The dressed photon as a member of the off-shell photon family

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Abstract

This article reviews recent progress in theoretical studies in off-shell science that has been recently established for correctly describing light–matter interactions. These studies produced the Clebsch-dual (CD) field theory to deal with the spacelike momentum field that is indispensable in such interactions. This theory describes that the spacelike momentum field is converted to a timelike field at a singular point in a host material, resulting in the creation of a timelike Majorana field of a particle–antiparticle pair. Annihilation of this pair creates a dressed photon (DP). Furthermore, based on the correlation between theoretical models of the CD field and dark energy, the maximum size of the DP is derived and is expressed by using basic physical constants. The derived value (40 nm) agrees with the experimental value. Finally, by noting the mechanism of creation of the DP, it is concluded that the DP should be described on the basis of the off-shell photon model, not the virtual photon model.

1. Introduction

Off-shell science was recently developed to study intrinsic features of the dressed photon (DP), or in other words, to study light–matter interactions in a nanometer-sized space. The DP is a quantum field that localizes in a nanometer-sized composite system composed of photons and electrons (or excitons) [1]. It is created as a result of the interaction between these elementary particles [2,3]. Off-shell science has been applied to develop a

variety of disruptive technologies (including nanometer-sized optical devices, optical information processing systems, nano-fabrication technology, and energy-conversion technology) that could never have been made possible as long as the products of conventional optical science were used [1,3].

This article reviews recent progress in theoretical studies in off-shell science. It also compares the features of a virtual photon and the DP.

2. Off-shell science for describing light–matter interactions

Experimental studies on the DP have found a variety of novel phenomena that deviate far from the commonly accepted picture based on conventional optical science [1,3]. In preliminary theoretical studies, these results have been analyzed, and the spatially localized DP has been identified as an off-shell quantum field [4-11]. These studies have shown that extensive investigations of light–matter interactions in a nanometer-sized space were required to correctly describe the intrinsic nature of the DP. Furthermore, the researchers pointed out that conventional on-shell science could not be used to describe these interactions because it did not deal with the spacelike momentum field that was indispensably involved in the description.

In order to produce a theory for correctly describing these interactions, off-shell science was developed by noting three facts [12-15]:

(1) Conventional quantum field theory has never provided any theoretical basis for describing the light–matter interactions in a nanometer-sized space.

(2) Conventional quantum field theory has excluded the particle field having a spacelike momentum by claiming that it was a “non-physical” field, i.e., that it could not be directly observed.

(3) Being independent of the conventional quantum field theory, it has been

pointed out that the spacelike momentum field [16] and the longitudinal electromagnetic field [17] were indispensably involved in the interactions.

By referring to these facts, the Clebsch-dual (CD) field theory was produced by using Clebsch variables: Maxwell's theory of the electromagnetic field was extended to the spacelike domain in the Minkowski spacetime by combining the theoretical formulations of the CD field and the hydrodynamic vortex. As a result, the spacelike momentum field and longitudinal electromagnetic field were successfully incorporated into the theory [15].

The CD field is a classical model that connects the longitudinal electromagnetic field [18] and a "non-physical" longitudinal virtual photon. The CD field theory claims that a quantum mechanical expression of the longitudinal virtual photon corresponds to that of the Majorana field [15].

Furthermore, from the CD field theory, it was found that a singular point in a host material played an essential role in the process of creating the DP. The spacelike momentum field, indispensably involved in the interaction, is converted to a timelike field at this point, resulting in the creation of a timelike Majorana field of a particle–antiparticle pair. Annihilation of this pair creates a longitudinal quantum field at this point whose spatial features are described by a Yukawa function. This field is no more than the DP.

Recent studies in off-shell science identified the CD field as a conformally extended electromagnetic field, and based on its intrinsic mathematical structure, it was found that the CD field structure contributed to estimating the magnitude of the dark energy that exponentially expands the universe. Furthermore, the CD field was also identified as being conformal to the quantized Snyder spacetime that has been used to guarantee the Lorentz invariance.

Based on these findings, these studies succeeded in deriving the maximum size of the DP, expressed by using basic physical constants, such

as the gravitational constant, the speed of light, Plank's constant, and the magnitude of the dark energy [19]. Amazing agreement between the derived value (40 nm) and the experimental value is encouraging the further promotion of off-shell science.

3. Off-shell photons and virtual photons

Conventional quantum field theory has classified particles into two groups: real particles and virtual particles. A real particle is experimentally observable, as has been popularly known. Special relativity theory has described the relation between the energy E, momentum p, and mass m of a real particle by the dispersion relation $m^2 = E^2 - p^2$. This particle has been named "an on-shell particle" after this relation.

A virtual particle, on the other hand, cannot be experimentally observed. Furthermore, it cannot be described on the basis of the dispersion relation above. Thus, it is "an off-shell particle". Conventional quantum field theory has claimed that a virtual particle is created and successively annihilated within a short duration during the interaction between elementary particles. This claim means that the conventional quantum field theory can never separate itself from the concept of the virtual particle for describing this interaction. A virtual photon is an example of such a virtual particle. The exchange of a virtual photon between charged particles creates a Coulomb force that follows the inverse square law. This force is the origin of the interaction between these particles.

As has been reviewed in Section 2, an essential issue is that the DP is created as a result of the light–matter interaction at a singular point in a host material. By this interaction, a part of the spacelike momentum field (which is an indispensable field for the interaction) is converted to a timelike momentum field and subsequently creates a localized DP at this singular point. The converted momentum field can be observed

experimentally, and it is no more than the DP field.

By considering the issue above, one can note that the term “off-shell” (or deviation from the dispersion relation) implies that the host material plays an essential role in the circumstances under which the created DP is allowed to localize at the singular point in a stable manner. By noting this implication, it can be found that the features of the DP are independent of those of the virtual photon above. This means that the DP should be described on the basis of on the off-shell photon model, not the virtual photon model that has been indispensable in conventional quantum field theory.

4. Summary

In order to establish novel off-shell science for correctly describing light–matter interactions, a Clebsch-dual (CD) field theory was produced to deal with the spacelike momentum field that was indispensably involved in the interactions. This theory proved that a singular point in the host material was essential to create the DP. The spacelike momentum field was converted to a timelike field at this point, resulting in the creation of a timelike Majorana field of the particle–antiparticle pair. Annihilation of this pair created the DP. Furthermore, the CD field was identified as a conformally extended electromagnetic field. By noting that the mathematical structure of this field contributed to estimating the magnitude of the dark energy, the maximum size of the DP was derived and was expressed by using basic physical constants. The derived value (40 nm) agreed with the experimental value. Finally, by noting the mechanism of creation of the DP, it was concluded that the DP should be described on the basis of the off-shell photon model, not the virtual photon model.

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