Dressed photon phenomena that demand off-shell scientific theories

M. Ohtsu

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3-13-19 Moriya-cho, Kanagawa-ku, Yokohama, Kanagawa 221-0022 Japan

Abstract

This paper presents experimental results on dressed photon (DP) phenomena that demand the quantum field measurement theory and quantum walk theory. In relation to the quantum field measurement theory, it is shown that disturbance of the DP momentum was observed. It is also shown that the linear relation between the cause and effect of the DP energy measurement is lost. An electric-dipole forbidden transition becomes an allowed transition, and the energy disturbance is enhanced by decreasing the probe–specimen distance. In relation to the quantum walk theory, it is shown that energy transfer of the DP and the Brownian motion of nanometer-sized particles were autonomously controlled.

1 Introduction

A dressed photon (DP) is a quantum field that is created in a nanometer-sized light–matter composite system [1]. Specifically, when a nanometer-sized particle (NP) is illuminated with light, a DP is created on the NP, and conventional scattered light is simultaneously created. The created DP localizes at an NP whose spatial extent is equivalent to the size (a) of the NP. Since this is much smaller than the wavelength (λ) of the illumination light, the uncertainty (Δp) of the DP momentum (p) is large ($\Delta p \gg p$), according to the uncertainty principle.

Due to the localized nature of the DP, it cannot be directly measured by conventional optical methods. Instead, it can be indirectly measured by inserting a second NP into the DP field, resulting in bidirectional transfer of the DP energy between the two NPs. A part of the transferred energy is dissipated during this transfer process, resulting in the creation of conventional propagating light that can be measured by a conventional optical method. This indirect measurement exhibits two features:
(1) The DP field is greatly disturbed by inserting the second NP.
(2) Causality in the measurement is lost due to the bidirectional DP energy transfer. That is, the two NPs are coupled to each other by exchanging the DP energy. Thus, they can be identified as devices neither for creating nor detecting the DP.

The two features above indicate that a novel quantum field measurement theory is required. Furthermore, the large uncertainty Δp indicates that the value of p is spread over a wide horizontal range of the momentum–energy dispersion relation, as shown by the green rectangular area in Fig. 1. It deviates from the mass shell in this figure, and thus, the concept and principle of the DP do not

overlap with those of the field on the mass shell (on-shell, for short). Furthermore, since the value of p correlates with the energy E, its uncertainty ΔE is also large ($\Delta E \gg E$). This means, also from the uncertainty principle, that the duration of the DP field is very short, and thus, it corresponds to a virtual photon. It should be pointed out that large uncertainties Δp and ΔE originate from the light–matter interaction in a nanometer-sized space. Since the DP field occupies the large green area in Fig. 1, space and time are mixed in its theoretical analysis, which indicates that the theory of relativity is required.

In summarizing the discussions above, the off-shell quantum field has the features of a localized photon and a virtual photon. The unified physical picture is the so-called DP. Off-shell science is a novel branch of optical science that deals with quantum fields in the off-shell region of the dispersion relation, including the DP.

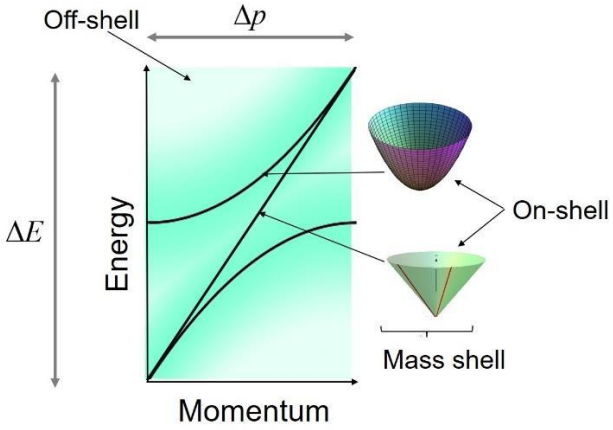


Fig. 1 Mass shell (on-shell) and off-shell in the dispersion relation.

2. Conventional theoretical studies on the dressed photon and their problems

Conventional on-shell scientific methods have been employed to describe the experimentally observed nature of the DP and relevant optical phenomena. This section reviews two of these theories and their associated problems.

[1] Creating the DP and coupling with phonons

In order to describe how a DP is created on an NP, the interaction between photons and excitons in an NP has been analyzed by using conventional on-shell scientific methods [1]. Specifically, the Hamiltonian operator of the DP had to be derived for this analysis. However, since the size of the DP is much smaller than the wavelength (λ) of the incident light, a problem was that one could not define the electromagnetic mode for the DP, which is indispensable for deriving the Hamiltonian operator. In order to solve this problem, the Hamiltonian operator was temporarily expressed by the sum of the

operators of an infinite number of electromagnetic modes of a free photon, based on conventional Fourier transform analysis. Furthermore, the number of energy levels of the exciton was assumed to be infinite. By diagonalizing this temporary Hamiltonian operator, the creation and annihilation operators of a quasi-particle participating in the interaction were derived. The creation operator, $\tilde{a}^{\dagger}$, was expressed as

$$\tilde{a}^{\dagger} = \sum_{\boldsymbol{k}\lambda}\left[\hat{a}_{\boldsymbol{k}\lambda}{}^{\dagger} + iN_{\boldsymbol{k}}\sum_{\alpha>F,\beta<F}\left(\rho_{\alpha\beta\lambda}(\boldsymbol{k})\hat{b}_{\alpha\beta}{}^{\dagger} + \rho_{\beta\alpha\lambda}(\boldsymbol{k})\hat{b}_{\alpha\beta}\right)\right]. \tag{1}$$

The first term, $\hat{a}^{\dagger}_{\boldsymbol{k}\lambda}$, represents the creation operator of a free photon of the incident light. $\sum_{\boldsymbol{k}\lambda}$ represents the infinite sum of the electromagnetic modes. In the second term, $\hat{b}^{\dagger}_{\alpha\beta}$ and $\hat{b}_{\alpha\beta}$ are the creation and annihilation operators of the exciton in an NP, respectively. $\rho_{\alpha\beta\lambda}(\boldsymbol{k})$ represents the spatial Fourier transform of the electric dipole moment. $\sum_{\alpha>F,\beta<F}$ represents the infinite sum of the exciton energy levels. Since the right-hand side is given by the sum of the operators for a photon and an exciton, this equation represents a novel quantum field that is created as a result of coupling between the photon and the exciton. This field is a photon that *dresses* the exciton energy, which is the origin of the name DP.

In the case where a crystalline NP is irradiated with light, a DP is created and localized at the $\boldsymbol{i}$-th atom in the crystal. Then, the DP hops to the adjacent atoms and excites phonons. Finally, the DP couples with these phonons. The creation operator $\hat{\alpha}_i^{\dagger}$ of the novel quasi-particle, created as a result of the DP–phonon coupling that is localized at the $\boldsymbol{i}$-th atom, is expressed as [2]

$$\hat{\alpha}_i^{\dagger} = \tilde{a}_i^{\dagger}\exp\left\{-\sum_{p=1}^{N}\frac{\chi_{ip}}{\Omega_p}\left(\hat{c}_p^{\dagger} - \hat{c}_p\right)\right\}. \tag{2}$$

The operator $\tilde{a}_i^{\dagger}$ on the right-hand side represents the creation operator (eq. (1)) of the DP localized at the $\boldsymbol{i}$-th atom. The exponential function is the displacement operator function composed of the creation and annihilation operators ($\hat{c}_p^{\dagger}$ and $\hat{c}_p$, respectively) of the p-th mode phonon (total number of modes: N). χ_{ip} is the coefficient representing the DP–phonon coupling strength. Ω_p is the angular frequency of the p-th mode phonon. This operator function creates a coherent phonon from vacuum.

Since the right-hand side is given by the product of the operators of the DP and the displacement operator function of phonons, it indicates that the DP excites multimode coherent

phonons and couples with them. That is, the quantum field created as a result of this excitation and coupling is a new type of DP that *dresses* the phonon energy. As a result of this coupling, the DP energy is expressed as $E_{DP} = h\nu_{in} + E_{exciton} + E_{phonon}$, which is larger than the incident photon energy ($h\nu_{in}$), where $E_{exciton}$ and E_{phonon} are the energies of the exciton and phonon, respectively.

[2] Localization of the DP

In order to describe the spatially localized nature of the DP, two NPs placed in close proximity to each other were assumed. The DP energy was bidirectionally transferred between them. It was also assumed that the microscopic system (composed of the DP and the two NPs (NP1 and NP2)) was buried in a macroscopic system (composed of a macroscopic host material and macroscopic incident light). For these two systems, the method of renormalization was employed so that the contribution from the macroscopic system to the DP energy transfer was expressed as the effective interaction energy between the two NPs. As a result, the magnitude of the effective interaction energy localized on NP$_i$ $(i = 1, 2)$ was given by the Yukawa-type function [3]:

$$V_i(r) \propto \frac{\exp(-r/a_i)}{r}, \tag{3}$$

where r is the distance measured from the center of NP$_i$. Since the spatial extent of this function is given by the size a_i of the NP$_i$, it was confirmed that the spatial extent of the localized DP was equivalent to the size of the NP.

It should be noted that this subwavelength-sized localization of the DP violates the long-wavelength approximation that has been employed to calculate the electric-dipole interaction probability for conventional light–electron interactions (on-shell science). Due to this violation, a conventional dipole-forbidden transition became an allowed transition in the case of the DP–electron interaction. Experimental results originating from this violation will be described in Sections 3.2 and 4.

[3] Theoretical problems and the road to a solution

The conventional theoretical studies reviewed in **[1]** and **[2]** have several problems. In the case of **[1]**, the problem was that the electromagnetic modes could not be defined for the DP due to its subwavelength size. To solve this problem, an infinite number of electromagnetic modes were summed, and a temporary solution was derived (eq. (1)). However, such a summation of the modes could not describe the interaction between photons and excitons in an NP. That is, the DP (off-shell quantum field) could not be described even when large numbers of lines and curves in Fig. 1 (on-shell fields)

were superposed. The off-shell quantum field is represented not by the superpositions of these lines or curves but by the large green area in this figure. In the case of **[2]**, a macroscopic system was required to describe the localization of the DP created on the two NPs. Curiously, the DP on the two NPs could not be described when they were installed in a vacuum.

The problems above indicate that the DP (off-shell quantum field) cannot be described even if the conventional on-shell scientific theories are modified or revised. This means that these theories are unsuitable for describing off-shell scientific phenomena. Therefore, the development of genuine off-shell scientific theories is required to solve these problems.

Even under such a situation in which there is a lack of suitable theoretical studies, experimental studies on the DP have been extensively carried out in the last two decades, and their applications have resulted in novel generic technologies [4]. They have produced novel optical devices, fabrication technologies, and energy-conversion devices that have resulted in disruptive innovations for modern technology. Some of them have already been put into practical use. The development of theoretical studies of off-shell science is required to promote further developments in the application of these technologies.

In order to meet this requirement, novel theories based on the augmented Maxwell theory covering the space-like momentum sector were developed recently in order to describe the origin of the DP and its physical picture [5,6]. Theories for measurement and energy transfer of the DP are under development based on the quantum field measurement theory [7] and quantum walk theory [8,9], respectively. Sections 3 and 4 review experimental results and show why these novel off-shell scientific theories are required.

3. Experimental results that demand the quantum field measurement theory

This section reviews experimental results that should be described by the quantum field measurement theory. They indicate that the momentum and energy of the DP are disturbed by the measurement, as will be reviewed in Sections 3.1 and 3.2, respectively.

3.1 Momentum disturbance

The momentum of the DP is largely disturbed by inserting a second NP for the measurement. Furthermore, the efficiency of DP energy transfer between the two NPs is highest when the sizes of the two NPs are equal. This phenomenon has been called size-dependent resonance [10], which corresponds to momentum conservation during transfer, according to the uncertainty principle. This resonance takes place even though the momentum is disturbed, as was described above. It should be pointed out that a novel hierarchical nature originating from this resonance has been found [11].

Based on the DP energy transfer above, a high-resolution microscope that has been developed and put into practical use enabled imaging of a specimen’s conformation and analysis of its structure

[12]. In order to acquire an image with super-resolution beyond the diffraction limit, a nanometer-sized fiber probe tip was used as the second NP to measure the DP created on the specimen's surface.

Spatial Fourier spectral analysis of the acquired images demonstrated that the image intensity was the highest when the size of the specimen was equal to that of the probe tip, due to the size-dependent resonance. That is, the spatial Fourier spectrum exhibited the nature of a band-pass filter. For comparison, in the case of a conventional optical microscope (on-shell science), the spectrum exhibited the nature of a low-pass filter with a high-frequency cutoff that was governed by the wavelength of light. Thus, the spatial resolution was limited by the diffraction of light [13]. Although an advantage of the image acquired by the DP (off-shell science) was that its spatial resolution was much higher than the diffraction-limited resolution, there still remained a problem to be solved: that is, the characteristics of the image acquired by the DP did not correlate with those of the image acquired by the conventional microscope, as was confirmed from the difference in the natures of their spatial filters. Strictly speaking, imaging with the DP is nothing more than evaluating the size of the fiber tip by using the specimen.

By analyzing images of flagellar filaments of bacteria, it has been found that the image characteristics depended on the distance between the probe tip and the specimen [13]: In the case of a short distance, an image of a thin filament was acquired, originating from the DP energy transfer from a thin filament to the small tip of the fiber due to the size-dependent resonance. In the case of a long distance, an image of a thick filament was acquired, originating from the transfer of the DP on a thick filament to the large-diameter root of the probe, also due to the size-dependent resonance.

3.2 Energy disturbance

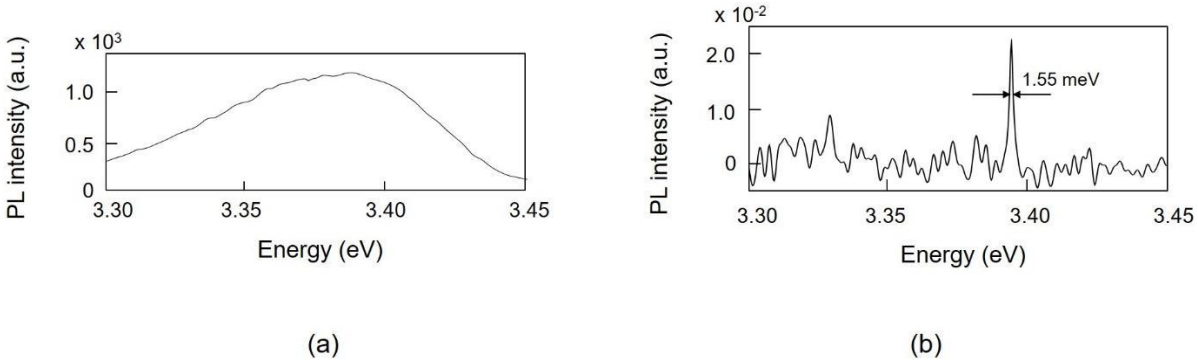
Three kinds of NPs were used as specimens to demonstrate the DP energy disturbance.

[1] The first specimen contained GaN-NPs [14, 15] that were buried immediately under the surface of an AlN substrate. Their diameters were 50–70 nm, and their heights were 7–10 nm. Figure 2(a) shows the photoluminescence (PL) spectral profile acquired by using a conventional microscope (on-shell science).

Since the peak energies of the narrow PL spectra from the GaN-NPs depended on their scattering sizes, the spectrum in Fig. 2(a) corresponded to the envelope of these scattered narrow spectra from a large number of the GaN-NPs, and thus, its width was very large. On the other hand, in the case where the fiber probe was used (off-shell science), it was expected that a few narrow spectra emitted from a few NPs located under the probe tip would be resolved.

However, as shown in Fig. 2(b), only an extremely narrow PL spectrum that originated from a single NP located exactly under the probe tip was acquired. This was because the DP energy was preferentially transferred from this NP to the probe tip most efficiently. This indicates that the DP energy transfers from other NPs, located slightly away from the probe tip, were suppressed, indicating

that the linear relation between the cause and effect of the DP energy measurement was lost, thus suggesting energy disturbance of the excitons and the DP.



(a) (b)

Fig. 2 PL spectral profiles from GaN-NPs, obtained using methods of on-shell science (a) and off-shell science (b).

[2] The second specimen contained nanometer-sized rings (NR) of GaAs that were buried immediately under the surface of an AlGaAs substrate (Fig. 3) [16]. Their diameters were in the range of 30–50 nm. The average thickness was 23 nm. It should be pointed out that the lowest excited energy level of the exciton in the NR is electric-dipole forbidden.

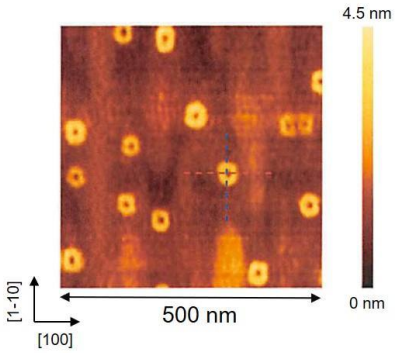


Fig. 3 Atomic force microscope image of GaAs-NRs.

PL emission spectra from these NRs were acquired by using the fiber probe. Here, the NRs were irradiated with a short optical pulse (400 nm wavelength, 25 ps duration, and 87 MHz repetition rate) in order to measure the temporal variation of the emitted light intensity. From these measurements, light emission from the electric-dipole forbidden energy level was clearly seen at a temperature of 7 K; such an effect has never been seen using the methods of on-shell science. This is evidence of violation of the long-wavelength approximation described in subsection **[2]** in section 2.

Figure 4(a) shows the temporal variation of the light intensity emitted from the electric-dipole forbidden level, which demonstrated an emission lifetime of 305 ps when the probe–specimen distance was 5 nm. Such a short lifetime indicates that the fiber probe disturbed the exciton energy and also the DP to trigger light emission from the forbidden state. As shown in Fig. 4(b), decreases of the fiber-specimen distance decreased the emission lifetime to 260 ps. This decrease in the lifetime indicates that the energy disturbance was enhanced by decreasing the probe–specimen distance.

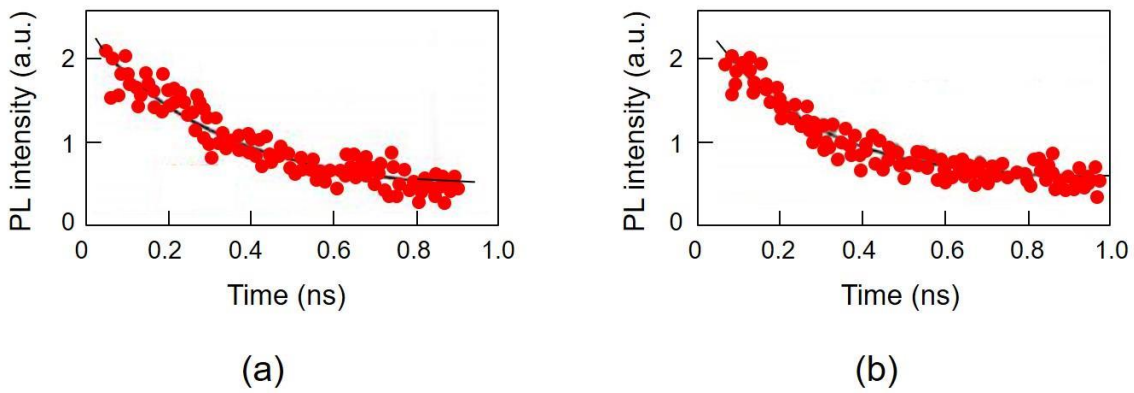


Fig. 4 Temporal variation of the light intensity emitted from the electric-dipole forbidden energy level.
Red circles represent the measured value. Black curves are the exponential functions fitted to them.
(a) The probe–specimen distance was 5 nm. The emission lifetime estimated from the fitted curve was 305 ps.
(b) The probe–specimen distance was <5 nm. The emission lifetime estimated from the fitted curve was 260 ps.

[3] The last specimen contained nanometer-sized cubic NPs (NP1 in Fig. 5) of CuCl that were grown in an NaCl host crystal [17]. Their average size was 4.3 nm. The quantum numbers (1,1,1) in Fig. 5 represent the lowest excited energy level of the exciton. By radiating light that was resonant with this energy level, an exciton was excited, creating the DP. A larger cubic NP (NP2) was installed in proximity to NP1. It played the role of a fiber probe tip for measuring the DP. Here, it should be noted that the second excited energy level (2,1,1) in NP2 was electric-dipole forbidden. However, in the case where it was resonant with the (1,1,1) level of NP1, the DP transferred from NP1 to NP2, turning the forbidden transition to an allowed transition due to the violation of the long-wavelength approximation described in subsection **[2]** of section 2. Thus, the exciton was excited to the (2,1,1) level. This exciton subsequently relaxed to the lower level (1,1,1) to emit light that could be measured by a conventional optical detector. This light emission is evidence of disturbance of the electric-dipole forbidden energy level of the exciton and also the DP energy.

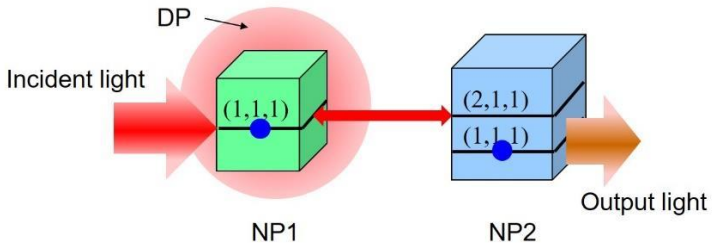


Fig. 5 DP energy transfer between cubic NPs, subsequent exciton relaxation, and light emission.

4. Experimental results that demand quantum walk theory

From the phenomena confirmed by using specimen type **[3]** described in Section 3.2, a large number of experimental results that should be described by quantum walk theory have been obtained. This

section reviews these results by taking DP devices and nano-droplets as examples.

4.1 DP devices

DP devices are nanometer-sized optical devices whose principle of operation uses the DP energy transfer and subsequent relaxation, as shown in Fig. 5. A variety of novel devices have been developed, some of which have already reached the level of practical use [18]. This section reviews two simple DP devices in order to demonstrate that their operation should be described by quantum walk theory.

[1] The first example is a nanometer-sized optical energy transmitter that was composed of a large number of small NPs (NP1 in Fig. 5) arranged in an array [19]. The DP created on an NP1 by applying input light was transferred to the adjacent NP1, and finally reached the large NP (NP2 in Fig. 5). NP2 generated output light after subsequent relaxation of the exciton. Since it was technically difficult to align these NPs accurately, a large number of NP1s were randomly dispersed on a substrate to compose the practical DP device. NP2 was installed among these NP1s. The DP was created on one NP1 and subsequently transferred in an autonomous manner. Finally, it reached NP2 to create the output light. It was confirmed that the optical energy transmission length, L, increased with increasing thickness H of the stacked layers of NP1. In the case where the device was composed by using spherical CdSe-NPs (the diameter of NP1 was 2.8 nm), L was as long as 12 μm at H=50 nm (the number of stacked CdSe-NPs was about 18), which was 40-times longer than the wavelength of the input light (306 nm). This transmission length was theoretically derived by using quantum master equations of the density matrix for the occupation probability of excitons. Although this is a conventional on-shell scientific method, the unique feature was that the Yukawa-type function of eq. (3) was used as the interaction Hamiltonian. The derived theoretical results agreed with the experimental results for the relation between H and L described above. Such a long transmission length indicated that the DP autonomously and ingeniously selected the route of its energy transmission to maximize the output light intensity.

[2] The second example is a nanometer-sized optical energy condenser that was used to concentrate incident light to a sub-wavelength sized volume [20]. A large number of small NPs were installed along the circumference of a circle. A large NP was installed at the center of the circle. Medium-sized NPs were installed between the small NPs and the large NP. These NPs were illuminated with light whose diffraction-limited (on-shell science) spot size was as large as the circle and whose photon energy was resonant with the exciton energy of the small NPs. DPs were created on the small NPs, and they were autonomously transferred to the large NP via transmission through the medium-size NPs so that the optical energy was concentrated to the large NP. Finally, light was emitted from the large NP. Its spot size corresponded to the size of the large NP, which was much smaller than the diffraction-limited spot size. In the case of the device using CuCl-NPs, the DP energy transfer time from the small NPs to the

large NP was about 1 ns.

It was experimentally demonstrated that the efficiency of the autonomous DP energy transfer from the small NPs to the large NP in this device was highest when the ratio of the numbers of the small NPs and the large NP was 4:1. This efficiency was also theoretically estimated by using the quantum master equations described above, and the estimated efficiency agreed with the experimental results [21]. These quantum master equations were also used to evaluate the transfer efficiency for the system in which interactions between some small NPs and the large NP were degraded or lost [21]. A unique feature derived from this evaluation was that the efficiency for the system with degradation was even higher than the system with no degradation.

It should be pointed out that the physical quantities indispensable for the estimation above were those of the DP, such as the creation probability of the DP or the magnitude of the DP energy transfer. Even though the derived occupation probability of the exciton may be proportional to the physical quantities of the DP above, the problem was that the quantum master equations were valid only for deriving the values of the physical quantities of the NP. Novel theoretical models in off-shell science should be developed to directly derive the required values of the physical quantities of the DP.

Since the phenomenon of autonomous DP energy transfer between NPs is similar to the inherent behaviors of amoeba that are used for bio-computing, several simulations have been carried out for application to novel non-Von-Neuman type computing systems in order to solve constraint satisfaction problems and decision making problems [22]. To make further progress in these applications, novel theories will be required to describe the phenomena reviewed above, especially the autonomous DP energy transfer.

Impulse response characteristics of the DP energy transfer from the small to large CuCl-NPs were evaluated in order to make progress towards developing such novel theories. Specifically, a short optical input pulse was applied to a small NP, and the temporal behavior of the output light intensity emitted from the large NP was experimentally evaluated. In the time range of $0 \leq t \leq 4$ ns, the output light intensity from the large NP increased with a rise time of 90 ps, which depended on the magnitude of the transferred DP energy. After the input pulse decayed, the output light intensity also decayed with a decay time of about 4 ns [23]. During this decay, a small-amplitude oscillation was found, which originated from the nutation of the DP energy between the small and large NPs. The period of oscillation was found to be about 400 ps. In a longer time range ($0 \leq t \leq 10$ ns), the first half showed temporal behavior of the output light intensity that was equivalent to that in the range of $0 \leq t \leq 4$ ns. In the later half, however, it decayed with a decay time much longer than 4 ns, due to the relaxation of the exciton. This long relaxation corresponded to a thermal effect that could be considered as a random walk process [24]. On the other hand, the shorter decay time in the first half was free from such a thermal effect, and thus, should be considered as a quantum walk process. This consideration indicates that quantum walk theory should be used to describe the autonomous DP energy transfer discussed in this section.

4.2 Nano-droplets

A nano-droplet (ND) is a small particle of resin in which semiconductor NPs are encapsulated. Table 1 shows four pairs of NPs (NP1 and NP2) that were encapsulated [25-28]. For forming the ND, these NPs were dispersed into a solution of ultraviolet (UV)-setting resin or thermosetting resin to allow the NPs to undergo Brownian motion.

Table 1 Pairs of NPs and resins used to form the ND.

NP1	NP2	Regin	Reference
CdSe	ZnO	UV-setting	[25]
CdSe	ZnO	UV-setting	[26]
CdSe	CdS	UV-setting	[27]
CdSe	CdS	Thermosetting	[28]

This solution was irradiated with visible light whose photon energy was resonant with the exciton energy, $E_{1\text{exciton}}$, in NP1 in order to excite the exciton. Here, it should be noted that the exciton in NP2 was not excited because its energy, $E_{2\text{exciton}}$, was much higher than the photon energy of the irradiated visible light. The exciton excited in NP1 created a DP, which could transfer to NP2 because its energy was as high as $E_{2\text{exciton}}$ due to the contribution of the energies of the exciton and phonon, as was shown at the end of subsection **[1]** in Section 2. This transfer took place only when the size of NP2 was equivalent to that of NP1 (size-dependent resonance). The transferred DP subsequently excited an exciton in NP2, resulting in the creation of another DP. The UV-setting resin solution was finally cured by this DP because the energy of the DP had been increased to an energy as high as the UV photon energy, also due to the contribution of the energies of the exciton and phonon. The spatial extent of the cured UV-setting resin solution was limited by that of the DPs on NP1 and NP2 (refer to the Yukawa-type function of eq. (3)).

NP1 and NP2 were encapsulated in a small particle of the cured resin called an ND, as schematically illustrated in Fig. 6(a) [26]. The optical microscope images in Fig. 6(b) demonstrated that a large number of spherical NDs were formed. They also demonstrated that the conformations and sizes of these NDs were homogenous, and this was attributed to the autonomous control of the Brownian motion of the NPs and the DP energy transfer.

It should be pointed out that the ND could be formed even by replacing the UV-setting resin solution with an optically transparent thermosetting resin. It has been known that the photon–electron interaction in such a resin is electric-dipole forbidden, and thus, this resin is optically transparent. However, the DP turned the transition to an electric-dipole allowed transition due to the violation of the long-wavelength approximation, resulting in curing of the resin and formation of the ND. The formed ND can be advantageously used due to the optical transparent nature of the cured resin. It is expected that quantum walk theory will describe the autonomous control of the Brownian motion and

DP energy transfer in the process of forming the ND.

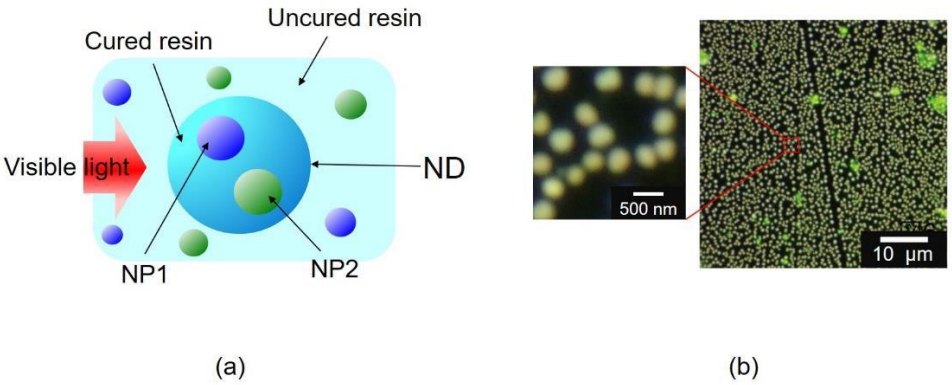


Fig.6 Schematic explanation of a nano-droplet (ND).

(a) Principles of formation. (b) Optical images of formed NDs.

NDs formed in this way have been used for optical energy down-conversion to generate visible light under UV light irradiation [26]. It should be noted that the direction of the DP energy transfer for this conversion was opposite to the one for forming the ND. That is, NP2 absorbed the irradiated UV light to create a DP that was subsequently transferred to NP1 to generate visible light. Figure 7 represents the PL spectra emitted from four independent NDs. It shows that their spectral profiles, including spectral peaks and widths, were equivalent to each other. They were well-fitted to the Lorentzian curve. From these spectral features, homogeneity of the optical properties of these NDs was confirmed.

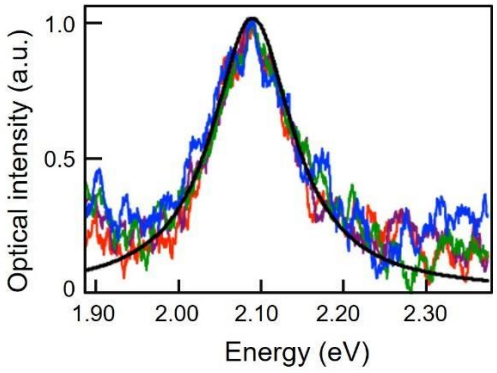


Fig.7 PL spectra from the NDs [25].

CdSe and ZnO were used as NP1 and NP2, respectively. They were encapsulated in a UV-setting resin. Red, green, blue and violet curves are the spectra from four independent NDs acquired under light irradiation with a photon energy of 3.06 eV. The solid curve is a Lorentz function fitted to these curves.

5. Summary

This paper presented experimental results on DPs that demand novel theories of off-shell science, namely the quantum field measurement theory and quantum walk theory. The experimental results

exhibited some unique features:

[In relation to the quantum field measurement theory] (1) The DP momentum was disturbed through its measurement process. (2) The DP energy was disturbed through its measurement process. The linear relation between the cause and effect of the DP energy measurement was lost. An electric-dipole forbidden transition became an allowed transition. The energy disturbance was enhanced by decreasing the probe–specimen distance.

[In relation to quantum walk theory] (3) Energy transfer of the DP and Brownian motion of the NPs were autonomously controlled in by the operation of the DP device and the formation of an ND.

It should be pointed out that the science and technology of the DP are merely one example of off-shell science. It has been confirmed that a variety of phenomena, to be studied by using off-shell science, exist in the natural world [29]. Since the existence of these phenomena indicates that off-shell science is not merely a narrow branch of modern science but a universal one, intensive studies on this science are expected to draw a physical picture of phenomena that are hidden behind the realm of on-shell science.

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