Off-shell Science for Dressed Photons

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Abstract: Based on a Clebsch dual field theoretical model, it is made clear that a dressed photon (DP) originates from a transition of the spacelike momentum of the Majorana field to a timelike one. This model derives a maximum size of the DP that has already been found by experimental studies. It is pointed out that, in the case where the timelike Majorana particle and anti-particle have anti-parallel spins, the pair annihilation creates a DP with a spin 0. The light converted from this DP can be a unique light field with spin 0, which behaves as a particle. It is experimentally confirmed that a cluster of photons emitted from an Si-LED behaves as such a particle.

1. Introduction

Dressed photon (DP) is a quantum field created as the result of the light–matter interaction that is induced by irradiating a nanometer-sized particle with light [1,2]. Thus, an interacting quantum field must be studied for constructing a theorical model for the DP. However, the existence of a nontrivial interacting quantum field model defined on a four-dimensional Minkowski spacetime has not yet been proven. Axiomatic approaches to quantum field theories have derived many fundamental theorems, including the Haag theorem [3,4]. It is a no-go theorem, implying that an "interaction picture exists only if there is no interaction" [5,6]. To put it roughly, we cannot go beyond the theories for free fields if we stick to the axioms for conventional quantum field theories. Intensive discussions on the theoretical methods based on classical Clebsch dual (CD) fields have been made in order to go beyond free fields, and a mechanism of DP creation has been made clear recently. These discussions have also succeeded in describing several experimental results by quantizing the DP energy [7].

2. Off-shell science theories for dealing with interaction

The DP originates from an off-shell electromagnetic field. Furthermore, this field is associated with the longitudinal Coulomb mode, which plays an important role in light–matter interaction [7-9]. A theory for the DP has to meet the requirement that has been stated by the Greenberg-Robinson (GR) theorem [10,11]. This theorem claims that not only the timelike and lightlike momenta but also the spacelike momenta are required for the interaction. The Maxwell equations can be expanded to the spacelike momentum region by using the CD field because it can introduce the longitudinal mode into the electromagnetic theoretical formulation. By this expansion, the conventional Maxwell equations can be analytically connected to the spacelike momentum region, and the longitudinal mode can be dealt with. Then, space-time can be quantized, which is consistent with the Lorentz covariance. Thus, the quantization of the spacelike CD field is consistent with the space-time quantization. This means that the classical Maxwell equations were successfully expanded from the lightlike to spacelike momentum region. Another important aspect of the quantization is that the length (or wavenumber) must be quantized in the Majorana field [9]. This corresponds to the successful derivation of space-time quantization performed by Snyder [12]. As a result, it is confirmed that a small DP field originates from a transition of the spacelike momentum of the Majorana field into a timelike one. However, this DP cannot be observed in the macroscopic area because it is much smaller than the wavelength of conventional propagating light. For measurement, the DP field must be disturbed to create free photons by inserting a probe into the DP field.

3. Maximum size of the dressed photon

The quantization of the Majorana field suggests that there exists a maximum size of the DP, whose value has been evaluated experimentally to be 40–70 nm [13]. This size is called the DP constant [14]. It is given by the geometrical mean of the smallest Planck length and the largest length associated with a newly modified cosmological constant. They are related to their dark energy model defined by the ground state of a spacelike Majorana field and to their novel dark matter model defined solely by the Weyl conformal tensor field, respectively [7-9].

4. Conversion from dressed photon to bullet-like propagating light

In the case of a pair annihilation of the timelike Majorana field involving anti-parallel spins, the created DP has a spin 0. Specifically, the light converted from the DP can be a unique light field with spin 0, which behaves as a particle. This particle-like behavior has been supported by the Wightman theorem [15] stating that: *A Lorentz or*

Galilei covariant massive system is always localizable. For the Lorentz case, the only localizable massless elementary system (i.e., irreducible representation) has spin 0. Here, localizability means that a position operator can be defined for this system. Quantum mechanically, the bivector for the CD field represents a Majorana field with spin 1/2; thus, a couple of anti-parallel vibector fields with spins 1/2 and −1/2 can be combined to yield a null energy–momentum current with spin 0, which can be regarded as a unique bullet-like light field with spin 0.

A silicon-LED (1.3–1.6 μm wavelength) [16] was used to verify the bullet-like behaviors of emitted light described above [7]. The values of the second-order cross-correlation coefficient (CC), measured by the Hanbury Brown-Twiss method [17], were less than unity in the range of time difference shorter than 20 ns. This indicates the photon anti-bunching, which is an inherent feature of a single photon. However, the CC took a nonzero value at null time difference even though it is less than 1×10^{-2}. This nonzero value is attributed to the photons emitted from multiple light sources located in close proximity with each other in the LED. These features suggest that a cluster of photons emitted from the LED behaves as a single photon. It is named DP-cluster light and is closely related to the localizable property of the spin 0 particle. Namely, if the observable positions of given spin 0 quantum particles are sufficiently close, the cluster of these particles would behave as if it were a single quantum particle with the accumulated amount of energy.

The experimental verification above suggests that such a peculiar propagating light field exists, whose energy-momentum tensor has exactly the same form as a free particle. If that is the case, a light beam consisting of such a light field would behave as a bullet and be free from diffraction. In regard to this peculiar light field, it is further conjectured that the mechanism of DP-cluster light may be involved in gamma ray bursts, one of the cosmological enigmas, as an intermittent extremely high-energy radiation with strong directionality that reaches the earth after travelling over an enormous distance of several billions of light years.

5. Summary

Based on a CD field theoretical model, it was made clear that a DP originates from a transition of the spacelike momentum of the Majorana field to a timelike one. This model succeeded in deriving a maximum size of the DP. This size was named the DP constant. It was found that, in the case where timelike Majorana particle and anti-particle have anti-parallel spins, pair annihilation creates a DP with a spin 0. The light converted from this DP can be a unique light field with spin 0, which behaves as a particle. It was experimentally confirmed that a cluster of photons emitted from an Si-LED behaved as such a particle and was named DP-cluster light [18].

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[18] For the present status of the theoretical studies on off-shell science, please refer to the Special Issue "Quantum Fields and Off-Shell Sciences", *Symmetry*, 2021, guest-edited by M. Ohtsu.