Surely You Must All be Joking: An Outsider's Critique of Quantum Physics

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Abstract

A critique of the state of current quantum theory in physics is presented, based on a perspective outside the normal physics training. From this perspective, the acceptance of quantum nonlocality seems unwarranted, and the fundamental assumptions that give rise to it in the first place seem questionable, based on the current status of the quantum theory of light. The relevant data can instead be accounted for using physically motivated local models, based on detailed properties of the experimental setups. The semiclassical approach, particularly in the form of the fully coupled Maxwell-Dirac equations with a pure wave ontology, seems to provide a satisfying, local, paradox-free physical model of the quantum world, that appears consistent with known phenomena. It is unclear why this approach is not pursued more vigorously in the field, given its clear potential to resolve all the conundrums that have perplexed generations of physicists.

Keywords: Quantum mechanics, Local realism, Bell's inequality, Maxwell-Dirac equations

1. Introduction

Sometimes an outsider can see things that those indoctrinated in a given field have become blind to. As a computational neuroscientist with a long-standing interest in the fundamental laws of the universe, I have followed developments in physics over the years. I've read various lay accounts of

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the mysteries of the quantum world and the quest for grand unified theories, including the Feynman classics, the inscrutable book by Hawking, and the compelling books by Brian Greene. Recently, I dug extensively into the primary scientific literature, in an attempt to gain clearer insight into the deeper mysteries facing the field since the founding of quantum mechanics (QM) in the early 1900's. I was sufficiently shocked by what I found, that I felt compelled to write this outsider's critique. It is written in a deliberately provocative tone, in the hopes of stimulating people into further reflection about some foundational issues in the way the field has developed.

The quantum world apparently exhibits a number of strange properties, including randomness, complementarity, wave-particle duality, and nonlocality. Virtually every major figure in the field has attested to the fundamental incomprehensibility of this world, e.g., Feynman's famous claim that "I think I can safely say that nobody understands quantum mechanics." As I've delved deeper into the primary literature, I can see why: the verbal descriptions of quantum physics in introductory material are often completely at odds with the actual mathematical and conceptual frameworks that experts actually use (e.g., Klassen, 2011), and these frameworks are obviously just calculational tools, rife with virtual, non-physical entities and gratuitous non-localities. But in this primary literature, I also found the apparently neglected work of a number of physicists, that seems to paint an entirely sensible and comprehensible alternative, physical model.

This physical model is based entirely on the ontology of waves, which is (to my surprise) in fact the effective ontology of the vast majority of the mathematics of QM (Nikolic, 2007), despite the seemingly perverse continued insistence on describing things in terms of particles. Doing away with particles entirely seems to resolve a large number of apparent paradoxes and fundamental confusions. To make this pure-waves viewpoint work, one still needs to wrestle with a number of unsolved problems, but there are plausible solutions to each of these problems, even with the tiny smattering of attention they have received. The prospects of obtaining a sane and comprehensible quantum worldview would seem to be sufficient motivation to put significant effort into solving these problems.

But there is one major roadblock for the purely wave-based approach, which seems to have caused most physicists to write it off from the outset. This problem is the apparent nonlocality of the quantum word. According to the standard interpretation, two *entangled* particles can interact with each other *instantaneously* at a distance, in principle even if they are at opposite ends of the universe! Despite many years and concerted effort, it seems that nobody has been able to provide a convincing way out of this conclusion,

and it has reduced many a respectable physicist to producing long rambling discussions that inevitably just seem to skirt the central issues, and dress them up in new terminology (quantum information, consistent histories, many worlds, relational, etc..).

However, I have yet to see anyone make the following argument, which questions the primary assumptions upon which quantum nonlocality is based:

- Only quantum entanglement of light can demonstrate nonlocality, because entangled massive particles can always interact via speed-of-light mechanisms.
- The QM description of light in terms of photons is a complete disaster from a conceptual point of view. There hasn't been a proper first quantized description of a photon wave function until relatively recently, and the only viable proposal propagates according to the same Maxwell's equations as the classical electromagnetic (EM) field (Bialynicki-Birula, 1994; Sipe, 1995). The second quantized version of the photon in quantum electrodynamics (QED) is manifestly both nonlocal and nonphysical it is a pure harmonic standing wave in Fourier space, stretching in principle across the entire universe. Indeed, QED is sufficiently underconstrained that it is not even clear within this framework if photons actually travel at the speed of light recent experiments confirm that in fact they do (Zhang et al., 2011).
- Thus, the idea that one can transparently derive a physically sensible prediction about the entangled behavior of photons within the QM framework seems rather suspect. However, every treatment of the standard QM predictions for entanglement experiments that I've seen uses a simple abstract Hilbert space formalism with no attempt to actually derive some kind of detailed physical model of what is actually going on in the exact experiments being performed. I genuinely have no precise idea what people are even referring to when they use the term "two entangled photons" certainly they cannot be referring literally to QED photons as standing waves stretching across the universe?
- The *semiclassical* approach to understanding quantum phenomena, where light is treated classically (i.e., regular old Maxwell's equations), and all the strange quantum behavior is attributable to the atomic system, has been successful beyond anyone's wildest expectations (Jaynes & Cummings, 1963; Jaynes, 1973; Mandel, 1976; Grandy,

1991; Gerry & Knight, 2005; Marshall & Santos, 1997). Indeed, this semiclassical approach appears to be widely used in the field of quantum optics, preferred in many instances over QED because it provides a much more natural physical picture of what actually seems to be happening in the relevant experiments (QED can give highly accurate results, but can also easily produce nonsense if not used properly) (Gerry & Knight, 2005; Roychoudhuri & Roy, 2003). To date, there do not appear to be any quantum phenomena that some semiclassical model can't account for, including the recent photon statistics experiments (anticorrelation and antibunching) (Marshall & Santos, 1988, 1997), which had been regarded as the strongest evidence in support of the photon concept, and against the semiclassical approach (Grainger et al., 1986; Hong et al., 1987).

- If it is true that Maxwell's equations provide a valid description of the quantum behavior of light, then there is no reason to believe that light should exhibit quantum entanglement! There is certainly nothing within Maxwell's equations that would support entanglement of two light waves that are moving away from each other at the speed of light. Given the success of the semiclassical approach in accounting in principle for all known quantum optics phenomena, shouldn't that give people considerable pause in accepting nonlocal entanglement? Have people really given sober consideration to the tradeoff between the various scepticisms about the semiclassical approach, weighed against the complete insanity of the orthodox view of quantum nonlocality? Or has any will to question the insanity been completely drained in the years of conceptual turmoil and systematic brainwashing?
- Meanwhile, there appears to be a relatively unquestioning acceptance of the empirical evidence for photon entanglement, in the face of what appear to be very strong limitations. What are commonly marginalized as "loopholes" seem instead like very plausible physical descriptions of the actual behavior of the polarization detectors used in these experiments. There are several principled local models that reproduce the observed data quite accurately (Marshall et al., 1983; Marshall & Santos, 1985; Thompson, 1996; Adenier & Khrennikov, 2003; Santos, 2005; Aschwanden et al., 2006; Adenier & Khrennikov, 2007), and one analysis that provides positive evidence that the main "loophole" is in fact operative according to the recorded data (Adenier & Khrennikov, 2007). Furthermore, some of the results have been discrepant with

QM predictions, and yet no attempt to replicate in the right way has been attempted (Santos, 2004).

One obvious reason that nobody questions the fundamental assumption that QM applies to photons must be that the QM framework is so incredibly successful, how could it possibly be wrong in this case? But outside of the peculiar Bell's inequality tests for quantum nonlocality, the vast majority of QM physics (in the pure wave ontology at least), is entirely compatible with locality (including all those supposedly quantum phenomena captured by the semiclassical approach). As we discuss later, it seems that the standard mathematical framework for QM just doesn't allow one to express the behavior of formerly entangled photons (absent a measurement or even decoherence), but this may very well just be a limitation of this descriptive framework, and the underlying physics could be different, without anyone ever noticing except in this very strange case.

In summary, it seems entirely plausible that there is no strong reason to believe that quantum physics is necessarily nonlocal. The things you have to "give up" to make it local seem like a very small price to pay in the grand scheme of things, and they feel like the true message that the quantum world has been trying to tell us all this time (but people have been too obsessed with particles to really see it): nature at its most fundamental level is made entirely of waves. Waves are intrinsically *contextual* — what you measure about them reflects properties of both the incoming wave and the measurement device, and they are spatially distributed, not discretely localized like particles. These properties have also been mistakenly interpreted as implying nonlocality.

Thus, in contrast to everything we have been told, it seems that there may in fact be a perfectly sensible physical model of the quantum world. This model would be based on locally propagating wave dynamics, with different kinds of waves (electromagnetic waves, electron waves, etc) interacting in potentially complex ways. This idea was originally espoused by Schrödinger, but discarded for reasons that may no longer hold up (Dorling, 1987). One of the major reasons for rejecting this idea was certainly the presumed nonlocality of the quantum world. Maybe it is time to take another look?

In the remainder of the paper, the above ideas are developed in greater depth, starting with some general terminological and conceptual clarifications.

2. Calculational Tools vs. Physical Models

To establish some terminology and a conceptual framework for the discussion, it is important to distinguish between two major categories of theory in physics: calculational tools and physical models. Calculational tools are systematic frameworks that provide a convenient representation of physical problems for computing predictions of experimental results, but the central constructs of these tools need not (and typically do not) provide a model of how physics is actually thought to operate in nature. There are often non-local abstractions, and many decisions that require expert human judgment in configuring the computations. Any physical framework that contains "virtual" or other non-physical entities is by definition a calculational tool.

In contrast, physical models realistically describe objective physical processes, operating universally and autonomously, that give rise to the observed physical phenomena. The notion of autonomy provides a critical distinction between the two kinds of frameworks: whereas calculational tools typically require lots of expert knowledge of how to represent a given physical situation, a physical model can just iteratively crank away without any expert intervention, and accurately reproduce the known physics. Perhaps the epitome of a physical model is the cellular automaton, which captures exactly this notion of a simple autonomous system cranking iteratively away, and numerous people have argued is the most compelling overall framework for fundamental physics (Ulam, 1952; Gardner, 1970; Zuse, 1970; Fredkin & Toffoli, 1982; Fredkin, 1990; Wolfram, 1983; Toffoli & Margolus, 1990; Poundstone, 1985; Bialynicki-Birula, 1994; Meyer, 1996). Calculational tools can typically produce results in one step, whereas physical models require integration over many steps, because they accurately reflect an underlying iterative physical process, and are thus typically more difficult to analyze mathematically.

To make these ideas concrete, and draw out the critical role of local mechanisms for realistic physical models, we consider a few examples:

Newton's theory of gravitation (still widely used) is a calculational tool that enables gravitational effects to be computed in terms of the respective masses (m_1, m_2) and distance r between the centers of mass of two bodies:

$$F = G \frac{m_1 m_2}{r^2} \tag{1}$$

But this is not a physical model that could function autonomously, because the math requires one to somehow know the physical distances between relevant objects (and their respective masses), and not only is this a nonlocal computation, there are a potentially infinite number of other bodies that need to be taken into account. The very notion of a celestial body of gravitational importance requires expert judgement, and is an example of a virtual object from the perspective of fundamental physics. In a physical model, one would expect that gravitation actually derives from the collective effects of each individual atom within all the different celestial bodies in the universe, at which point the Newtonian computation is completely unworkable and absurd.

Einstein's general theory of relativity, on the other hand, shows how entirely local, speed-of-light propagation of spacetime curvature, operating according to uniform functions at each location in space and time, can convey gravitational forces without any of the problems associated with the Newtonian calculational tool. It is a true physical model of the first order: the mathematical constructs map directly onto physical processes that are entirely plausible and compelling for what nature can be autonomously doing to produce the phenomenon of gravitation.

Coulomb's law for the strength of the electric field as a function of distances between charged particles is very similar to Newton's gravitational formula, and similarly represents a useful calculational tool, but is not a good model of how physics actually operates, for all of the same reasons. Similarly, the Coulomb gauge formulation of Maxwell's equations implies immediate action at a distance for the electrical potential, which is clearly incompatible with special relativity. It turns out that some nonlocalities in this framework actually cause the observed EM fields to still propagate at the speed of light, but one can still get into trouble using this gauge incorrectly (Brill & Goodman, 1967; Jackson, 2002; Onoochin, 2002).

In contrast, Maxwell's equations in the Lorenz gauge provide a very appealing physical model of electrodynamics, involving simple local wave propagation dynamics operating on the four-vector potential:

$$\partial_{\mu}\partial^{\mu}A^{\mu} = k_{\mu}J^{\mu} \tag{2}$$

where the four-potential is: $A^{\mu} = (A_0, \vec{A}) = (A_0, A_x, A_y, A_z)$, and the four-current is: $J^{\mu} = (\rho, \vec{J}) = (\rho, J_x, J_y, J_z)$, and the four-constants are: $k_{\mu} = \left(\frac{1}{\epsilon_0}, \mu_0, \mu_0, \mu_0\right)$. In this physical model, EM waves naturally propagate at the speed of light, everything is automatically consistent with the constraints of special relativity, and it is again easy to imagine how autonomous physics can happen like this.

The clear pattern here is that plausible autonomous physical models leverage *local* propagation of signals according to simple laws, which avoids the immediate difficulties that are encountered in nonlocal frameworks.

Once interactions become nonlocal, they typically become infinite in scope, because anything can potentially influence anything else, and thus any kind of autonomous physical process becomes inconceivable. How is nature possibly going to manage all this infinite bookkeeping? A great way to appreciate this difficulty is to attempt to construct an autonomous computer algorithm that implements a nonlocal interaction, in a way that can apply to large scale systems with many interacting entities — the exponential character of these systems makes them essentially intractable. And yet nature just does it, autonomously and "effortlessly".

The currently popular gambit that one can leverage the supposedly non-local quantum computations that nature is performing to do more powerful computation than a regular computer, can be turned on its head: exactly how is nature doing all this nonlocal computation, really? Is there any possible way to efficiently carry out a nonlocal computation, that nature could be leveraging? If there were, we could just implement that on a regular computer. Thus, the very promise of quantum computers suggests that we have absolutely no idea how nature could possibly function at the quantum level, if it is truly nonlocal.

In short, it seems that the local nature of physical laws is an essential component for an autonomous, objective physical reality. More than any other factor (e.g., deterministic vs. stochastic behavior) the issue of locality vs. nonlocality is a fundamental dividing line between physical models and calculational tools.

It should be clear that both calculational tools and physical models play essential and complementary roles in the field, and should in no way be construed as mutually exclusive (even though people inevitably do). Even though physical models are often not convenient frameworks for calculation, they play a crucial role in grounding and constraining physical intuition, which should then inform the application of calculational tools. In particular, calculational tools often contain shortcuts and simplifications relative to the underlying physical model, and one can obtain nonsensical results if these are not appreciated (e.g., accidental violations of speed-of-light propagation in the Coulomb representation).

3. The Unfortunate State of Quantum Physics

In quantum mechanics (QM), there are no physical models, only calculational tools, and most physicists would likely argue that it is impossible to develop a realistic physical model. The strict Copenhagen interpretation of QM specifically disavows the notion of a physical reality outside the scope

of measurements, and Everett's Many Worlds interpretation postulates that the universe splits into multiple different copies at each measurement event. We don't need to belabor how insane this all seems, and yet physicists have resigned themselves to just accepting this insanity, and look upon those who protest it with disdain. The motto appears to be, "shut up and calculate", which is precisely consistent with a field dominated by calculational tools. But from the arguments above, made on firmer ground, it is clear that one should harbor a strong mistrust of nonlocal calculational tools for telling you with perfect accuracy about how a physical system should behave. Unfortunately, without a plausible physical model, physicists have nowhere to turn, and the resulting insanity just seems to compound itself, with ever more bizarre mathematically-motivated ideas being passed off as physical models (e.g., curled-up invisible extra dimensions, multiverses, etc). Put on your tin foil hats folks, and be on the lookout for wormholes to those carefully hidden extra dimensions and parallel universes!

What if all this insanity is just based on an unfortunate sequence of misunderstandings, which have hardened over the years into an unnecessary rejection of the possibility of obtaining a physical model? That would be embarrassing! But I can't quite seem to escape this conclusion.

From the beginning, it seems that those who have advocated for realistic physical models of quantum mechanics have adopted an overly restrictive set of constraints for what features a physical model must possess, and much of the debate has been distracted by the resulting confusion. In particular, there has been a strong focus on determinism, for example Einstein's claim that "God does not play dice..", and the specific idea that a hidden variable model should *simultaneously* determine the outcomes of all possible measurements. But as we can see from the consideration of physical models above, *locality* is by far the more important constraint, and in fact the strong determinism of Einstein seems entirely inappropriate when considering the fundamental wave nature of quantum physics as we discuss more later.

Thus, we focus for now squarely on the issue of locality, in the context of the strongest existing demonstrations of quantum nonlocality.

4. Quantum Entanglement, Nonlocality, and Bell's Inequalities

The strongest case for quantum nonlocality comes from John Bell's treatment (Bell, 1964, 1987) of a thought experiment initially conceived by Einstein, Podolsky & Rosen (1935) (EPR). There is a massive literature on this topic, so this discussion will be very brief, although the specific path of

reasoning here seems relatively novel and very clearly illustrates the absurdity of the standard QM assumptions when applied to "photons". The key idea is that according to QM, if two particles happen to interact locally in such a way that their states become entangled, and they then separate from each other, their states somehow remain interconnected, such that a measurement conducted on one particle (call it A) will predict the outcome of a separate measurement on the other particle (B). Mathematically, it is said that the two particles share the same state function, which is in a state of uncertainty (a superposition of multiple possible states). To greatly simplify the basic predictions of QM in this case, we consider instead what would happen if you perform two successive measurements on the same particle, instead of two separate measurements on the two different entangled particles — these two situations should be mathematically identical according to QM.

If A and B are photons created (as they are in the relevant experiments described later) from an atomic cascade or spontaneous parametric down conversion, then they should be entangled, and either have the same polarization or 90 degree opposite polarization (depending on the details of the procedure). A polarization measurement is made by placing a photodetector behind a polarizing filter. If we happen to know the exact polarization angle of a light source (call it θ_s), a classical EM result known as Malus's law states that the polarization filter will allow $\cos^2(\theta_s - \theta_f)$ amount of light through, where θ_f is the angle of the filter. This is 100% if the angles are the same, and 0% if they are 90 degrees apart, and somewhere in between otherwise. You can try it out yourself by tilting your head while looking at your laptop or any other LCD screen with polarized sunglasses on.

Using these facts, we can calculate what would happen if we could make two successive polarization measurements on the same photon (the photodetector absorbs the photon so this technically isn't possible in this case, but it is with other isomorphic cases). The result of the first measurement (M1) is always going to be completely random, because the polarizations of the photons are unknown and unlikely to be biased in any way, and the angle of the polarization detector used for M1 is totally arbitrary. However, at the next measurement (M2), we can make some very strong predictions. If M2 is set to the same angle as M1, then there should be a 100% coincidence rate between the two detectors. That is, if M1 registers a detection event, then M2 should as well, and vice-versa. And if M2 is 90 degrees off of M1, there should be a 0% coincidence rate. And for any angle in between, the probability of M2 firing given that M1 did should be $cos^2(\theta_2 - \theta_1)$ based on the respective angles of the detectors.

Here is the first critical point: these predictions are true regardless of how you rotate the polarizing detectors. The only way for this to be the case is if the first measurement actually rotates the polarization of the light to align with its filter. Otherwise, if instead you thought that the photon had some specific polarization angle that remained unchanged by M1, the results of M2 would be given by $\cos^2(\theta_s - \theta_2)$, where θ_s is this true "source" polarization angle. This case would clearly have absolutely no relationship to the angle on M1. This difference of a cosine relationship between the two detector angles vs. an independent relationship between the two detector angles is the basis for Bell's inequalities, which simply quantify this difference in a way that is amenable for empirical tests. However, in this case of two sequential measurements, it is trivial to conduct this experiment yourself and see the results. Just take two polarized sunglasses and rotate them relative to each other. It doesn't matter what angles you choose, you'll always observe that the first polarizer does indeed rotate the light to its angle, so that there is always a $\cos^2(\theta_2 - \theta_1)$ function to the light intensity that makes it through both glasses. Note that we don't actually measure the light after the first polarization step, so we avoid that problem in this experiment.

From this experiment, it is obvious that the "measurement process", at least for light waves, does not immaculately reveal the "true" polarization state, but rather reflects an interaction between the incoming light wave properties and the properties of the measuring device. The measuring device imposes a good bit of its own "reality" onto the state of the light wave. In QM terminology, this means that the measurement is *contextual* (Shimony, 1984; Gudder, 1970; Khrennikov, 2001; Rovelli, 1996). I cannot imagine any measurement taking place on a wave that would not be contextual in this way. It also appears to be true of spin measurements on electrons. Waves are way too fluid a thing to stand up to the kind of abuse applied by a measurement device unscathed! Einstein apparently didn't seem to catch the wave vibe from quantum mechanics, and postulated that measurements should not be contextual, and instead should reflect some kind of deeper hidden variables possessed by particles. But this doesn't even explain the behavior of classical EM for successive measurements, as we just saw, and seems completely untenable. It would seem that only a strong adherence to the particle model (as Einstein unfortunately maintained), with the hard little particle somehow possessing very definitive properties, would motivate such a belief.

And now for the second critical part: We take our results from the two sequential measurements, and attempt to apply them, as QM says we should, directly to the two separate "photons," A and B. The theory says (with a

straight face), that if we perform polarization measurement M1 with a given angle on photon A, it must somehow influence things such that measurement M2 on B obeys the very same equation as for two sequential measurements: $\cos^2(\theta_2 - \theta_1)$. Yes, the angle of the M1 polarizer must somehow influence the behavior of the measurement process on B. Even if A and B have had enough time to fly arbitrarily far apart (e.g., in principle to the opposite ends of the universe). It gets better: this is all supposed to happen absolutely instantly. No time delay at all.

To which I say: "Surely you must all be joking!?" This is a good candidate for the most fantastical, absurd prediction in the history of science, and nearly everyone in quantum physics swallows it whole. It is a completely non-physical, non-local, non sequitur. The physics of two sequential measurements on one photon versus two separate measurements on two separate photons are entirely different, and it is just not clear why anyone would think they should correspond to the exact same thing. This seems like a classic case of the calculational tools of QM being misapplied, and a cross-check with some kind of physical model would quickly reveal the error. But because there is no accepted physical model in QM, there really isn't a suitable fallback position, and so people just seem to accept what the calculational tools tell them.

However, there really is a de-facto widely accepted physical model for the behavior of photons, and it is none other than classical EM (i.e., Maxwell's equations). As we discuss in greater detail later, the semiclassical approach is widely used to calculate a great variety of quantum optics effects. If we apply the classical EM physical model to the two photon entanglement case, it is patently obvious that no such entanglement phenomena should or could be observed. As we just described above, the physics behind the two successive measurements is completely obvious and sensible — you can visualize the polarization of the light waves rotating around as they pass through the M1 filter, thus affecting the results for the M2 measurement.

The extension to two separate photons makes absolutely no sense — how can a local interaction between a polarization filter and a light wave possibly affect a similar such interaction separated by an arbitrary distance, when the two light waves have been traveling apart at the speed of light!? There is simply no way within the classical EM framework for light waves to continue to interact once they start heading in different directions — everybody's moving at the speed of light, and nothing sticks around in between to mediate any kind of connection between them. Furthermore, EM waves do not even have any way of interacting with each other — there is no physical basis for any kind of "signal" to be sent from one EM wave to

another — the only medium for such a signal would be the EM field itself, and it just passes right through due to linear superposition. Thus, there is no plausible mechanism that could mediate an entanglement state in the first place, at least according to the classical EM model.

To understand how the field could have come to this point of unquestioning belief in the applicability of entanglement to light, we next review the shocking state of the QM approach to light, which reveals how stunningly non-physical a calculational tool the standard QM model (QED) is. Indeed, practicing physicists apparently avoid using QED whenever possible, and instead rely on good-old-fashioned classical EM in the context of the semiclassical approach, which is reviewed thereafter.

5. The Quantum Theory of Light

The notion of a photon conveyed by descriptions of paradigmatic quantum phenomena such as the photoelectric effect described by Einstein in 1905 strongly connotes a physical entity that is absorbed and emitted by atoms as they jump up and down in energy levels (Klassen, 2011). The photon has a frequency, and we inevitably picture some kind of little wave packet vibrating with that frequency, somehow combined in an inexplicably weird way with a hard little photon particle. For all the myriad discussion of photon-based phenomena in QM textbooks (e.g., the two slit experiment), one naturally assumes that the Schrödinger wave packets shown in the diagrams actually represent these photon wave packets. However, I was astounded to discover that until relatively recently (Bialynicki-Birula, 1994; Sipe, 1995), photons had no proper Schrödinger-like wave function in the standard QM framework. Instead, the only actual mathematical treatment of the photon concept comes from Quantum Electrodynamics (QED), which has such a strange representation of a photon that is essentially unrecognizable from the above picture (see the excellent papers in the 2003 special issue of Optics and Photonics News Trends (Roychoudhuri & Roy, 2003) for expert discussion, and e.g., Lamb 1995).

QED is a calculational tool par excellance, in part because it is based on a Fourier transformed representation, replacing the usual space and time coordinates with frequency and phase coordinates. Mathematically, Fourier space can represent any kind of wave function that might occur in the real world, and lots of things are more convenient to calculate in Fourier space. But I was truly shocked to finally understand that the QED notion of a photon is actually defined in this Fourier space representation, instead of in the real spacetime coordinates: a photon is a fundamental mode of vibration

at a given frequency in Fourier space. As such, a photon is *intrinsically nonlocal*, spanning across the universe in effect! To obtain any kind of localized wave function, you need to combine many different photons at different phases and frequencies. Thus, the perfectly intuitive wave packet model of the photon sketched above in fact corresponds to a huge raft of QED "photons," constructed just so as to produce what one would otherwise assume occurs quite naturally through the emission and absorption process.

This Fourier space is quantized, in a process referred to as second quantization, making it a Quantum Field Theory (QFT), known as a Fock space. This allows you to count the number of different photons associated with each vibrational mode, and there are operators that create and destroy these photons. This ability to formalize the creation and destruction process appears to be one of the great advantages of the QED framework, making it such a useful calculational tool. But the cost of this move is being stuck in this nonlocal, nonphysical Fourier space: this quantum field is nothing like a classical EM field.

This second quantization process apparently leads directly to the notion of a zero point field (ZPF), which is the ground state of the quantum field. The ZPF describes the quantum state of the vacuum, and a huge amount of the power of QED comes from the "vacuum fluctuations" — energy can be temporarily "borrowed" from the vacuum to create "virtual" particles which then interact with "real" particles, in ways that produce subtle but measurable effects. It is also said that these virtual particles mediate the actual EM forces, e.g., by electrons passing them back and forth all the time. In contrast, the classical EM equations (e.g., in the Lorenz gauge shown above) explain the same EM forces without any reference to these mythical "virtual" entities. And classical EM does so in a very local, emergent, physically compelling way, in contrast to this clumsy picture of electrons somehow tossing virtual balls back and forth to each other. Discretizing a continuous force field into imaginary virtual particles definitely seems like a major step backward.

In any case, it is evident that the constructs in the calculational tool of QED can be mapped onto other kinds of constructs in other frameworks. And when one framework has to label a majority of what it contributes with the term "virtual", it seems obvious that it is a tool, not a physical model. Unfortunately, they didn't label the entire apparatus of QED with the term "virtual" — the fact that some things were explicitly virtual somehow tends to give the other non-virtual things more credibility, but really the notion of a photon in this framework is just as virtual as anything else.

The math of QED is based on infinite sums, and these quickly diverge

to infinity. Through heroic efforts, a scheme for renormalizing away these infinities was constructed, and the resulting framework is rightly celebrated for being able to calculate extremely accurate numerical predictions, which fit all the known experimental results. Thus, it is clear that this tool captures something very powerful and true about the way physics works, but any attempt to ascribe physical reality to its central constructs, e.g., the notion of a photon, or passing virtual particles around, seems like pure folly. Indeed, several of the developers of this framework regarded it with disgust and disappointment, even as they used it to compute important results (Jaynes, 1978; Grandy, 1991).

In summary, the QED calculational tool is intrinsically nonlocal and its central notion of a photon is manifestly non-physical. Thus, it is perhaps not too surprising that the crazy non-local behavior ascribed to photons in the entanglement case doesn't seem that objectionable to most physicists. But the recently-developed "first quantized" wave function for photons, and the classical EM framework, both seem at odds with the QM entanglement prediction as described above. We discuss next that there is no solid basis in any existing experimental data to reject these localist models as plausible physical models underlying the phenomena that QED describes in its own weird way.

6. Semiclassical Models

Another shock in digging deeper into the literature was that the vaunted photoelectric effect, the paradigmatic quantum phenomenon that gave birth to the notion of a photon, can be accounted for within the semiclassical or neoclassical approach, where the EM field is treated entirely classically (i.e., Maxwell's equations), and only the atomic system is quantized (e.g., Jaynes & Cummings, 1963; Jaynes, 1973; Mandel, 1976; Barut, 1991; Grandy, 1991; Gerry & Knight, 2005; Marshall & Santos, 1997). Not only the photoelectric effect, but literally every other major phenomenon that was initially thought to uniquely reflect the existence of a photon particle (or more accurately, the formalism of QED and second quantization of the EM field) has been accounted for within the semiclassical approach, including the Lamb shift, Compton scattering, vacuum polarization, the anomalous magnetic moment of the electron, etc.

The frontier is ever expanding, however, and the most recent debates concern various photon statistics effects, for example an anticorrelation effect described by (Grainger et al., 1986), and the antibunching effect described by (Hong et al., 1987). These results can be accounted for with

a version of semiclassical theory that also contains the zero point field (ZPF) from QED, which go by the name stochastic electrodynamics (SED) (Marshall & Santos, 1988, 1997). It is also possible to account for some of the effects due to limitations of the apparatus (Sulcs, 2003; Sulcs & Osborne, 2002). Pushing back the other way, Marshall (2002) showed that the SED model of spontaneous parametric down conversion also predicts spontaneous parametric up conversion, which apparently is not something that QM would predict. Recent evidence confirms this prediction Sun et al. (2009); Akbar Ali et al. (2010), which both supports the SED model and challenges the conventional QM model.

To provide some context for the role of the ZPF in the semiclassical approach, it is important to appreciate that the semiclassical approach is based on approximations to the fully coupled Maxwell-Dirac system, which we discuss in greater detail later as a plausible physical model. These equations are relatively simple to analyze individually, but very complex when coupled in the natural way. Importantly, the Maxwell-Dirac coupling naturally produces a self-field or radiative reaction produced by the electron back onto itself. Many of the phenomena accounted for through the ZPF in QED can be traced to the self-field in the Maxwell-Dirac system (Milonni, 1984; Barut, 1991; Grandy, 1991). As Jaynes (1978) nicely explains, the only vacuum fluctuations in the ZPF that really matter are the ones right near the electron, and in fact the electron is directly responsible for creating these fluctuations in the first place through its self-field. It remains unclear (to me at least) if this argument goes all the way through for the photon statistics effects described by the SED theory, and there appears to be some ambiguity about whether everything can truly be accounted for just by the self-field (Milonni, 1984; Grandy, 1991).

Despite all these successes in terms of seemingly compelling physical models of otherwise mysterious quantum phenomena, it seems that most people regard semiclassical approaches as being fundamentally wrong, and thus not worth changing their world view over. No single semiclassical model can account for all the relevant data, and there are various problems found in each of the different models (e.g., Mandel, 1976). For example, there is apparently a *chirp* (corresponding to a dynamical transition of some sort) in the Lamb shift of Jaynes' model, which is not present in QED and has not been found experimentally. However, other semiclassical models do not make this prediction apparently (Milonni, 1984). Another problem concerns the rate of absorption of a quantum of energy from the EM field into an atomic system — can it happen as quickly as the instantaneous effects predicted by QED, which seem to be consistent with experimental data

(Mandel, 1976)? Interestingly, Mandel (1976) shows that this problem goes away with a wave packet model of the photon, which seems quite plausible. He however then goes on to argue that such a model is inconsistent with the photon anticorrelation data, but SED shows that this may not be a problem.

The bottom line appears to be that to convince a physicist of something, you have to be able to derive accurate calculational results, and short of that, the physical plausibility of the model does not count for much. Even if there is every indication that the full Maxwell-Dirac system could potentially account for all the relevant results, and at least no solid evidence that it cannot, the fact that it is too difficult to analyze renders it largely irrelevant in the daily life of a practicing physicist. And all of the various approximations that are more analytically tractable and form the basis of the semiclassical approach have clear limitations, so they are not worth bothering with either, unless they turn out to be useful calculational tools within their realm of applicability (which actually appears to be the case in a number of instances, e.g., Gerry & Knight 2005; Roychoudhuri & Roy 2003).

But from the outside looking in, and putting an absolute premium on finding a local physical model that could potentially explain the quantum world, the semiclassical approach seems exceptionally promising. Despite every attempt to prove otherwise, the classical Maxwell's equations provide an incredibly accurate, and appealing, physical model. In every case, the origins of quantum weirdness can be traced back to the behavior of atomic systems (and perhaps the ZPF), not to the EM field itself. At the very least, it would seem difficult for someone to strongly refute this possibility. Thus, by extension, the assumption that light should somehow obey the strange quantum property of entanglement seems entirely suspect, and given how much weight this carries for our fundamental understanding of the nature of physics, it seems nothing other than completely insane that the entanglement of light goes apparently unquestioned by the vast majority of physicists.

A major factor for this state of affairs is the seeming confirmation of the QM photon entanglement predictions in a series of experiments testing Bell's inequalities, as we discuss next.

7. Experimental Tests of Bell-type Inequalities

A number of experiments using entangled photon sources with separate measurements of polarization (as described earlier) have been conducted, and their results appear to confirm the QM entanglement predictions (e.g., Aspect et al., 1982a,b; Tittel et al., 1998). In one case, the two measurements were separated by 10km (Tittel et al., 1998)! Although discussion of these experiments is dutifully accompanied with mention of certain "loopholes," these are very often presented as contortionist exercises in deflating the orthodox interpretation. People complain that one loophole is used in one case, and another in another case — does nature choose which loophole to exploit depending on the circumstances?

In delving deeper into this literature, I was again shocked to find that these so-called "loopholes" appear instead to be accurate physical models of the actual experiments, and there are very good physical reasons to consider different such "loopholes" for different experimental situations. The major "loophole" for the experiments based on photons is known as the detection/fair sampling loophole, which basically states that the QM predictions depend on the detectors reporting a fair sample of the photons that are generated from the source, and enough of them to make sure that all the relevant statistics are being counted. Well, it turns out that even the best current photodetectors can only detect up to 30% of the photons, and furthermore, there are strong physical reasons to believe that the polarization angle strongly influences the detection probability, violating the fair sampling assumption. Detailed models of this sort can reproduce the observed data quite accurately, for a variety of experimental configurations (e.g., Marshall et al., 1983; Marshall & Santos, 1985; Thompson, 1996; Adenier & Khrennikov, 2003; Santos, 2005; Aschwanden et al., 2006; Adenier & Khrennikov, 2007). Interestingly, one of these analyses (Adenier & Khrennikov, 2007) shows that accepting the fair sampling assumption produces results that violate the "no signalling" property of the standard QM prediction,

As for the other major loophole, amusingly enough called the "locality" loophole, it pertains to experiments on massive particles, which are apparently the only ones that can practically close the detection loophole (with rates > 90%; Rowe et al. 2001). If locality is considered a loophole, something is seriously wrong with the term "loophole". And the distinction between massive and massless (photons) that determines which "loophole" applies is anything but arbitrary. Two massive entangled particles can always communicate via light-speed interactions (e.g., EM waves) by virtue of the Lorentz contraction effects of special relativity, which ensure that even when massive objects are moving near the speed of light, light still moves at the speed of light relative to them. Indeed, in the Rowe et al. (2001) experiment, the two atoms in question were strongly interacting via a Coulomb (EM) force, over a very short distance. Furthermore, there are other prob-

strongly implicating that fair sampling has been violated.

lems associated with these experiments related to errors in the measurement angles (Santos, 2009).

Thus, again, one cannot help but conclude that any reasonable person who appreciated the true importance of the construct of locality for understanding how nature actually works, would recognize that these experiments provide woefully ambiguous support for the standard QM model of entanglement, and indeed could be seen as providing increasingly strong support against the standard view, given the increasing passage of time without a more definitive experiment that overcomes the "loopholes" (Santos, 2005).

In the next section, we revisit the assumptions that lead to the QM description of entanglement, and consider how the calculational tool of QM may prevent a more accurate description of the underlying physical processes in terms of the distinction between massive and massless particles.

8. Quantum Entanglement Revisited

Why does QM predict this bizarre entanglement phenomenon in the first place, and is there some way to generalize the theory that would accommodate a strong locality constraint on entanglement? These are generally questions beyond my ability to answer, but here are a few physical intuitions that may be of relevance — they certainly help me feel like I understand better what is going on.

The central features of entanglement that need to be captured in any framework are that the states of the two particles are unknown, and yet there are strong constraints on their states (either they must be the same or opposite, depending on the specific case in question). Representing exactly this kind of situation for a single particle is the forté of QM: the unknown state is represented by a superposition of multiple possible states, and the strong constraints come from the basic conservation laws built into QM, which define how states are affected by measurements. Interestingly, the mathematics of QM can be derived very generally from certain kinds of conservation laws, suggesting that the standard QM formalism is really just an abstract probability calculus, with these strong conservation laws, which manifest as a requirement for continuous reversibility (Hardy, 2001), or in the purification postulate (Chiribella et al., 2011).

One mental image for this is that the measurement process in QM is really just about *rotating* things around in state space, e.g., on the surface of a (Bloch) sphere — you never lose (or gain?) any information about the system in question, you just rotate that information around on different axes. If we go back to our polarization detectors, these just rotate the polarization

state of the photon around to different angles, but do not fundamentally alter the magnitude of the polarization property itself. In contrast, if the measurement process did not rotate the polarization state of the photon, then it would be possible to setup a sequence of measurements that eliminate the polarization state entirely — it would end up with no measurable polarization at all! Hence, the contextuality of the measurement process is really just a manifestation of this conservation principle that lies at the heart of QM. Another potentially useful image is a ball of mercury — you can squeeze it into many different shapes, but it fundamentally conserves its overall properties. If you try to measure how tall it is, that squeezing process may cause it to squirt out in the horizontal dimension, and vice-versa. This captures the fundamental uncertainty principle — squeezing things one way causes them to squirt out in other ways, meaning that you can't measure both properties simultaneously.

All of this makes sense for the state of a single coherent entity (a "particle"), which is generally indivisible and really should always behave like that tight little ball of mercury. But does it make sense for two separate entangled particles? Mathematically, QM represents the two entangled particles just like a single unknown particle, because that is presumably the only way to capture the appropriate properties of the state being in a superposition and yet strongly constrained. But what if QM could be extended to represent nonlocal entanglement in a different way?

For example, one critical question about the QM conservation principle is, over how big of a system do you need to apply it? When you make a measurement, we know that the measuring device imparts its state onto the state of the "particle." But wouldn't it also make sense that the particle imposes some of its state onto the measuring device? Under this view, what is conserved is the total state of the particle + measuring device, not just the particle by itself. Does this have any implications for the entangled case? It might suggest that we treat M1 + A as one quantum state, and M2 + B as another, separate quantum state, each of which then will obey the proper conservation dynamic. But this will lose the constraint that A and B share some critical property, which nevertheless remains unknown (in a state of superposition for both). So really you need to represent the whole thing: A + B + M1 + M2 as one big state. But this is then a manifestly nonlocal state. Nevertheless, this is how it is routinely done in QM — many QM states are defined in high-dimensional, nonlocal configuration space.

There are a few observations we can draw from this:

• The calculational tools of QM are very much like a Coulomb or New-

tonian representation of the problem — they strongly encourage non-local configuration space representations, and really all the physics is being captured by virtue of this fundamental rotational conservation property of the quantum world, which can be applied at many different levels of analysis. As we know from the EM and gravitational domains, the existence of a convenient nonlocal configuration-space calculational tool does *not* preclude the existence of a local realistic physical model.

• There does not seem to be any way in the QM calculational tool to represent the presence of two unknown states that are nevertheless constrained to be initially identical (or opposite). This raises the possibility that entanglement is a kind of mathematical accident of the limitations of the calculational framework — it just cannot represent this state accurately. Note that there does not need to be any kind of violation of the all-important conservation laws for this case, because M1+A and M2+B can each still be conserved, and A and B each just rotate around anyway — they just have some kind of shared heritage that cannot be properly represented. This could be construed as a very weak form of hidden variables.

These considerations suggest that an underlying physical model, which obeys the locality constraint, might give rise to a spectrum of entanglement scenarios. In the most obviously entangled case, you have particles that remain in close physical proximity and are thus continuously entangled it seems clear here that a first measurement M1 on particle A would likely produce strong disruption of the state of particle B, such that a second measurement M1 on B would very plausibly be affected by M1, exactly as the standard QM entanglement model holds. In this case, the underlying physical model accords well with the assumptions required from the calculational tool, and everything is consistent. The case of entangled photons represents the other extreme, which could be described as formerly entangled, and is simply not representable within the QM formalism. Hence all the confusion surrounding this erroneous case. In between, one might imagine some kind of continuum, where some degree of continued interaction produces some level of correlation in the measurements, but not as strong as one would expect from the continuously entangled case.

This spectrum is based on the idea that physical locality drives entanglement, which seems to be an important component of the standard QM model already. Specifically, the *source* of entanglement in the first place is

directly tied to physical proximity according to the conventional description. Therefore, it doesn't seem to be a particularly radical suggestion that the continued maintenance of entanglement should also depend on continued physical proximity. It is not clear how to mathematically integrate this locality constraint into the QM formalism, but given that it is merely a calculational tool, it is to be expected that there are things that it cannot accommodate.

Lastly, we consider the actual paradox behind the EPR thought experiment (Einstein et al., 1935). This paradox is that the entanglement scenario appears to allow one to determine more information than would otherwise seem possible about the state of a particle, by performing separate measurements on each of two entangled particles, instead of two sequential measurements on a single "particle." As initially formulated, this paradox was erroneous from the standard QM perspective, because EPR assumed that the two measurements would not affect each other, and yet that M1 on A would nevertheless tell you something precisely about B. This is having your quantum cake and eating it too — the only way M1 can tell you something definitive about B is if it actually affects B in exactly the same way it affects A. Thus, once M1 affects B and thus M2, then it really is identical to two sequential measurements, and there is no paradox.

Conveniently, the spectrum outlined above does nothing to introduce a new paradox. Never do we adopt the untenable assumption of hidden states that simultaneously determine all measurements — each measurement is an interaction (i.e., contextuality). For the formerly entangled case of photons, the outcome of M1 on A doesn't tell you very much about what is going to happen with M2 on B — in the case of polarization you really only know that A (and thus B) is not polarized 90 degrees relative to the angle on M1 — it could be 89 or 91 or any other polarity (and this assumes perfect polarizers which is never possible in reality). Thus, the "heritage" information is much weaker than the continuously entangled case, and much weaker than what was envisioned in the EPR hidden variables.

9. Toward a Realistic Physical Model of the Quantum World

Finally, we conclude with some considerations for what a realistic, local, physical model of the quantum world should look like. As noted earlier, the clearest indication of a calculational tool is the appearance of "virtual" entities, which abound in QED for example, and the clearest indication of a true physical model is the *complete absence* of such virtual entities. In the standard QM formalism, the most glaring virtual entity is the wave

function itself, which is not regarded as physical, and instead only provides the probabilities for experimental outcomes.

Given that the quantum wave function determines actual physical behavior, it seems that we simply cannot escape the conclusion that a realistic physical model must have a physically real wave function. Together with the local propagation constraint, this strongly suggests that our model of the electron should be like that initially suggested by Schrödinger, where the wave function defines the evolution of a distributed mass of charge density, and that is all there is. Once you have a real wave function, there is really no room for the particle concept, which after all is the source of so many conceptual difficulties anyway (as enumerated below, including the case of the pilot wave deBroglie-Bohm alternative model).

Schrödinger apparently abandoned this pure-wave model when he realized that his wave functions had to be defined within high-dimensional configuration space, and he also thought the spread of the wave packet seemed unrealistic, given for example the tracks of particles through cloud chambers. We discuss these and other concerns after describing the Maxwell-Dirac system as the preemptively obvious candidate for a realistic physical model that satisfies the constraints above.

9.1. The Maxwell-Dirac System

The two primary wave fields of interest are the classical EM field coupled with a wave function describing the behavior of the electron (other such fields concern the strong nuclear force presumably, but we can focus on the basic EM phenomena to explore the relevant issues). As reviewed above, the best physical model of the EM field is Maxwell's equations in the Lorenz gauge:

$$\partial_{\mu}\partial^{\mu}A^{\mu} = k_{\mu}J^{\mu} \tag{3}$$

The most accurate physical model for the electron, which is manifestly covariant and thus automatically compatible with special relativity, and describes a wave of charge density, is given by Dirac's equation, which can be written (unconventionally) in a second-order form that strongly resembles Maxwell's equations:

$$\[\left(i\hbar \partial_{\mu} - \frac{e}{c} A_{\mu} \right)^{2} + \frac{e}{c} \vec{\sigma} \cdot \left(\vec{B} + i\vec{E} \right) \] \psi = m_{0}^{2} c^{2} \psi \tag{4}$$

where ψ is a state field defined over standard 3 dimensional space that has two complex numbers (i.e., 4 degrees of freedom, coincidentally the same number of degrees of freedom in the four-potential A), \vec{E} and \vec{B} are the

electric and magnetic fields derived directly from A, and $\vec{\sigma}$ are the standard Pauli matricies that describe the electron's spin:

$$\vec{\sigma} = \left(\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \right)$$
 (5)

The charge density ρ and current density \vec{J} of this Dirac electron are given as follows, which then constitute the four-current $J^{\mu} = (\rho, \vec{J}) = (\rho, J_x, J_y, J_z)$ that is the driving source in Maxwell's equations:

$$\rho = \frac{i\hbar e}{2m_0 c^2} \left(\psi^* \frac{\partial \psi}{\partial t} - \psi \frac{\partial \psi^*}{\partial t} \right) \tag{6}$$

$$\vec{J} = -\frac{i\hbar e}{2m_0} \left(\psi^* \vec{\nabla} \psi - \psi \vec{\nabla} \psi^* \right) \tag{7}$$

Critically, charge is conserved by the Dirac equation.

A great deal of confusion has surrounded the fact that the energy associated with the Dirac wave can be negative. Although Dirac initially came up with a somewhat contrived solution to this issue involving a sea of electrons filling the vacuum states, it is now understood that the Dirac equation describes both the electron and its antiparticle, the positron, with the positron corresponding to the negative energy solutions. There is an intimate relationship between the electron and positron, for example the fact that they can be created from just high energy EM waves, and similarly when they collide they annihilate back into high energy EM radiation. The Dirac equation naturally handles this most mind-bending of phenomena.

This fully coupled Maxwell-Dirac system could in principle provide a fully accurate representation of quantum electrodynamics, with only two main equations and entirely local, simple propagation dynamics. Unlike so many attempts to understand what the electron spin is in terms of a hard little particle somehow spinning, we can instead just take the 4 dimensional state values in the ψ electron wave function as a literal substrate over which the Dirac wave dynamics operate, in exactly the same way the 4 dimensional potential A^{μ} is the substrate on which Maxwell's wave equations operate. In the cellular automaton framework, these state values are just that: local state values that the local equations update as a function of their neighbors. In this case, spin just amounts to the fact that the state values are constantly rotating through each other, corresponding to the *zitterbewegung* ("trembling motion") of the electron. It is a parsimonious, appealing physical model. I find it astounding that this simple set of coupled equations

could possibly describe much of what happens in the universe. This is exactly the kind of fundamental simplicity you would expect from fundamental physics.

However, one of the biggest barriers to the exploration of this Maxwell-Dirac system is that, despite the apparently simplicity of the basic equations, its aggregate behavior is exceptionally complex to analyze mathematically, having resisted many attempts to understand its full complexity. Nevertheless, considerable progress has been made using simplified subsets of the full system. Approximations of this system are the basis for the semiclassical approach described earlier (Jaynes & Cummings, 1963; Jaynes, 1973; Barut, 1991; Grandy, 1991; Marshall & Santos, 1997). The Schrödinger wave equation itself can be derived as a non-relativistic, first-order version of this second-order Dirac equation. From these windows into the full system, we gain considerable insight and confidence that it could actually describe our physical reality. Also, it would seem that numerical simulation techniques could be productively brought to bear on this system — it does not appear that this approach has been explored to any significant degree yet.

If the coupled Maxwell-Dirac system is an accurate physical model, it must correspond in some way to QED, which we know provides highly accurate calculational results. As is nicely explained by Grandy (1991) (and summarized briefly earlier), there are strong reasons to believe that there is a direct correspondence between the two frameworks, which basically provide two different mathematical representations for the same underlying physical process of the self-field of the electron (also known as the radiation reaction). This self-field is directly physically manifest by the coupling of the Maxwell-Dirac equations through A and J, whereas in QED they emerge through virtual particle interactions via the zero point field (ZPF). Thus, again we see that the physical model has a simple physical basis for this effect, while the calculational tool invents something virtual to account for it. Regardless of this difference, both frameworks capture the same key physical phenomena, including the Lamb shift in the spectrum of Hydrogen emissions, the anomalous magnetic moment, and spontaneous emission from excited atomic states in terms of the effects of the self-field (see Barut, 1991; Grandy, 1991; Jaynes, 1978, for reviews). In addition, other effects associated with the ZPF in QED, including the Casimir effect, vacuum polarization, and the Unruh effect can be shown to emerge from the Maxwell-Dirac self field in the approach taken by Barut (1991).

Interestingly, the notion of a self-field is fundamentally incompatible with the idea of a point particle, because the self-field becomes infinite at this point. For this reason, it is completely neglected within the standard (first quantized) QM framework, which thus remains incapable of accounting for the above effects. In the second-quantized QED framework, the infinity is renormalized away, using a mathematical slight of hand that is apparently quite complex and only can work for some cases, one of which happens to be QED. Renormalization appears to be generally regarded with disgust in the physics community, but because it works, it is also widely accepted. It is however yet another indicator of this strong dichotomy between QED as a calculational tool with all manner of physically absurd properties, and the simple elegance and natural physicality of the Maxwell-Dirac system.

A remaining question is whether there are physical phenomena associated with the ZPF that cannot otherwise be attributed to the self-field effects (Milonni, 1984; Grandy, 1991), for example, the photon antibunching effects described by the stochastic electrodynamics (SED) models (Marshall & Santos, 1988, 1997)? Given the simplifications present in the existing semiclassical models, it seems at least possible that the more complete electron wave function provided by the Dirac equation, which includes for example the high-frequency *zitterbewegung* oscillation property, could produce a self-field that has the same effects as those captured in the SED models through the ZPF mechanism. If not, perhaps the model needs to be augmented with a full-fledged ZPF mechanism, as in SED, but this apparently comes at a considerable cost due to the physically implausible properties of the ZPF. Clearly more work needs to be done here to figure out these and many other outstanding problems.

9.2. Can we Really Dispense Entirely with Particles?

The obvious difficulty in adopting a pure-wave alternative is accounting for all the phenomena otherwise attributed to particles. In the standard QM framework, almost all particle-like effects are associated directly with the measurement process and an associated collapse of the wave function, which is one of the most contentious and mysterious aspects of standard QM. During this measurement process, the wave function is said to collapse into a discrete state, which is somehow associated with the concept of the particle. How can this happen within the pure waves-only model? In addition to these problems, we have Schrödinger's two concerns mentioned above (high-dimensional configuration space and apparent localization in the cloud chamber). These issues appear to stem from the linearity of the Schrödinger equation, as contrasted with the nonlinear Maxwell-Dirac system.

9.2.1. Linear vs. Nonlinear Systems and Configuration Space

The linearity of the Schrödinger wave equation means that these waves cannot represent any interactions — two waves just superpose right through each other. Thus, any kind of interaction dynamics between multiple particles requires a higher-dimensional configuration space. Physically, higher-dimensional configuration space doesn't make any sense because the number of particles is not a constant, so the dimensionality of the space is undefined (dealing with this fluidity in particle number is one of the major strengths of the Fock space in QED). This is a clear indication that configuration space is a calculational tool, not a physical model.

In contrast, the nonlinearities of the Maxwell-Dirac system mean that it does not in principle require high-dimensional configuration space to deal with multi-particle interactions. Thus, it is possible that a simple 3+1 dimensional wave state space can represent any number of particles and their relevant interactions, which is an absolute requirement for a local physical model. Fortunately, a plausible basis for thinking that the 3+1 dimensional Maxwell-Dirac system can describe arbitrary numbers of particles is provided by Dorling (1987). He leverages the fact that the Dirac equation actually describes both electrons and positrons, and fully allows for them to be created and destroyed. Thus, the Dirac equation is already a 2 particle equation with effective creation and annihilation operators, and one can adopt an argument due to Feynman to generalize this into an N particle equation in a seemingly mathematically sound manner.

Another strong basis for optimism about being able to remain in real 3+1 dimensional spacetime comes from the density functional theory (DFT), which represents electrons in atoms in terms of an electron cloud density surrounding the nucleus, in simple 3 dimensional space (e.g., Argaman & Makov, 2000). There are various corrective terms that must be added to account for electron-electron interactions, but overall highly accurate predictions can be obtained from this system, and it has apparently become the dominant formalism for quantum chemistry.

More generally, the behavior of electrons in the atomic context seems to be well-described by wave dynamics. Contrary to the naïve atomic models based on electrons actually orbiting the nucleus, they instead behave like standing waves, with no orbital momentum in most cases. And these standing waves are somehow superimposed on top of each other in a completely intermingled fashion. As captured in the DFT models, the atom really does seem to have a dense cloud of electron charge surrounding it, and it stretches the imagination to think of hard little particles bouncing around

in this context, each tied to their own wave functions which are nevertheless completely intermingled.

The critical property that the Maxwell-Dirac system must exhibit to accurately capture atomic behavior in real 3+1 dimensional space is the Pauli exclusion principle. Interestingly, although the spin-statistics theorem that underlies this principle is very difficult to prove (or understand) in the case of point particles, it is more transparent for spatially distributed entities, as in the Dirac electron waves (Duck & Sudarshan, 1998). Specifically, for a spatially extended spin $\frac{1}{2}$ entity with "strings" attached to the surrounding space (e.g., coupling to the Maxwell field), it is clear that a 2π rotation or an exchange of two particles (which can be envisioned as rotating the two as a unit around their common center by π , followed by an additional π rotation for each individual to get them facing each other again) leaves things still twisted, which is indicated by the asymmetric minus sign applied for this case. Only an additional 2π rotation (or re-exchange) fully untwists everything. This topological proof, originally due to Feynman, is considered unacceptable for point particles (points don't face in any direction for example, and don't have any obvious "strings"), but we would seem to avoid that problem in the distributed, coupled Maxwell-Dirac system. Nevertheless, actually demonstrating that the Pauli exclusion principle emerges from this system, for example in the context of the multi-electron interactions in He and Li atoms, would seem to be a high priority early test for this framework.

9.2.2. The Measurement Process

The existing semiclassical approach provides a critical insight into the measurement process: many features of what is measured may be attributed to the measuring device itself, not to what is being measured! Thus, instead of thinking that the EM field exhibits quantum behavior itself, we can instead attribute the quantum behavior to the atomic system that the EM field interacts with. This situation is equivalent to the structure of many magic tricks — you are systematically misled to attribute properties to one "obvious" system (e.g., the rabbit that seems to disappear), when in fact there is a less obvious system that is actually responsible (e.g., an extra pocket in the magicians hat, that holds the rabbit hidden from view). It seems that perhaps people have been systematically misled by quantum magic to attribute properties to the item being measured (e.g., a supposed "photon"), when in fact the measuring device is really responsible.

It seems clear that all quantum measurements involve interactions with atomic systems, as this is what our macroscopic devices are made from. The discrete set of standing waves that are supported by the atomic system is the

source of the quantum nature of electromagnetic interactions. Furthermore, atomic systems are also involved as the *sources* of most things that are measured, and it is critical to consider how this generation process shapes the resulting waves (e.g., spontaneous emission of "photons" is likely to produce discretized wave packets, instead of the plane waves often considered in simplified analyses).

Thus, at a physical level, wave function collapse and measurement involve waves nonlinearly interacting with quantized atomic systems, and it is this chaotic, nonlinear interaction that creates the appearance of particlelike properties out of the otherwise continuous wave functions. Going back to the polarization filters we considered earlier, the so-called wave function collapse really amounts to a rotation of the polarization angle of the photon, or the reflection or absorption of that photon if it doesn't make it through. This is clearly a nonlinear interaction of the incident wave packet with the atoms in the polarizing filter, and it can unfold directly through the nonlinearities present in the Maxwell-Dirac system. Similarly, the photodetection process starts with the photoelectric effect, which also represents a resonance dynamic between the incoming EM waves an the atomic system, described again by (simplifications of) the Maxwell-Dirac system. Thus, it would seem that this single coherent Maxwell-Dirac system can provide a unified account of both state propagation and the measurement process, thereby healing a longstanding rift in the standard QM model.

Further insight into the wave function collapse dynamics comes from analyses undertaken within the *objective collapse* theories of QM, for example the work of Pearle (2007, 2009) and Ghirardi et al. (1986). They have identified the principle of qamblers ruin as critical to deriving the Born probability rule for a discrete measurement from the wave function. Gamblers ruin is basically a negative feedback loop dynamic characterizing someone who eventually loses a series of gambles, whereby the less money you have, the lower your odds are of winning money. Conversely, a mirror-image positive feedback loop holds for the winner. In the actual quantum measurement process, this merely requires that during an iterative unfolding dynamic measurement process the probability of increasing the wave strength for a given measured state is proportional to its current strength. Thus, once one side of this tug-of-war gets a bit of an advantage, its advantage will increase further, leading to a "collapse" into one alternative at the expense of the other. Note that the conservation property automatically enforced by the wave function itself provides a key "zero sum" constraint in this process. This kind of dynamic can also be highly chaotic, in the sense that small initial differences in the strength (probability) of one value in the wave function are magnified. Assuming a reasonable amount of variability in the states of the wave functions for the "identically prepared" incoming wave packets being measured, and of the measuring device itself, it is not hard to see that each of the different states can be sampled effectively at random over repeated measurements.

In summary, particle-like discrete properties should emerge from continuous wave dynamics in the Maxwell-Dirac system through nonlinear interactions with quantized atomic systems, providing a seemingly natural and satisfying physical model of the measurement process.

9.2.3. Free electrons really seem like particles

Whereas electrons in atomic bound states really seem to behave like waves, free electrons seem more particle-like than a pure-waves view would appear to suggest. They seem to be localized (e.g., Schrödinger's concern for the cloud chamber tracks), they seem to have unitary charge whenever we measure them, and they just seem to cohere as a unit more than you'd expect from flimsy waves. In short, if everything was just waves, you would expect lots of splatter and extra bits of goo getting left behind all over the place, instead of the seemingly tidy and neat, quantized behavior we seem to observe for free electrons.

Interestingly, the first problem of dispersion of the wave packet is really a problem for standard QM as much as it is for anything else (Dorling, 1987). In the specific case of the cloud chamber, it would seem that the electron is constantly interacting with molecules in the water vapor, and this interaction serves to constrain the packet diffusion. In other words, there is a continuous measurement process that imposes discretization and localization of the electron trajectory. In a classic quantum complementarity situation, the wave packet only spreads when you don't measure it, and then how do you know it has spread!? Once you look at it, that very process of measurement re-localizes the wave. But somehow if the wave packet really were to get so very widely spread out, it seems that it would be very difficult for it to not leave some distant parts behind during the collapse process.

It would resolve a lot of problems if somehow the electron wave packet exhibited some kind of emergent localization property, such that it cannot spread much beyond some critical limit (e.g., the Compton wavelength). This would have to be due to some kind of nonlinear interaction in the coupled Maxwell-Dirac system that is not otherwise represented in the linear Schrödinger wave function. Given the spin and zitterbewegung dynamic, plus the complex interactions this must engender with the Maxwell field, it seems clear that the electron in this system is very much a complex dynamic

entity, which could very well exhibit this kind of emergent behavior. Indeed, Jaynes (1991) showed that the zitterbewegung property could produce a net self-attractive force on the electron cloud, that would cause it to cohere. Furthermore, any additional electromagnetic interactions with other electron clouds should produce a repulsive force from the like-charges repelling, which will help to keep the charge cloud localized. Other analyses have shown exponential decay in the Maxwell-Dirac density, and otherwise shown spatial localization (e.g., solving the Cauchy problem) (Chadam, 1973; Flato et al., 1987; Esteban et al., 1996; Radford, 2003).

Another related problem is charge quantization — why would an electron wave always have a unitary elementary charge associated with it? The linear Schrödinger equation suffers from the unrestricted ability to perform arbitrary scaling of the wave amplitudes, which then affects the net amount of charge it represents. There is nothing to fix a preferred level of charge within a given wave packet. But if the Jaynes and other analyses are correct, the emergent localization property of the Maxwell-Dirac system could also fix a given level of charge for this stable wave configuration. Another potential source of charge quantization is to trace it back to the strongly localized protons in atomic nuclei. The atomic charge then traps exactly corresponding amounts of electronic charge clouds. If early in the big bang everything was tied up in Hydrogen atoms, then this would make everything initially quantized in this way.

In summary, one could reasonably be optimistic that the various particle-like effects can be understood as emerging from the core nonlinearities of the Maxwell-Dirac system, plus additional constraints from the strongly localized nuclear particles. But clearly a huge amount of work remains to be done to explore these possibilities.

9.2.4. Beyond Electrodynamics

The Dirac wave function can be configured in principle to have zero charge value, which could potentially provide a model of the neutrino. Furthermore, one result from semiclassical theory is that a substantial portion of the electron's measured mass comes from its electromagnetic self-energy (e.g., Crisp, 1996). Thus, one would expect Dirac waves that do not have charge would have considerably less mass, perhaps consistent with that of the neutrino. Furthermore, the other members of the lepton family (muon and tau) could have more energetic electromagnetic dynamics, and thus a larger amount of self-energy, producing their larger observed masses. Thus, there is at least the potential for an elegant way of understanding all of the members of the lepton family (and by potential extension, the similar 3 lev-

els of the quarks). Note also that there does not appear to be any need for the Higgs mechanism to generate a particle's mass — the increasing lack of evidence for the Higgs boson is thus consistent with this overall framework.

Lastly, one of the major barriers to a fully unified description of all known forces in nature, including gravitation, is that the virtual particle energy at small length scales in the ZPF of the QED model seems incompatible with general relativity — spacetime would be massively warped by this field, and if there really are random vibrations at these very high energies, then it turns into some kind of ugly quantum spacetime foam. To the extent that we can eliminate the ZPF entirely within the Maxwell-Dirac framework, and explain everything in terms of self-field effects, this would appear to be entirely compatible with general relativity. Indeed, it becomes just another mutually-coupled field, and the Maxwell-Dirac-Einstein system has actually been analyzed (Finster et al., 1999), with the result that gravitation may actually play a role in emergent localization.

9.2.5. deBroglie-Bohm Pilot Wave Theory

Another possible physical model of quantum mechanics is the deBroglie-Bohm pilot wave theory, where the quantum wave function is considered real, and it guides the behavior of the underlying particle (Bohm, 1953; Bohm & Hiley, 1993; Holland, 1993). Although acknowledging the realism of the wave seems like progress, this wave remains very mysterious and seems physical in name only — its only purpose is to guide the behavior of the particle (which interestingly has no effect back on the wave itself). Because it is formulated using linear Schrödinger waves (with significant difficulties in extending to the relativistic Dirac equation), it requires high-dimensional configuration space to describe multi-particle states, which makes it intrinsically nonlocal. The undefined nature of the dimensionality of configuration space is thus a severe barrier to regarding this as a physical model. In short, it seems that this attempt to provide a physical interpretation that considers both the wave and the particle to be real just serves to highlight how nonphysical and nonlocal the standard QM calculational model really is.

9.2.6. Problems with Particles

Although there are certainly some significant problems that need to be solved for the waves-only model, it is important to give equal time to the even more significant problems associated with any notion of particles. Whereas the problems with waves take the form of technical challenges and promissory emergent properties, the problems with particles seem more fundamental. Here is a quick sampling:

- Particles are only good for creating paradoxes: The classic two-slit experiment is only paradoxical if you believe in particles. There is absolutely nothing paradoxical about a wave packet going through both slits and then collapsing onto a detector somewhere to register a discrete detection event.
- How can particles ever cross nodal points in wave functions? For example, we are to believe that electrons zoom around in the wave functions associated with the various atomic orbitals, but many of these have nodal points where the probability of finding an electron should be precisely 0 how do they ever cross these zero points (Nelson, 1990)?
- Point particles necessarily cause infinite self-field effects close to the point, requiring ugly renormalization procedures. How would nature renormalize this problem away in an autonomous fashion?
- How does one explain particle creation and destruction processes, if we attribute some kind of solid reality to the particle itself? As Feynman's father apparently asked, "was the photon inside the atom before it got emitted through spontaneous emission?" To which Feynman had no good answer. In the waves-only model (and even in QED), this is not a problem particles are just emergent wave configurations, and when these wave dynamics change, it appears as though particles were created or destroyed.
- The stochastic electrodynamics (SED) model of the atomic system is apparently based on the premise of a point electron, which, being an essentially classical framework, suffers from the classical energy radiation problem, causing it to fall into the nucleus. But the ZPF energy in SED is thought to rescue this problem, by providing a stabilizing feedback dynamic. However, this turns out to break down for non-circular orbits, which apparently fatally undermines the SED model of atomic systems (de la Pena & Cetto, 1996). It is not clear how such an approach would have dealt with the lack of angular momentum associated with electron orbitals in the first place, which seems to strongly undermine any kind of literal particle orbiting theory. Seems that this point electron assumption may be more trouble than it's worth.

In summary, it seems that there are many fundamental problems associated with particles that are obviated by the waves-only viewpoint. If one can actually account for all the particle-like properties from within the waves-only model, then this seems like the best path to a paradox-free model of quantum physics.

10. Conclusions

By recognizing the critical differences between calculational tools and physical models, it seems clear that quantum mechanics is completely dominated by the tools, and suffers from the lack of physical models. People have systematically mistaken things like the high-dimensional configuration space in the standard QM formalism as somehow a reflection of physical reality, when it seems to derive instead from the kinds of simplifications (e.g., the linear nature of the Schrödinger wave function) that make it an extremely useful calculational tool. Recent analyses suggest that the true nature of this framework is as an abstract probability calculus, not a physical model (Hardy, 2001; Chiribella et al., 2011). Similarly, in attempting to provide physical interpretations of the manifestly nonlocal, nonphysical Fourier space of QED, all manner of absurdity has been promulgated (Nikolic, 2007), for example the idea that a frequency mode in Fourier space corresponds to a physical entity described by the term "photon." If instead these tools were properly recognized for what they are, many layers of confusion would be removed, and people could use these tools for all they are worth, without suspending the quest for an underlying physical model.

Is it really possible that there is a sensible physical model for the quantum world? Without locality, it seems impossible. With locality, it actually seems relatively trivial (in the grand scheme of things) and already well known and partially understood: the coupled Maxwell-Dirac system (for electrodynamics). Indeed, this system can seemingly be derived just by systematically forbidding the usual trick of calling various things "virtual" that nevertheless produce actual physical effects. The quantum wave function must be real, because it certainly has real physical effects. The wave equation that best describes the electron (and positron) in its full glory is the Dirac equation. It produces a conserved charge value. Hence, the electron is this charge wave. Once the Dirac equation is coupled with its self-field in Maxwell's equations, it becomes nonlinear, and lots of interesting physical phenomena ensue, that have otherwise been attributed to "virtual" particles in QED. Ockham's razor, plus a number of arguments as given above, suggest that this may be as far as we need to go, at least until proven otherwise.

Given that quantum nonlocality is the single greatest barrier to the development of this elegant physical model, one really needs to apply an extremely high standard of proof for this nonlocality, and deeply question whether it is truly mandated by the physical world, or might instead be an accident of the standard QM calculational tools. Does the existing experimental evidence meet this standard? Santos (2005) provides a very strong conclusion:

In any case I claim that local realism is such a fundamental principle that should not be dismissed without extremely strong arguments. It is a fact that there is no direct empirical evidence at all for the violation of local realism. The existing evidence is just that quantum mechanical predictions are confirmed, in general, in tests of (non-genuine Bell) inequalities like (18) or (14). Only when this evidence is combined with theoretical arguments (or prejudices) it might be argued that local realism is refuted. But, in my opinion, this combination is too weak for such a strong conclusion. Thus I propose that no loophole-free experiment is possible which violates local realism.

But even Santos is apparently too cautious to argue that the evident success of the semiclassical approach effectively undermines the basic predictions of quantum mechanics regarding entangled photons in the first place. And it is only this entangled photon case that provides a sound basis for proving quantum nonlocality. If we can reject the premise that photons remain entangled, because they are actually just classical EM waves, and we can very reasonably question the empirical demonstrations of nonlocal photon entanglement, then the only compelling argument left is just that QM is so accurate in all other ways. But it seems that entanglement is treated inconsistently within QM (e.g., locality is required for the creation of entanglement, but not its maintenance), and there does not seem to be a good way to represent a formerly entangled state, which seems like a more accurate model of photon behavior. Putting all of this together, the case for quantum nonlocality seems extremely shaky. Does this shaky case really win out when pitted against the very compelling, paradox-free physical model provided by the Maxwell-Dirac system? I for one would require a much stronger, iron-clad case for nonlocality before abandoning such a promising prospect for finally understanding the beautiful mysteries of the quantum realm.

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References

- Adenier, G., & Khrennikov, A. Y. (2003). Testing the fair sampling assumption for epr-bell experiments with polarizer beamsplitters. ArXiv:quant-ph/0306045v6.
- Adenier, G., & Khrennikov, A. Y. (2007). Is the fair sampling assumption supported by epr experiments? *Journal of Physics B: Atomic, Molecular and Optical Physics*, 40, 131.
- Akbar Ali, S., Bishit, P. B., Nautiyal, A., Shukla, V., Bindra, K. S., & Oak, S. M. (2010). Conical emission in beta-barium borate under femtosecond pumping with phase matching angles away from second harmonic generation. *Journal of the Optical Society of America B.*, 27, 1751–1756.
- Argaman, N., & Makov, G. (2000). Density functional theory: An introduction. *American Journal of Physics*, 68, 69–79.
- Aschwanden, M., Philipp, W., Hess, K., Barraza-Lopez, S., & Adenier, G. (2006). Local time dependent instruction-set model for the experiment of pan et al. *Quantum Theory: Reconsideration of Foundations*, 810, 437–446.
- Aspect, A., Dalibard, J., & Roger, G. (1982a). Experimental test of bell's inequalities using time-varying analyzers. *Physical Review Letters*, 49, 1804–1807.
- Aspect, A., Grainger, P., & Roger, G. (1982b). Experimental realization of einstein-podolsky-rosen-bohm gedankenexperiment: A new violation of bell's inequalities. *Physical Review Letters*, 49, 91–94.
- Barut, A. O. (1991). Brief history and recent developments in electron theory and quantum electrodynamics. In D. Hestenes, & A. Weingartshofer (Eds.), *The Electron: New Theory and Experiment* (pp. 105–148). Dordrecht: Kluwer Academic.
- Bell, J. S. (1964). On the Einstein-Podolsky-Rosen paradox. *Physics*, 1, 195–200.

- Bell, J. S. (1987). Speakable and unspeakable in quantum mechanics (collected papers in quantum philosophy). Cambridge: Cambridge University Press.
- Bialynicki-Birula, I. (1994). Weyl, Dirac, and Maxwell equations on a lattice as unitary cellular automata. *Physical Review D*, 49, 6920–6927.
- Bohm, D. (1953). Proof that probability density approaches j/j 2 in causal interpretation of quantum theory. *Physical Review*, 89, 458–466.
- Bohm, D., & Hiley, B. J. (1993). The Unidivided Universe: An Ontological Interpretation of Quantum Theory. London: Routledge.
- Brill, O. L., & Goodman, B. (1967). Causality in the coulomb gauge. American Journal of Physics, 35, 832–837.
- Chadam, J. M. (1973). Global solutions of the cauchy problem for the (classical) coupled maxwell-dirac equations in one space dimension. *Journal of Functional Analysis*, 13, 173184.
- Chiribella, G., D'Ariano, G. M., & Perinotti, P. (2011). Informational derivation of quantum theory. *Physical Review A*, 84, 012311.
- Crisp, M. D. (1996). Relativistic neoclassical radiation theory. *Physical Review A*, 54, 87–92.
- Dorling, J. (1987). Schrodinger's original interpretation of the schrodinger equation: A rescue attempt. In C. W. Klimister (Ed.), *Schrodinger: Centenary Celebration of a Polymath* (pp. 16–40). Cambridge: Cambridge University Press.
- Duck, I., & Sudarshan, E. C. G. (1998). Toward and understanding of the spin-statistics theorem. *American Journal of Physics*, 66, 284–303.
- Einstein, A., Podolsky, B., & Rosen, N. (1935). Can quantum-mechanical description of physical reality be considered complete? *Physical Review*, 47, 777–780.
- Esteban, M. J., Georgiev, V., & Sere, E. (1996). Stationary solutions of the maxwell-dirac and the klein-gordon-dirac equations. *Calculus of Variations and Partial Differential Equations*, 4, 265–281.
- Finster, F., Smoller, J., & Yau, S.-T. (1999). The coupling of gravity to spin and electromagnetism. *Modern Physics Letters A*, 14, 1053–1057.

- Flato, M., Simon, J., & Taffin, E. (1987). On the global solutions of the maxwell-dirac equations. *Comm. Math. Physics*, 113, 21–49.
- Fredkin, E. (1990). Digital mechanics. Physica D, 45, 254–270.
- Fredkin, E., & Toffoli, T. (1982). Conservative logic. *International Journal of Theoretical Physics*, 21, 219–253.
- Gardner, M. (1970). Mathematical games: The fantastic combinations of *john conway's* new solitare game "life". *Scientific American*, 223, 120–123.
- Gerry, C. C., & Knight, P. L. (2005). *Introductory Quantum Optics*. Cambridge: Cambridge University Press.
- Ghirardi, G. C., Rimini, A., & Weber, T. (1986). Unified dynamics for microscopic and macroscopic systems. *Physical Review D*, 34, 470–491.
- Grainger, P., Roger, G., & Aspect, A. (1986). Experimental evidence for a photon anticorrelation effect on a beam splitter: A new light on single-photon interferences. *Europhysics Letters*, 1, 173–179.
- Grandy, W. T. (1991). The explicit nonlinearity of quantum electrodynamics. In D. Hestenes, & A. Weingartshofer (Eds.), *The Electron: New Theory and Experiment* (pp. 149–164). Dordrecht: Kluwer Academic.
- Gudder, S. P. (1970). On hidden-variable theories. *Journal of Mathematical Physics*, 11, 431–436.
- Hardy, L. (2001). Quantum theory from five reasonable axioms. ArXiv:quant-ph/0101012v4.
- Holland, P. R. (1993). The Quantum Theory of Motion: An Account of the de Broglie-Bohm Causal Interpretation of Quantum Mechanics. Cambridge: Cambridge University Press.
- Hong, C. K., Ou, Z. Y., & Mandel, L. (1987). Measurement of subpicosecond time intervals between two photons by interference. *Physical Review Letters*, 59, 2044–2046.
- Jackson, J. D. (2002). From lorenz to coulomb and other explicit gauge transformations. *American Journal of Physics*, 70, 917–928.

- Jaynes, E. T. (1973). Survey of the present status of neoclassical radiation theory. In L. Mandel, & E. Wolf (Eds.), *Coherence and Quantum Optics* (pp. 35–81). New York: Plenum Press.
- Jaynes, E. T. (1978). Electrodynamics today. In L. Mandel, & E. Wolf (Eds.), *Coherence and Quantum Optics IV* (pp. 495–509). New York: Plenum Press.
- Jaynes, E. T. (1991). Scattering of light by free electrons as a test of quantum theory. In D. Hestenes, & A. Weingartshofer (Eds.), *The Electron: New Theory and Experiment* (pp. 1–20). Dordrecht: Kluwer Academic.
- Jaynes, E. T., & Cummings, F. W. (1963). Proceedings of the IEEE, 51, 89.
- Khrennikov, A. (2001). Linear representations of probabilistic transformations induced by context transitions. *Journal of Physics A: Mathematical and General*, 34, 9965–9981.
- Klassen, S. (2011). The photoelectric effect: Reconstructing the story for the physics classroom. *Science and Education*, 20, 719–731.
- Lamb, W. E. (1995). Anti-photon. Applied Physics B: Lasers and Optics, 60, 77–84.
- Mandel, L. (1976). The case for and against semiclassical radiation theory. *Progress in optics*, 13, 27–68.
- Marshall, T., & Santos, E. (1988). Stochastic optics: A reaffirmation of the wave nature of light. Foundations of Physics, 18, 185–223.
- Marshall, T. W. (2002). Nonlocality the party may be over! ArXiv:quant-ph/0203042v1.
- Marshall, T. W., & Santos, E. (1985). Local realist model for the coincidence rates in atomic cascade experiments. *Physics Letters*, 107, 164–168.
- Marshall, T. W., & Santos, E. (1997). The myth of the photon. In S. Jeffers (Ed.), *The Present Status of the Quantum Theory of Light* (pp. 67–77). Dordrecht: Kluwer Academic.
- Marshall, T. W., Santos, E., & Selleri, F. (1983). Local realism has not been refuted by atomic cascade experiments. *Physics Letters*, 98, 5–9.

- Meyer, D. A. (1996). From quantum cellular automata to quantum lattice gasses. *Journal of Statistical Physics*, 85, 551–574.
- Milonni, P. W. (1984). Why spontaneous emission? American Journal of Physics, 52, 340–343.
- Nelson, P. G. (1990). How do electrons get across nodes? *Journal of Chemical Education*, 67, 643–647.
- Nikolic, H. (2007). Quantum mechanics: Myths and facts. Foundations of Physics, 37, 1563–1611.
- Onoochin, V. V. (2002). On non-equivalence of lorenz and coulomb gauges within classical electrodynamics. *Annales de la Fondation Louis de Broglie*, 27, 163–184.
- Pearle, P. (2007). How stands collapse i. *Journal of Physics A: Mathematical and Theoretical*, 40, 3189–3204.
- Pearle, P. (2009). How stands collapse ii. In *Quantum Reality, Relativistic Causality, and Closing the Epistemic Circle* (pp. 257–292). Springer.
- de la Pena, L., & Cetto, A. M. (1996). The Quantum Dice: An Introduction to Stochastic Electrodynamics. Dordrecht: Kluwer Academic Publishers.
- Poundstone, W. (1985). The Recrusive Universe. Chicago, IL: Contemporary Books.
- Radford, C. J. (2003). The stationary Maxwell-Dirac equations. *Journal of Physics A: Mathematical and General*, 36, 5663–5681.
- Rovelli, C. (1996). Relational quantum mechanics. *International Journal of Theoretical Physics*, 35, 1637–1678.
- Rowe, M. A., Kielpinski, D., Meyer, V., Sackett, C. A., Itano, W. M., Monroe, C., & Wineland, D. J. (2001). Experimental violation of a bell's inequality with efficient detection. *Nature*, 409, 791–794.
- Roychoudhuri, C., & Roy, R. (2003). The nature of light: What is a photon? Optics and Photonics News: Trends, 14, 1–36.
- Santos, E. (2004). The failure to perform a loophole-free test of bell's inequality supports local realism. *Foundations of Physics*, 34, 1643–1673.

- Santos, E. (2005). Bell's theorem and the experiments: Increasing empirical support for local realism? Studies in History and Philosophy of Modern Physics, 36, 544–565.
- Santos, E. (2009). Relevance of a random choice in tests of bell inequalities with two atomic qubits. *Physical Review A*, 79, 044104.
- Shimony, A. (1984). Contextual hidden variables theories and bell's inequalities. *British Journal for the Philosophy of Science*, 35, 25–45.
- Sipe, J. E. (1995). Photon wave functions. *Physical Review A*, 52, 1875–1883.
- Sulcs, S. (2003). The nature of light and twentieth century experimental physics. Foundations of Science, 8, 365–391.
- Sulcs, S., & Osborne, C. F. (2002). Computer simulation of photon anticorrelation expriment using additive pre-detection noise and finite instrument bandwidth. *International Journal of Modern Physics C (IJMPC)*, 13, 823–828.
- Sun, J., Zhang, S., Jia, T., Wang, Z., & Sun, Z. (2009). Femtosecond spontaneous parametric upconversion and downconversion in a quadratic nonlinear medium. *Journal of the Optical Society of America B.*, 26, 549–553.
- Thompson, C. (1996). The chaotic ball: An intuitive analogy for epr experiments. Foundations of Physics Letters, 9, 357.
- Tittel, W., Brendel, J., Gisin, B., Herzog, T., Zbinden, H., & Gisin, N. (1998). Experimental demonstration of quantum-correlations over more than 10 kilometers. *Physical Review A*, 57, 3229.
- Toffoli, T., & Margolus, N. (1990). Invertible cellular automata: A review. *Physica D*, 45, 229–253.
- Ulam, S. (1952). Random processes and transformations. Proceedings of the International Congress on Mathematics, 1950, 2, 264–275.
- Wolfram, S. (1983). Statistical mechanics of cellular automata. Review of Modern Physics, 55, 601–644.
- Zhang, S., Chen, J. F., Liu, C., Loy, M. M. T., Wong, G. K. L., & Du, S. (2011). Optical precursor of a single photon. *Phys. Rev. Lett.*, 106, 243602.

Zuse, K. (1970). Calculating Space. Cambridge, MA: MIT Press.