scalar waves whose amplitudes depend only on the distance to the centre of the system: $A_1 = A_2 = A(r)$. Let us also assume that the wave frequency is constant for one set of observers so that $\omega_1 = \omega_2 = \omega$ where ω is a constant, and we have $k_1 = k_2 = k$. For these observers, the superposition is then the real part of:

$$\psi = \psi_1 + \psi_2 = A\left[e^{i\phi_1} + e^{i\phi_2}\right] = 2A\cos\left(\frac{\phi_1 - \phi_2}{2}\right) e^{\frac{i(\phi_1 + \phi_2)}{2}} \quad , \tag{13}$$

where $\phi_n = \boldsymbol{k}_n \cdot \boldsymbol{r} - \omega_n t$. Now, consider the same system from the point of view of an observer moving at speed v in the –ve x direction, whose coordinates are (x', y', z', t') with the frames in standard configuration. The relativistic Doppler shift result gives the frequency of each wave in the primed frame as:

$$\omega'_n = \gamma\omega(1 + \beta\cos\theta_n) = \gamma\omega\left(1 + \beta\frac{k_{n1}}{k}\right), \tag{14}$$

where $\beta = v/c, \gamma = \sqrt{1/(1-\beta^2)}$ and θ_n is the angle between $\boldsymbol{k}_n$ and the x-axis. Using (14) with the relativistic aberration result and the fact that $c = \omega'_1/k'_1 = \omega'_2/k'_2 = \omega/k$, gives the wave vectors in the primed frame as:

$$\boldsymbol{k}'_n = \gamma(\beta k + k_{n1})\hat{x}'_1 + k_{n2}\hat{x}'_2 + k_{n3}\hat{x}'_3. \tag{15}$$

Using (14), (15), $x = \gamma(x' - vt'), y = y', z = z'$ (frames in standard configuration) and $\omega\beta = kv$ gives $\phi'_1 - \phi'_2 = (\boldsymbol{k}_1 - \boldsymbol{k}_2)\cdot\boldsymbol{r}$ and $\phi'_1 + \phi'_2 = 2\gamma\beta k x' - 2\gamma\omega t' + (\boldsymbol{k}_1 + \boldsymbol{k}_2)\cdot\boldsymbol{r}$, and using these in (13) gives the superposition for the primed observer, which is the real part of:

$$\psi' = 2A\cos\left[\frac{1}{2}(\boldsymbol{k}_1 - \boldsymbol{k}_2)\cdot\boldsymbol{r}\right] e^{i\left[\gamma\beta k x' - \gamma\omega t' + \frac{1}{2}(\boldsymbol{k}_1 + \boldsymbol{k}_2)\cdot\boldsymbol{r}\right]}. \tag{16}$$

A de Broglie wave propagates at speed c/β with a wave-number corresponding to the linear momentum of the modelled particle: $p = \gamma m v = \gamma\hbar\omega\, v/c^2 = \hbar(\gamma\beta k)$, so the real part of $e^{i[\gamma\beta k x' - \gamma\omega t']}$ is a de Broglie wave propagating in the x direction and (16) is a de Broglie wave

reaction operate in every incremental volume so, unlike the Lorentz Force Law, a valid force law would conserve momentum, locally and globally.

multiplied by terms in $1/2\,(\boldsymbol{k}_1 - \boldsymbol{k}_2)\cdot\boldsymbol{r}$ and $1/2\,(\boldsymbol{k}_1 + \boldsymbol{k}_2)\cdot\boldsymbol{r}$. The conditions under which (16) replicates the observed interference phenomena [24] can now be identified by considering two special cases.

Case I --- Radial propagation: $\boldsymbol{k}_n \cdot \boldsymbol{r} = \pm kr$

Consider the particular case of a spherical wave model with balanced waves in the unprimed frame that propagate radially inwards and outwards with respect to the centre of the particle [25]. In this case, $\boldsymbol{k}_1 = -\boldsymbol{k}_2$, $\boldsymbol{k}_n \cdot \boldsymbol{r} = \pm kr$ and (16) reduces to:

$$\psi = 2A cos(kr) e^{i(\gamma\beta kx' - \gamma\omega t')} \tag{17}$$

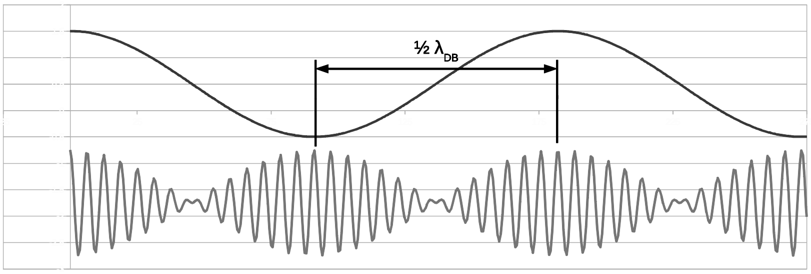

Figure3. *The de Broglie wave (top) and the real part of (17) plotted against x' for $t' = 0$, $y' = z' = 0$ and $\beta = 0.0345$, an example where the spherical wave model leads to constructive interference in screen regions where the de Broglie wave alone interferes destructively.*

The author of [25] claims that de Broglie overlooked the significance of the new term[10], $cos(kr)$, multiplying the de Broglie wave, which he interprets as a carrier wave that is modulated by the superluminal de Broglie wave. However, the real part of (17) is plotted in Fig. 3 and it is readily seen that it does not produce the usual interference pattern at the screen in, say, a 2-slit interference experiment. For example, if we consider screen regions where the path difference is half the de Broglie wavelength, so that the (exponential) de Broglie term by itself would interfere destructively, (17) may exhibit anything between constructive and destructive interference, depending on the much shorter wavelength of the cosine term. De Broglie waves are also solutions to the Klein Gordon and Schroedinger Equations, whereas (17) is not. Consequently, rather than concluding that de Broglie overlooked this term, it is shown here that the combination of de Broglie waves with Lorentz invariant fields excludes classical models with radially propagating fields.

Case II --- Transverse propagation: $\boldsymbol{k}_n \cdot \boldsymbol{r} = 0$

Clearly, in order to reproduce the observed interference phenomena, we require $(\boldsymbol{k}_1 - \boldsymbol{k}_2)\cdot\boldsymbol{r} = 0$, in which case the wave vectors in the unprimed frame must have equal radial components. However, allowing $(\boldsymbol{k}_1 + \boldsymbol{k}_2)\cdot\boldsymbol{r} \neq 0$ in (16) also leads to a problem. Let us write $\alpha = 1/2\,(\boldsymbol{k}_1 + \boldsymbol{k}_2)\cdot\hat{\boldsymbol{r}}$. Then the real part of the exponential term in (16) is $cos(\gamma\beta kx' - \gamma\omega t')\,cos(\alpha r) - sin(\gamma\beta kx' - \gamma\omega t')\,sin(\alpha r)$. In this case, the de Broglie wave is modified by a rapid, position dependent phase shift that similarly destroys the interference phenomenon.

Thus we require both $(\boldsymbol{k}_1 - \boldsymbol{k}_2)\cdot\boldsymbol{r} = 0$ and $(\boldsymbol{k}_1 + \boldsymbol{k}_2)\cdot\boldsymbol{r} = 0$, which can only be satisfied if both $\boldsymbol{k}_1 \cdot \boldsymbol{r} = 0$ and $\boldsymbol{k}_2 \cdot \boldsymbol{r} = 0$. Substituting these in (13) and (16) gives:

$$\psi = 2Ae^{-i\omega t} \rightarrow \psi' = 2A\, e^{i(\gamma\beta kx' - \gamma\omega t')}, \tag{18}$$

which is just the usual formulation of de Broglie waves.

In order to correctly reproduce de Broglie waves and the experimentally observed interference patterns, the wave vectors, as seen from the unprimed frame, should be transverse to the position vector. Any field line of the wave vector then exists on the surface of some sphere at rest in the unprimed frame, which is therefore the comoving frame of the particle[11].

10 Superpositions in [25] were formed by subtraction instead of addition, so the corresponding term, see (15) of [25], became $sin(kr)$ but this is of no consequence here.

11 Recall that this frame was identified by the condition $\omega_n = \omega$ where ω is constant, independent of x, y, z and $\hat{\boldsymbol{k}}$.

This wave trajectory structure may be compared with the little group of transformations that preserves the linear momentum of a particle in Special Relativity [26, 27]. For rest particles, the little group reduces to the spatial rotations group, SO(3). The internal evolution of a particle as seen from the comoving frame involves no radial movements and the trajectory of any internal movement lies on the surface of some sphere at rest in this frame. Since the wave vector gives the direction of movement of a wavefield, a wave model must comply with the little group in order to produce de Broglie waves.

While any wave trajectory at any given point is arguably “spinning”, that does not imply that the modelled particle as a whole carries any nett angular momentum or spin. However, it seems reasonable to anticipate that wave solutions that conform to the little group could also incorporate angular momentum and spin observables. The same cannot be said for radially propagating waves.

5.2. Cellular Microstructure of the Electron Field

The question remains how a widely distributed field that propagates at c can satisfy the little group. The various constraints on the field lines of the wave vector can be summarised as follows:

1. In the comoving system, any field line of the wave vector evolves at c on the surface of a sphere.
2. The wave frequency, and the wavelength along the trajectory, are constrained by $E = \hbar\omega = 2\pi\hbar\, c/\lambda = mc^2$.
3. The phase along any trajectory must satisfy a resonance condition.
4. The space independent phase applies to the standing wave as a whole, not just a particular trajectory or subset of trajectories.

There are many ways to inscribe a trajectory on the surface of a sphere, but, given the second and third constraints, any choice of the trajectory geometry singles out one, and only one, radius, r_s, for the sphere. For example, if we consider circumferential trajectories, then the resonance condition is $2\pi r_s = n\lambda$. Setting n=1 gives:

$$r_s = \frac{\hbar}{mc} = \frac{\lambda_c}{2\pi} = \lambda\!\!\!^{-}_c, \tag{19}$$

where $\lambda_c = 2.426x10^{-12}$metres is the Compton wavelength.

Non-circumferential paths generally involve at least two frequencies, the frequency of geometrical cycles as the path weaves around on its spherical surface as well as the wave frequency $E = \hbar\omega$ along the path. In this context, recall that the Zitterbewegung frequency - related to internal movements of the electron - is $\omega_z = 2\omega$[12]. While the specific choice of trajectories is irrelevant here, it is germane to note that such paths generally serve to reduce the radius, r_s, of the sphere.

Thus, the constraints above imply a single definite radius for the sphere, r_s, on the order of the reduced Compton wavelength, $\lambda\!\!\!^{-}_c$, which is at least several orders of magnitude smaller than the length scales associated with de Broglie waves, slit systems in matter beam interference experiments, long range Electromagnetic interactions or EPR correlations. These macroscopic phenomena are clearly inconsistent with the image of an electron localised in a region of radius r_s.

The resolution of this is to recognise that not all trajectories of the wave vector have to lie on the surface of the same sphere[13]. Instead, wave trajectories of the global field solution must lie on a myriad of spherical surfaces, all of which share the same radius, r_s , but whose centers are dispersed throughout the entire space in accordance with a global energy density profile such as (1-2).

The rest electron is thus seen as a cloud of spherical energy droplets, or cells. Every cell is a quantum oscillator, of frequency ω. There is no basis to presume that cells have persistent identities. Since the cell energy is well-localised in a region of dimension $\sim r_s$, local action means that only overlapping cells, whose centres are separated by less than $\sim 2r_s$, may interact with each other.

The fourth constraint implies that the system must be coupled together by these short range interactions to form a single, distributed whole, which has the same phase everywhere[14]. This

12 The seam on a tennis ball is an example of a path with two geometrical cycles per transit around the sphere.

13 Note that the Lorentz group is a subgroup of the Poincaré group.

14 The existence of de Broglie waves in moving frames actually requires these inter-oscillator couplings to implement an active Einstein synchronisation protocol.

distributed system of wave trajectory couplings corresponds to the usual quantum potential, as is most clearly explicated in [28], where the quantum potential generates a coupled wave trajectory formalism for both the Schroedinger and Helmholtz equations[15].

The three dimensional picture of the electron here is analogous to the 2-D mechanical model that de Broglie used to help readers visualise the space independent phase:

> *"Consider a large, horizontal circular disk, from which identical weights are suspended on springs. Let the number of such systems per unit area, i.e., their density, diminish rapidly as one moves out from the center of the disk, so that there is a high concentration at the centre. All the weights on springs have the same period; let us set them in motion with identical amplitudes and phases. The surface passing through the center of gravity of the weights would be a plane oscillating up and down. This ensemble of systems is a crude analogue to a parcel of energy as we imagine it to be."* --- Louis de Broglie [23].

Each oscillator cell corresponds to one of the springs in de Broglie's mechanical model. A similar picture, the "mattress model", is frequently used to explain Quantum Field Theory to a lay audience [29]. The next section will show that this distributed picture provides all the physical connections necessary to generate EPR correlations. Before proceeding with that, it is worth noting how the cellular field microstructure completes the discussion of the causal structure of long range interactions at the end of section 4.

Under distributed action, interactions between quantum systems don't travel between their respective centers; they occur in parallel throughout the entire space, wherever their fields overlap. An individual interaction between cells of different quanta colocated at some point, P, instantly introduces a pointlike distortion into both field systems. For example, an interaction that exchanges linear momentum displaces each of them away from its equilibrium position relative to its neighbours, who are affected via the above inter-oscillator couplings. Immediate neighbours then affect their neighbours in a chain reaction process that is limited by the speed of light in luminal field models. The total interaction between two quanta thus consists of many *instantaneous*, pointlike interactions between different fields at the same place, followed by *retarded* self-interactions that distribute the impacts to different places in the same field.

Since there is no interaction mediating agent travelling between the particle locations, it cannot be presumed that causal relations between point events would be governed by relativistic causality. However, Lorentz covariance is guaranteed by the restriction to luminal fields [21], so it is now clear that Special Relativity (by itself) never did imply the traditional formulation of relativistic causality.

Since all oscillator cells have the same phase, this distributed model of the electron features instant correlations at a distance that evolve in parallel at every space point under strictly local interactions. Clearly, the two electrons in a de Broglie-Bohm EPR experiment are never truly separated from each other, because there are cells of Alice's electron that are colocated with Bob, and vice versa.

While the door is now open to EPR correlations, such instant *ontological* correlations at a distance are not logically sufficient to allow spacelike causal correlations between point events at the *epistemological* level. In order to isolate and resolve the remaining obstacles, the next section develops a 1D schematic toy model, where the energy droplet oscillators in subsection 5.2 are replaced by cells of a cellular automaton. This is no physics theory, just a proof that Bell locality can be violated without violating Field locality.

6. EPR CORRELATIONS IN SYSTEMS OF CELLULAR AUTOMATA

The term "cellular automaton" has been defined as follows:

> *"A cellular automaton is a system with localised, classical, discrete degrees of freedom, typically arranged in a lattice, which obey evolution equations."* --- 't Hooft [12].

Local action will be implemented by replacing the short range interactions in subsection 5.2 with nearest neighbour rules that govern the evolution of each cell's contents, which are continuous variables here.

15 It is unnecessary to develop this further, but see section 7 for some more detail on the point.

It is quite valid to think of the entire reality as a single cellular automaton, specified on a fixed space-time lattice [30], and it was shown how this approach can also generate ontological correlations at a distance. However, the focus here is on spacelike *causal* correlations, between events at the epistemological level, and it is hard to specify causal relations between distinct quantum systems while treating them all as one system.

In particular, 't Hooft's discussions on EPR correlations made little progress towards a credible explanation. For example, the following “toy model” conditional probability for the (hidden variable) polarisation state of photons in the singlet state appears in subsection 3.6 of [12]:

$$w(c|a,b) = \frac{1}{2}|sin(4c - 2a - 2b)|, \tag{20}$$

where a and b are the measurement axes. Although superdeterminism is argued as the root of it, (20) is not just nonlocal and contextual, but also retrocausal. This section shows how to violate Bell locality without any such “spooky” or “disgusting” extravagance, to borrow 't Hooft's adjectives.

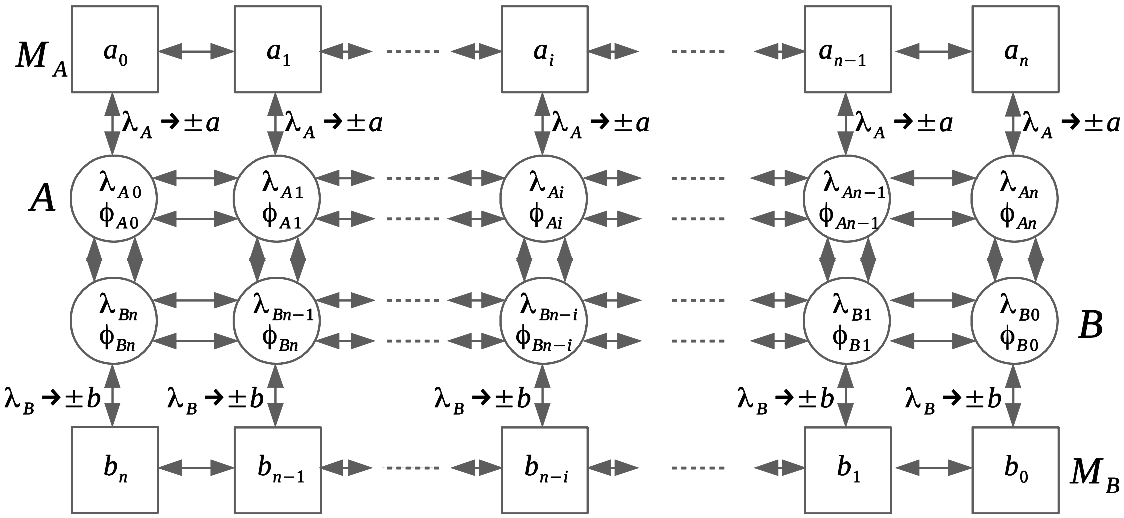

Figure4. *1D cellular automata schematic of a Bell measurement. The measurement devices are M_A and M_B (first and last rows). The electrons are A and B (middle rows). Circles represent electron cells, squares represent measurement device cells. Horizontal arrows show the nearest neighbour interactions within each subsystem that regulate its distributed variables. Vertical arrows between circles are the entanglement bonds, ensuring that, at the first measurement (Alice's), $\lambda_A = -\lambda_B$ and $\phi_A = \phi_B = \omega_\sigma t$. Measurement interactions (vertical arrows between squares and circles) are synchronized by the range variable in each cell, represented here by the subscript, i. At Alice's measurement, $\lambda_A \to \pm a$, $\lambda_B \to \mp a$, and then the entanglement bonds are broken. At Bob's, $\lambda_B \to \pm b$.*

Each particle will be treated here as a cellular automaton specified on a Lorentz covariant lattice[16] that comoves with it. The basic result that nearest neighbour evolution rules can generate instant correlations at a distance (within each automaton), will be extended to spacelike *causal* correlations between point events by including interactions between colocated cells of different automata, which is to say between different quanta. However, contextuality will be avoided because this will be restricted to only the quanta that are entangled.

This section follows the usual convention, where the experimenters in each arm of the apparatus are named Alice and Bob; their respective measurement outcomes are A and B; their electrons are electron A and electron B; and their measurement axes are labelled a and b. Their measurements commute, so it will be assumed without loss of generality that Alice makes the first measurement.

Fig. 4 shows a schematic model of a de Broglie-Bohm EPR experiment. Each subsystem is represented by a 1-D cellular automaton whose cells span the space between Alice and Bob, located at points A and B respectively, whose measurements are spacelike separated. There are three main steps to discuss: distributed variables; entanglement as interaction; and distributed Bell measurements.

16 Recall that the cells correspond to physical objects rather than abstract boundaries. The lattice seen by a given observer is Lorentz covariant because they are constructed from energy that propagates at c [21].

6.1. Distributed Variables

The space independent phase in section 5 is the archetypal distributed variable. Given that the angular momentum of each oscillator is proportional to its rate of change of phase, the field angular momentum (density) is also distributed, as shown in Fig. 4 by a second distributed variable, λ, that represents the internal state associated with the electron's angular momentum. It will be sufficient to let λ be an angle in the range $[-\pi, \pi]$, such that λ_{Ai} is the value recorded in the i^{th}cell of Alice's electron. Similarly for Bob's.

Two manifestly local realist proposals regarding the evolution of distributed variables between preparation and measurement will be asserted. The first of these is that distributed variables are regulated by nearest neighbour interactions, corresponding to the retarded self-interactions of subsection 5.2. This provides noise immunity in case individual cells are perturbed by interactions with the environment.

For example, the following local interaction model implements a proportional control mechanism that smooths out perturbations across space[17]:

$$\frac{d\lambda_{Ai}}{dt} = \alpha\Big(\big(\lambda_{Ai+1}(t_r) - \lambda_{Ai}(t)\big) + \big(\lambda_{Ai-1}(t_r) - \lambda_{Ai}(t)\big)\Big). \tag{21}$$

Where $t_r = t - r_s/c$ is the retarded time, r_s is the cell spacing and c is the characteristic velocity. Similarly for the λ_{Bi}.Of course, the speed of any such algorithm in smoothing out perturbations across space is inevitably limited by the speed of light, far too slow to allow perturbations near Alice to influence affairs near Bob within the time window of a Bell measurement [3].

In an imperfect real world, such a control mechanism might also have a role in measurement interactions, as discussed below. However, the measurement model, (24), can be assumed to work perfectly, creating the same measurement outcome in every cell, which renders this possibility moot.

Thus, all that is being asserted here is the notion, already well known in field theory, that correlations at a distance existing in each electron at preparation would persist until measurement.

6.2. Entanglement Bonds

While every electron has its own distributed variables, as discussed above, what distinguishes the singlet state is that, at preparation, these variables are common to both members of the entangled pair.

The second proposal is that this status quo is also maintained between preparation and the first measurement by a further interaction that operates between colocated cells of Alice and Bob's electrons, see Fig. 4. These "entanglement bonds" implement a second control mechanism, like (21) but operating between the entangled particles to ensure that the phase is common to both electrons while λ is equal but opposite: $\lambda_A = -\lambda_B$.This results in a 2-particle system with zero angular momentum, and where the entanglement also displays noise immunity. Again, there is no violation of locality involved.

Entanglement bonds are the essential feature that enables EPR correlations in this model, and their existence is testable, as discussed at the end of section 7.

6.3. Distributed Measurements

In the de Broglie-Bohm EPR experiment, as soon as Alice has measured the spin component of her electron A, quantum mechanics makes a prediction with certainty about the result upon measuring the same spin component of Bob's electron B. It follows that, if Alice's result is $< UP >$ along $\hat{a}$, which will be written as $< +_a >$, then *after* her measurement B is in the pure state $< -_a >$for which $\lambda_B = a - \pi$. Similarly, if her result is $< -_a >$ then $\lambda_B = a$. (The question of what state either electron was in *before* Alice's measurement is irrelevant.)

The measurement model here deals with the general case, where the B electron spin is actually measured along $\hat{b}$, where in general $\hat{b} \neq \hat{a}$. However, there is no doubt that this counterfactual is

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17 Or, for a discrete time version: $\lambda_{Ai}(t_{n+1}) = \lambda_{Ai}(t_n) + \beta\Big(\big(\lambda_{Ai+1}(t_n) - \lambda_{Ai}(t_n)\big) + \big(\lambda_{Ai-1}(t_n) - \lambda_{Ai}(t_n)\big)\Big)$, where the timestep, $t_{n+1} - t_n$, is of the order r_s/c. It is straightforward to verify the stability of this for small β, but the details of the algorithm will be of little consequence in what follows.

valid as this is an experimentally verified prediction of quantum mechanics concerning spin observables of different particles (which always commute).

Bob's measurement is therefore a case of a spin measurement on a single electron prepared in a known state, the usual quantum probability for which is:

$$P(+b|\theta_B) = cos^2\left(\frac{\theta_B}{2}\right) = \frac{1+cos\,\theta_B}{2}, \tag{22}$$

where $\theta_B = \lambda_B - b$. There is no shortage in the literature of arbitrary looking local hidden variables models for (22), beginning with Bell's own illustration [4].The quantum mechanical correlation function is then calculated as:

$$C(a,b) = \frac{P_{++}+P_{--}-P_{+-}-P_{-+}}{P_{++}+P_{--}+P_{+-}+P_{-+}} = -\hat{a}\cdot\hat{b}, \tag{23}$$

Where P_{++} is the probability of finding both $A =<+_a>$ and $B =<+_b>$ in a given trial and so on.

As for the first measurement, Alice's possible results are actually equiprobable, $P(A =<+_a>) = P(A =<-_a>) = 0.5$, so the entire mystery is how distributed action enables Alice's measurement to prepare Bob's electron in a known state. Given the proposed entanglement bonds, this may seem straightforward enough at first glance: At Alice's measurement, λ_A rotates onto either $\hat{a}$ or $-\hat{a}$. λ_B, being coupled to λ_A, rotates onto $-\hat{a}$ or $\hat{a}$ respectively. Once this has occurred, and Alice's measurement outcome has been determined, the entanglement bonds are broken.

While that covers the B electron's cells in Alice's vicinity, according to Field locality, any impact on those cells has no immediate effect on the B cells near Bob. Therefore, the measurement interactions must also be distributed. Since magnetic fields are related to angular momenta, and each measurement device is constructed from quantum systems that have their own sets of distributed variables, there is nothing new in requiring that a and b are also distributed variables, as shown in Fig. 4. In effect, Fig. 4 shows multiple copies of the same measurement scenario, distributed throughout the entire space.

Now we come to the main obstacle to generating EPR correlations without violating Field locality, namely the specification of a suitable measurement interaction model. There are two issues involved.

First, Alice's measurement has to be synchronised so that all her measurement interactions happen at the same instant, t_{mA}, in Bob's vicinity as well as in her own. This can be accomplished in various ways without introducing any nonlocality. The method used here is to add a new variable to each cell that encodes its range to the center of the subsystem to which it belongs[18].

The measurement occurs at the moment when all the corresponding range variables match, which is to say when the measuring and measured systems become colocated. This is represented in Fig. 4 by using subscripts that increase in the direction away from the relevant experimenter: Alice's measurement device and electron subscripts start at 0 at A and increase towards n at B and *vice versa* for Bob's. This implements a “distributed collapse” upon measurement.

Second, if the *random* process, (22), were to apply in every cell, the result would be that some A cells rotate toward the $<+_a>$ state while others go toward the $<-_a>$ state. It might be thought that the control algorithm, (21), would *eventually* sort things out, but what if there were more cells in the $<+_a>$ state in Alice's vicinity and more in the $<-_a>$ state in Bob's vicinity?

Recalling that the cell dimension, r_s, is on the order of the reduced Compton wavelength, a region of dimension 1 nanolightsecond is 35 orders of magnitude larger than the cell size, and the cells in subsection 5.2 overlap, so there is a vast number of cells in any small space region. Unless θ_B in (22) is exactly equal to $\pi/2$ (which has probability 0), the control algorithm, (21), operating in parallel with the measurement interaction, might rapidly ensure the same decision independently in every space region, on a timescale many orders of magnitude faster than the light time from Alice to Bob.

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18 Note that while $E = \hbar\omega$ means the energy of the whole is quantised and all oscillator frequencies in section 5 are identical, their amplitudes can be range dependent. Each cell can use locally available information to identify the direction of the energy density gradient, the range variable in the adjacent cell, and the distance to it, so this is a local realist protocol.

Such a mechanism is, however, unacceptable because, if $P_{cell}(+) > 0.5$ in the *random* process (22), (21) drives the whole measurement result into the $<+>$ state with probability 1, which is inconsistent with the quantum predictions. In order to replicate them correctly, $P(+|\theta)$ in (22) must be interpreted as the probability that a majority of cells produce the $<+>$ result, which is satisfied, of course, if every cell produces the same result. In this case, the measurement model must be *deterministic* as opposed to *random*.

As suggested by Jaynes [9], hidden variables may also obey equations of motion, and the probabilistic outcome of (22) can be implemented by a *time dependent*, *deterministic* and *local* process that produces the same result in every cell, as follows. Consider a modification of Bell's toy model for (22), such that his random variable, λ, plays no role. In [4], the particle's spin is prepared in the $<+_{p}>$ state along $\hat{p}$ and then measured along $\hat{a}$. Bell's preparation axis, p, corresponds to the internal state here, $\lambda_{Ai} = \lambda_A$ for all i. To reproduce the quantum predictions, let the outcome in the i^{th}cell be:

$$A_i = SGN[sin(\omega_{\sigma i}\, t_{mA}) - f(\theta_{Ai})], \tag{24}$$

where $\theta_{Ai} = \lambda_{Ai} - a_i = \lambda_A - a = \theta_A$; t_{mA} is the measurement time; ω_σ is a frequency associated with the time evolution of the spin, common to all cells with a space independent phase $\phi_A = \omega_\sigma t$, as shown in Fig. 4; finally, (24) implies $P(+|\theta_{Ai}) = \left(\pi - 2sin^{-1}f(\theta_{Ai})\right)/2\,\pi$. Substituting (22), $f(\theta_{Ai}) = sin(-\pi/2\,cos\theta_{Ai})$ yields the same measurement outcome in every cell, but in accordance with the usual quantum probability, (22). As mentioned above, any role for (21) in the measurement process is thus rendered moot.

Since the initial state, λ, is unknown, in the A measurement, (24) combines with the entanglement bonds to project the two particle entangled state onto one or other of the states $< A = +_a, B = -_a>$ or $< A = -_a, B = +_a>$ with equal probability. In the B measurement, (24) then projects the B electron state onto either $<+_b>$ or $<-_b>$ in accordance with (22), where $\theta_B = a - \pi - b$ or $\theta_B = a - b$ respectively. A straightforward calculation using (23) shows that this replicates the complete set of quantum predictions for any choice of the measurement axis settings, a and b.

It remains only to mention the case of delayed choice experiments, where these choices are delayed until just before the first measurement. Once it is recognised that implementing any such choice is itself an inevitably distributed process, this ceases to be an issue.

The Bell Inequalities have now been violated without invoking any form of action at a distance.

7. Discussion

An hypothesis is usually falsified in Physics when some theoretical predictions are NOT found experimentally. The Bell Inequalities are qualitatively different in that the orthodox hypothesis, "Quantum systems can be described by LHV models.", is falsified by confirming the usual quantum predictions. Instead of supporting one particular model, successful EPR experiments exclude the entire class of LHV models, so it is important not to "throw the baby out with the bath water" (by excluding a broader set of physical models than is actually necessary).

The measurement process depicted schematically in Fig. 4 only involves interactions between cells that are colocated while both the measurement interaction model, (24), and the self-interaction model, (21), (which regulates distributed variables between preparation and measurement) depend only on quantities that are locally defined, so the entire mechanism satisfies Field locality. The fact that the complete set of quantum predictions can be reproduced this way proves that violating a Bell Inequality does not require any nonlocal action at a distance between ontological elements of reality.

Nonetheless, it is often presumed that such violations imply "spooky" action at a distance. The above example shows that this is incorrect and the source of this misconception can now be understood.

Causal analysis of EPR experiments [6] turns on backward and forward lightcones emanating from the pointlike measurement events. This highlights the implicit additional assumption, over and above *local action*, that any hidden variables that "correspond" (in the sense of the EPR sufficiency condition [5]) to a point event, must also be *well-localised* in its vicinity.

However, in a distributed interaction between two distributed subsystems, each of which features correlations at a distance, local interactions can produce an arbitrarily widely distributed set of hidden variables. With the above Bell measurement model, all these hidden variables correspond to Alice's measurement result and some of them are in the spacelike separated vicinity of Bob's measurement.

Consequently, the main result of this paper is that Bell Inequality violations do not exclude all hidden variable models that satisfy Field locality. Bell's LHV models are indeed excluded, but they are just the subset with hidden variables that are also *well-localised* in the vicinity of the point events to which they correspond. This is the extra condition that cannot be presumed in a local realist field model, as defined in section 2.

This distinction between Field locality and Bell locality is crucial for the EPR discussion because local realist field models do routinely feature correlations at a distance, while the experimental fact of de Broglie waves implies that *suitable* correlations are inherent in the quanta. Spacelike causal correlations can then be understood upon replacing the point particle / retarded interaction paradigm with a field models / distributed action paradigm.

Before moving on, it may be noticed that relations like (20) are *sensu stricto* possible under distributed action, however the notion that the internal state of an electron depends on the setting of devices it has never interacted with involves what is usually regarded as an overwhelmingly implausible conspiracy. The mechanism above requires no conspiracy, no contextuality, no retrocausality, no superluminality and no superdeterminism. The entangled particles do interact, but that is hardly unreasonable in a distributed model where the finest details of their respective structures are shared by strictly local interactions. Therefore, not only do EPR correlations not imply action at a distance but also they do not require any other profligate or exotic kind of explanation.

7.1. Relation between the Physical Model and Physics

Like Bell's theory independent concept of LHV models, section 6 proceeded in a theory independent way, focussing on what is physically possible under local action. The result is not a theory, but merely a toy physical model whose only purpose is to show that local realist field models can predict spacelike causal correlations. While entanglement bonds have testable consequences, as discussed below, there is no reason to think that the microworld in any way resembles the model. Having said that, the concept of a cellular field microstructure arose directly from de Broglie wave Theory, so it is worth summarising briefly how this idea might relate to the existing theoretical landscape.

A vast number of physical models for the electron has been reported. Many are pointlike models with energy distributed on or in a sphere with a radius related to the Compton wavelength and many physical properties of the electron have been correctly predicted this way [31, 32]. Generally speaking, such models do not address the full range of observed quantum phenomena, including especially matter beam interference and spacelike causal correlations.

The suggestion of this Article is that, while some of them provide valuable insights, they are not in fact models of the electron *per se*, but should be interpreted as models of the parts of an electron: the springs of de Broglie's mechanical model or the pointlike oscillator cells of subsection 5.2. In fact, suitable pointlike solutions to the Dirac equation were already identified numerically in [33], where the wave function for $r > r_s$ varies as e^{-r}/r. Note that this function is a solution to the equation $\nabla^2 f = f$, so the quantum potential of these solutions is constant in the asymptotic region, corresponding to a short range quantum force.

Madelung decomposition of any of the Helmholtz [28], Schroedinger, Pauli or Dirac equations [34] leads to a Quantum Hamilton-Jacobi equation that includes, alongside the Electromagnetic potentials, quantum potential terms that are built up from these short range, coherent quantum forces, revealing the inner workings of the wave quanta. Just as these terms explain the stability of the Hydrogen atom in Bohmian Mechanics, stability of the electron requires that they balance the usual electrostatic self-repulsion of the field.

The cellular microstructure may also provide further insight into de Broglie's classical prediction of matter beam interference phenomena. His analysis [23] produced a plane wave because it was based on a function, $e^{i\omega t}$, that is infinitely distributed in space. This renders its use as a particle model specious because one cannot obtain the particle's finite total energy, $E = \hbar\omega$, as a space integral of its field energy density. Nor does the analysis account for the wave-particle duality aspects of matter beam experiments, where the interference pattern is washed out by “which way” detection.

Both these issues may be resolved by recalling that quantum systems obey wave equations, which must be solved subject to boundary conditions, so that the energy density distribution of the electron inevitably depends on the context:

Consider an electron beam with one electron at a time in the apparatus. The boundary conditions allow the central energy density plateau in (1-2) to spread out into a planar de Broglie wave that occupies the full dimension of the beam[19], providing for the observed interference phenomena with a finitely distributed particle. On the other hand, detecting a particle at one of the slits appears to impose a boundary condition such that the size of the energy density plateau is reduced to the precision of the measurement. With r_0 less than or equal to the slit width, and a far field as per (2), almost all the energy that reaches the screen comes from just the one slit and the interference pattern is washed out.

7.2. An Experiment to Test for Entanglement Bonds

Regardless of how the energy density distribution depends on boundary conditions, the far field asymptote must decay at least as rapidly as $1/r^4$ to keep the total particle energy finite. This implies that the strength of the proposed entanglement bonds linking two particles in the singlet state is range dependent. Therefore, the presence of such bonds can be tested experimentally by testing the range dependence of the noise immunity of the fringe visibilities in a de Broglie-Bohm EPR experiment such as the Delft experiment [3].

It is relevant to test this in two ways, by varying the noise intensity while holding constant the duration for which noise is applied and by varying the duration with the intensity held constant. A suitable noise source must be developed which can degrade the experimental visibilities in a controllable and repeatable manner, but this hardly seems beyond the ingenuity of modern experimental science [35, 36]. In each arm of the apparatus, the spatial relationship between the noise source and the electron should be fixed as the range between Alice and Bob is varied.

One practical difficulty is the low success rate reported for the Barrett-Kok entanglement swapping protocol, $6.4x10^{-9}$. Spacelike separation between Alice and Bob is not required so the experiment could be done in a laboratory, with separations up to, say, 20 or 30 metres. The removal of 1.7 km of fibre optic, with an insertion loss of 8 dB/km, will allow the visibilities to be measured more rapidly. It may be feasible to increase the protocol success rate further. For example, the authors state that their experiments do not use cavities to couple the herald photons into the fibre optic cables and they state elsewhere [37] that this may have reduced the success probability by several orders of magnitude. Good progress has been made towards implementing suitable cavities [38].

It is noteable that the difference in the protocol success rate between [3] and [37] is explained (approximately) by the insertion loss of the extra fibre optic cable, so there was no discernible range dependence of the underlying protocol success rate. If there is similarly no discernible range dependence of the relation between noise level and visibility degradation, then models like the one in section 4 can be rejected. On the other hand, if there is, a new door opens to the investigation of entanglement bonds.

8. CONCLUSIONS

The idea that energy quanta are widely distributed field systems is commonplace and it is often speculated that this may relate to EPR. It has been confirmed here that EPR correlations are indeed plausible in a local realist, classical field setting, without recourse to profligate or exotic notions such as contextuality, conspiracy, superdeterminism, superluminality, retrocausality and the like.

Fields can provide all the essential physical connections between spacelike separated point events, as was shown in a schematic model of a Bell measurement, which was based on three key concepts:

1. Distributed variables. De Broglie's space independent phase was the leading archetype;
2. A distributed system of entanglement bonds that couple the two electrons' fields in the spin entangled state;
3. Distributed measurement interactions, operating in parallel on the entire electron field at the moment when measuring and measured systems become colocated.

19 This can be accommodated without altering either the field energy density asymptote or the total field energy of the profile (1-2) by replacing ρ_{E0} in (1) by a central plateau energy density, ρ_{EP}, so it reads: $\rho_E(r < r_0) = \rho_{EP}$, while (2) is unchanged: $\rho_E(r \geqslant r_0) = \rho_{E0}(r_0/r)^4$.

This concrete example proves a proposition first argued by Redhead [13]: Ontological locality does not preclude epistemological nonlocality or, equivalently, local action does not forbid spacelike causal correlations. When properly defined, *i.e.* without presuming an ontology of pointlike particles, local realism is alive and well.

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