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Quantum cellular automaton theory of light

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ABSTRACT

We present a quantum theory of light based on the recent derivation of Weyl and Dirac quantum fields from general principles ruling the interactions of a countable set of abstract quantum systems, without using space–time and mechanics (D'Ariano and Perinotti, 2014). In a Planckian interpretation of the discreteness, the usual quantum field theory corresponds to the so-called relativistic regime of small wave-vectors. Within the present framework the photon is a composite particle made of an entangled pair of free Weyl Fermions, and the usual Bosonic statistics is recovered in the low photon density limit, whereas the Maxwell equations describe the relativistic regime. We derive the main phenomenological features of the theory in the ultra-relativistic regime, consisting in a dispersive propagation in vacuum, and in the occurrence of a small longitudinal polarization, along with a saturation effect originated by the Fermionic nature of the photon. We then discuss whether all these effects can be experimentally tested, and observe that only the dispersive effects are accessible to the current technology via observations of gamma-ray bursts.

1. Introduction

A Quantum Cellular Automaton (QCA) describes an evolution step of a discrete set of abstract quantum systems, each one unitarily interacting with a bounded number of neighbors. Since the early work of Feynman [1], which introduced QCAs for describing many body physics and quantum field dynamics, QCAs have become increasingly popular in the theoretical physics community, starting from the

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early works [2–4], followed by mathematical formalizations [5–8], applications to quantum computation [9–12] and quantum field theory QFT [13–16], and experimental implementations [17,18].

In the recent work [19] QCAs have been involved in a formulation of QFT starting from general principles – such as homogeneity, locality, isotropy, and unitarity – ruling the interactions of a countable set of abstract quantum systems. This theory assumes no mechanics, and as such it has no space–time background, and is quantum ab initio, needing no quantization procedure. Remarkably, mechanics and Lorentz covariance emerge from the interactions between the abstract quantum systems. In the mentioned work, along with Refs. [20,21,19], we also assumed linearity of the automaton evolution, which makes the automaton equivalent to a quantum walk, and leading to the free QFT. In these papers the Weyl and Dirac field theories have been derived: the purpose of the present paper is to complete the picture by including the Maxwell field.

In this paper we will see how the electromagnetic field emerges as the relativistic regime of two Weyl QCAs of Ref. [19]. In the ultra-relativistic regime, however, the discreteness of the Planck scale manifests itself in terms of deviations from Maxwell's equations, most notably a wave-vector dependent speed of light. Such a feature has already been considered in some approaches to quantum gravity, and can be in principle experimentally detected in astrophysical observations [22–30]. In the present approach the photon is an entangled pair of non interacting massless Fermions, a scenario resembling the neutrino theory of light of De Broglie [31–36]. The latter theory has been discarded because the composite particle does not obey the exact Bosonic commutation relations [37]. However, as shown in Ref. [36], the non-Bosonic terms introduce negligible contribution at ordinary energy densities, and, as we will see in this paper, in our case the saturation effect originated by the Fermionic nature of the photon is far beyond the current laser technology.

A quantum walk leading to Maxwell's equations was constructed in Ref. [13], by a reverse-engineering technique starting from differential equations. In the present approach we start from two Weyl automata, and find Maxwell's equations as the effective evolution of special entangled pairs, in an appropriate regime. As a consequence, the present model of Maxwell field is not naturally described by a quantum walk, and as such it is very different form the proposal of Ref. [13]. In the present framework, free electrodynamics is recovered without any additional assumption as a special regime of the Weyl QCA, thus emerging from the axioms discussed above. Moreover, this approach allows us to solve the challenging issue of Bosonic statistics without assuming a Bosonic field in the first place, as would be required in the approach of Ref. [13].

In Section 2, after recalling some basic notions about the QCA, we review the Weyl automaton of Ref. [19]. In Section 3 we build a set of Fermionic bilinear operators, which in Section 4 are proved to evolve according to the Maxwell equations. In Section 5 we will show that the polarization operators introduced in Section 4 can be considered as Bosonic operators in a low energy density regime. As a spin-off of this analysis we found a result that completes the proof, given in Ref. [38], that the amount of entanglement quantifies whether pairs of Fermions can be considered as independent Bosons. Section 6 presents the phenomenological consequences of the present QCA theory, the most relevant one being the appearance of a **k**-dependent speed of light. In the same section we discuss possible experimental tests of such **k**-dependence in the astrophysical domain, and we compare our result with those from Quantum Gravity literature [22–30]. We conclude with Section 7 where we review the main results and discuss future developments.

2. The Weyl automaton: a review

The basic ingredient of the Maxwell automaton is Weyl's, which has been derived in Ref. [19] from first principles. Here, we will briefly review the construction for completeness.

A QCA represents the evolution of a numerable set G of cells $g \in G$, each one containing an array of Fermionic local modes. The evolution occurs in discrete identical steps, and in each one every cell interacts with the others. The Weyl automaton is derived from the following principles: unitarity, linearity, locality, homogeneity, transitivity, and isotropy. Unitarity means just that each step is a unitary evolution. Linearity means that the unitary evolution is linear in the field. Locality means that at each step every cell interacts with a finite number of others. We call cells interacting in one step *neighbors*. The neighboring notion also naturally defines a graph Γ over the automaton, with g as