Progress in off-shell science in analyzing light–matter interactions for creating dressed photons

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Abstract

This article reviews the recent progress in theoretical studies on mechanisms of creating dressed photons (DPs) by focusing on the light–matter interactions in a nanometer-sized space. First, the intrinsic nature of the DP is reviewed, and fifteen experimentally observed phenomena are described. Second, it is pointed out that the conventional on-shell scientific method has intrinsic problems in describing these interactions. Finally, the off-shell scientific method, which can overcome these problems, is reviewed, and it is demonstrated that this method, relying on the Clebsch dual (CD) field, has succeeded in identifying the mechanism of creation of the DP, specifically: the spacelike CD field (Majorana fermion (MF) field) interacts with the timelike components of the 4-momenta field, and the MF field subsequently creates a timelike particle and antiparticle forming a pair. This pair is annihilated promptly because of its non-propagating nature. However, a non-propagating electromagnetic field remains in the interacting system, which is the very field of the DP.

1. Introduction

A dressed photon (DP) is a quantum field created by light–matter interaction in a nanometer-sized space. More specifically, it is the quantum field of a composite system composed of photons, electrons, and phonons [1]. In other words, it is not a solitary free photon. DP energy transfer among nanometer-sized materials (NMs) originates also from this interaction. A variety of experimental results involving this interaction have been observed and reviewed in the *Off-shell Archive* series [2-11]. By referring to these articles, the present paper reviews the recent progress in theoretical studies on the mechanism of DP creation. Section 2 reviews the intrinsic nature of the DP and presents experimental evidence. Section 3 points out that the conventional quantum field theories have intrinsic problems in describing the above interaction. Section 4 introduces off-shell scientific methods and reviews the Clebsch dual field as a promising theoretical model for overcoming these problems.

2. Experimental demonstration of novel phenomena originating from dressed photons

The straight line and curves in Fig. 1 represent the dispersion relation between the momentum and energy of a free photon that propagates through a macroscopic-sized vacuum and a material, respectively. They have been derived by quantum field theory and represent what is called the mass shell. That is, a free photon is an on-shell quantum field, and the science of studying this field has been called on-shell science.

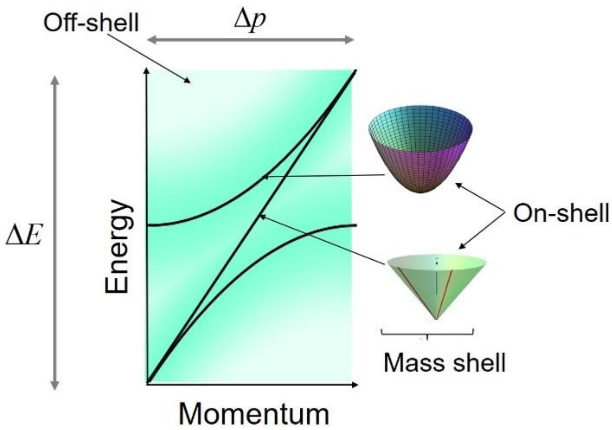

Fig. 1 On-shell (on the mass shell) and off-shell in the dispersion relation.

It should be noted that a DP is created by a light–matter interaction in a nanometer-sized space. In other words, it is created by the exchange of momenta and energies among photons incident on a nanometer-sized material (NM), electrons (or excitons) and phonons in the NM. The created DP localizes at the NM, and its spatial extent is equivalent to the size a of the NM. The DP has been called an optical near field due to this localized feature.

Since a is much smaller than the wavelength λ of the incident light, Heisenberg's uncertainty principle indicates that the uncertainty Δp of the DP momentum p is large ($\Delta p \gg p$). Furthermore, since the energy E depends on the momentum, the large uncertainty Δp indicates a large uncertainty of the energy ($\Delta E \gg E$). It is also indicated by Heisenberg's uncertainty principle that the DP is a virtual photon because the duration Δt ($= h / \Delta E$, where h is Planck's constant) of the DP is short.

In summary, the DP has the natures of both an optical near field and a virtual photon. It should be noted here that its dispersion relation deviates from the mass shell due to the large uncertainties Δp and ΔE. That is, the DP is an off-shell quantum field that exists in the green area in Fig. 1. The science of studying this field has been called off-shell science. The off-shell quantum field can never be represented by the superposition of the electromagnetic modes of the on-shell free photons.

This indicates that off-shell and on-shell sciences do not overlap, as indicated by Fig. 1. They play complementary roles in modern science.

Conventional optical science falls under the category of on-shell science and treats the response of a macroscopic vacuum or material to the propagating free photons. The particle natures of these photons have been studied by using the conventional quantum theory of light in which the light–matter interaction has been described by a perturbative method using a virtual photon model. However, this method is incapable of describing the DP, which is an off-shell quantum field of a nanometer-sized complex system.

Table 1 summarizes novel phenomena originating from DPs, observed in the author's experimental studies [12]. Even though novel theories on light–matter interactions are required to analyze these phenomena, on-shell science has never met this requirement [1)].

Table 1 Novel phenomena originating from dressed photons

No	Phenomena
1	An off-shell field is created and localized on a sub-wavelength material.
2	The DP energy transfers back and forth between two NMs.
3	The DP field is conspicuously disturbed and demolished by inserting NM2 for detection.
4	The efficiency of the DP energy transfer between two NMs is highest when the sizes of the NMs are equal.
5	An electric-dipole forbidden transition is allowed in off-shell science.
6	The DP energy transfers among NMs autonomously.
7	The DP energy transfer exhibits hierarchical features.
8	The photon energy $h\nu$ can be lower than the excitation energy of the electron $E_{ex} - E_g$, where E_{ex} and E_g are the energies of the excited and ground states of the electron, respectively.
9	The maximum size $a_{DP,Max}$ of the DP is 50–70 nm.
10	The DP is created and localized at a singularity such as a nanometer-sized particle or impurity atom in a material.
11	The spatial distribution of B atoms varies and reaches a stationary state autonomously due to DP-assisted annealing, resulting in strong light emission from the Si crystal.
12	The length and orientation of the B atom pair in a Si crystal are autonomously controlled by DP-assisted annealing.
13	A light emitting device fabricated by DP-assisted annealing exhibits photon breeding (PB) with respect to photon energy; i.e., the emitted photon energy $h\nu_{em}$ is equal to the photon energy $h\nu_{anneal}$ used for the annealing.
14	By DP-assisted annealing, a Si crystal works as a high-power light emitting device even though it is an indirect transition-type semiconductor.
15	A semiconductor SiC crystal was made to behave as a ferromagnet as a result of DP-assisted annealing and exhibited a gigantic magneto-optical effect in the visible region.

3. Reasons why the on-shell scientific method does not meet the requirement

Haag's theorem describes the reasons why the requirements mentioned at the end of Section 2 have not been met by on-shell science [13]. The claims resulting from this theorem are summarized as follows:

(1) The off-shell and on-shell quantum fields cannot be mutually transformed by a unitary transformation. This means that there is a theoretical gap between nanometer-sized and macroscopic quantum fields, and thus, they are incompatible with each other.

(2) The quantum field created by the interaction among multiple elementary particles in a nanometer-sized complex system is a non-particle field[2)] that is unrelated to the fields of its constituent particles. This means that this quantum field cannot be represented by the superposition of the modes of free quantum fields.

(3) It is not possible to describe the temporal and spatial behaviors of the quantum field by linear equations. This impossibility is equivalent to the limit of applicability of the conventional quantum theories for describing the interaction[3)].

However, conventional quantum field theories can be easily used for describing quite a large number of optical phenomena by neglecting Haag's theorem and its claims (1)–(3) above. An example of such easy use is found in representing the quantum field by superposing the modes of the on-shell quantum field [14]. Here, it should be noted that this expansion is allowed only when the bases (modes of the on-shell quantum field) form a complete set. However, the intrinsic problem is that the timelike and lightlike components, popularly used in on-shell science, are not sufficient to form this set. The Greenberg–Robinson's theorem [15] claims that the spacelike components in the 4-momenta field are indispensable for this formation[4)] (Fig. 2).

It has been experimentally found that a DP is created and localized at the position where a field varies discontinuously, for example, at the apex of a fiber probe or at a boron (B) atom. High-wavenumber modes must be involved in the mode-superposition when a step-function is used to represent this discontinuous electromagnetic field. However, the use of modes of the timelike and lightlike components in the 4-momenta field is insufficient because the energies of the high-wavenumber modes are much higher than that of the photon of the visible light that serves as a source for creating the DP. The high-wavenumber modes of the spacelike components are required because their energy is sufficiently low to be safely used. This is the reason, found in experimental studies, why the spacelike components of the 4-momenta field are required to represent the creation and localization of the DP.

The next section reviews the creation and localization of the DP by referring to the spacelike components of the 4-momenta field, for which the Clebsch dual (CD) field is used.

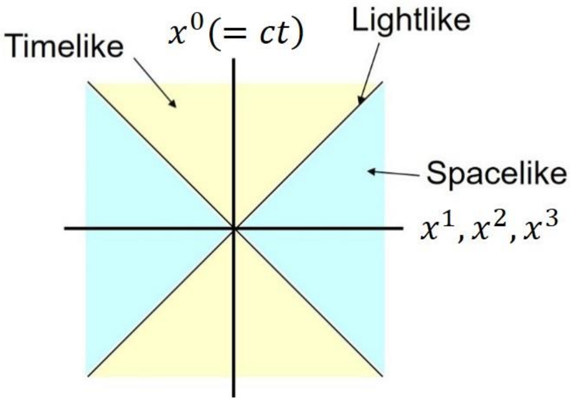

Fig. 2 Minkowski spacetime.

4. Description of dressed photons by the off-shell scientific method

Off-shell scientific studies on the mechanism of DP creation have recently made progress by carefully examining the interaction between electromagnetic fields and matter fields. Details have been published in [16]. They are summarized as follows:

Step 1: Spacelike components in the 4-momenta field play indispensable and essential roles in the quantum field interaction.

Step 2: The quantum field of the spacelike components is expressed by the CD field.

Step 3: The CD field corresponds to a vector boson that is composed of a set of Majorana fermion fields.

Supplementary explanations of **Steps 1–3** are given in the following:

Step 1: This step corresponds to the claim given by the Greenberg-Robinson theorem [15] mentioned in Section 3. This theorem relies on the axiomatic quantum field theory and indicates the indispensable and essential roles of the spacelike components.

Step 2: Detailed analyses of Maxwell's equations based on relativistic theory have found that the spacelike electromagnetic field is expressed by the CD field. Here, the CD field is given by the external product of two gradient vectors (C_i, L_i) that are mutually orthogonal (Fig. 3). When the vector potential is lightlike (that is, a null vector), C_i corresponds to the lightlike longitudinal electric field. This fact indicates that the longitudinal electric field is involved in the interaction of **Step 1** above[5)]. On the other hand, L_i is a spacelike vector and is normal to the vector C_i, by which L_i is regarded as representing the magnetic field. This fact indicates that the CD field is a spacelike electromagnetic field[6)]. By surveying the energy-momentum tensor of the CD field, it has been found that the wave representation and particle representation of the CD field are equivalent to each other. The particle representation is given by $\rho C_i C_k$, which is isomorphic to the energy-momentum tensor of the free fluid. The quantity ρ corresponds to the fluid density, which is given by $L^m L_m$. It should be pointed out that this quantity ρ takes a negative value, and therefore, it has been considered as a non-physical quantity. This non-physical nature indicates the reason why the longitudinal electric field has been excluded over a period of many years from the on-shell scientific studies on quantizing the electromagnetic field under the Lorentz-covariance condition[7)]. However, thanks to the recent progress made in off-shell scientific studies, it was found that such a non-physical mode is required for describing the interaction, and in addition, that the spacelike components of the 4-momenta field are required (**Step 1**).

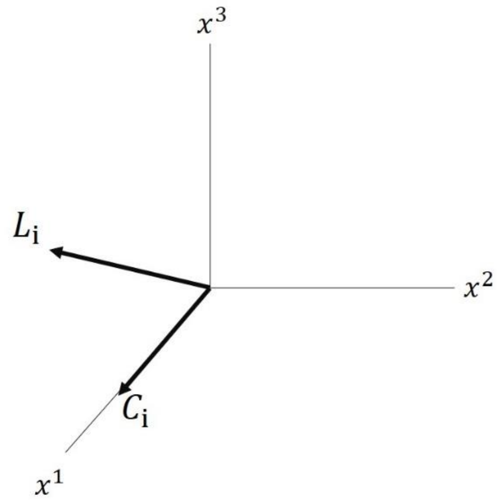

Fig. 3 Four-dimensional vectors C_i and L_i displayed in (x^1, x^2, x^3)-space.

The 0-th axis x^0 is not shown. The field propagates along the x^1-axis.

Step 3: The spacelike components above can be represented by the spacelike Klein-Gordon's (KG) equation, which is derived by replacing the effective mass term m in the timelike KG equation by $i\kappa_0$. By noting that Dirac's equation corresponds to the square root of the KG equation, the equation for the Majorana fermion (MF) is derived by replacing m in the timelike Dirac's equation by $i\kappa_0$. The MF represents an electrically neutral quantum field whose particle and antiparticle components are represented by identical equations. From the relations among the timelike KG equation, the spacelike KG equation, and Dirac's equation above, it was found that the quantum mechanical expression of the spacelike CD field was equivalent to that of the MF field.

By referring to the discussions in **Steps 1–3**, the mechanism of DP creation was described from the viewpoint of the interaction, specifically: the spacelike CD field (MF field) interacts with the timelike components of the 4-momenta field [8)], and the MF field subsequently creates a timelike particle and antiparticle forming a pair. This pair is annihilated promptly because of its non-propagating nature[9)]. However, a non-propagating electromagnetic field remains in the interacting system, which is the very field of the DP[10)].

5. Summary

This article has reviewed the recent progress made in theoretical studies on mechanisms of DP creation by focusing on the light–matter interaction in a nanometer-sized space. First, the intrinsic nature of the DP was reviewed, and fifteen experimentally observed novel phenomena were described. Second, it was pointed out that the conventional on-shell scientific method has intrinsic problems in describing the above interaction. Finally, the off-shell scientific method, which can overcome these problems, was reviewed, and it was demonstrated that the Clebsch dual (CD) field can be appropriately used for the description. The mechanisms of DP creation, identified by theoretical analysis using the CD field, are: the spacelike CD field (Majorana fermion (MF) field) interacts with the timelike components of the 4-momenta field, and the MF field subsequently creates a timelike particle and antiparticle forming a pair. This pair is annihilated promptly because of its non-propagating nature. However, a non-propagating electromagnetic field remains, and this is the very field of the DP.

Footnotes

(1) Since conventional optical theory is a branch of on-shell scientific theories, it does not explain the nature of the DP. For example, this theory claims that the zero-mass photon with a non-zero spin cannot be spatially localized in the sense that its position operator cannot be defined.

(2) Such a field has been called the Heisenberg field.

(3) For example, let us consider the case of exciting a free quantum field by injecting energy to the system under study. The excited field interacts with the existing field, and this interaction is described by Newton's equation of motion in the classical theory. Although this equation is linear as long as the magnitude of the injected energy is low, it becomes nonlinear when the energy is increased. Here, the problem is that such nonlinear equations have never been derived in quantum theory.

(4) In the conventional theories of elementary particles, the spacelike component of the 4-momenta field has been excluded from the theoretical model because of its superluminality and thus, non-physical nature.

(5) As an example, a longitudinal electric field is involved in the well-known Coulomb interaction.

(6) This indication is based on the fact that the vector potential satisfies the spacelike Proca's equation even though it is a null vector.

(7) By noting that the quantum field with an infinite degree of freedom is composed of multiple sectors [17], it can be realized that the non-physical longitudinal electric field exists in such a sector that is disjoint with the sector to which the conventionally approved transverse electromagnetic field belongs.

(8) By irradiating an NM with light, CD fields are excited simultaneously with the timelike components of the 4-momenta field. These CD fields are the basic modes for creating the fields of the spacelike components. Since the CD fields correspond to the MF fields (**Step 3**), these MF fields interact with the timelike components at the NM.

(9) Its spatial extent is expressed as the Yukawa-type function $\exp(-r/a)/r$, where a is the size of the NM, as was given in Section 2.

(10) In the case where the spins of the particle and antiparticle are parallel to each other, a zero-spin electric DP is created. In the case where they are anti-parallel, on the other hand, a magnetic DP whose spin is unity is created.

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