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An "experiment to throw more light on light"

Yutaka Mizobuchi and Yoshiyuki Ohtaké
Central Research Laboratory, Hamamatsu Photonics K.K., Hamakita Research Park, Hamakita 434, Japan

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We performed an experiment which was proposed by Ghose, Home and Agarwal showing both classical wave-like and particle-like behaviors of single photon states of light in a single experiment, in conformity with quantum optics.

The wave–particle duality of light is one of the oldest and still on-going mysteries of quantum mechanics. These opposite natures of light have been thought to appear only in a mutually exclusive way; namely, light cannot behave like a classical wave and a particle at the same time in a given experiment. Although there are many different experiments showing classical and non-classical effects of light, there is as yet no *single* experiment showing both *classical wave-like and particle-like behaviors of light* [1,2].

In a recent Letter, Ghose, Home and Agarwal [1] (GHA, for brevity) propose an experiment which provides the classical wave and particle pictures of light simultaneously in "single photon states". The basic idea is to perform an experiment, originally done by Bose [3,4] [#1] way back in 1897 with microwaves, using the single photon states of light: Waves directed at a 45° prism are totally internally reflected from the 45° face. When a second prism is placed in contact with the first one, however, the waves pass straight through. Furthermore, when we control the gap between the prisms and make it about one tenth of the wavelength, about a half of the beam will be internally reflected while the other half will tunnel across the gap. These phenomena can be confirmed with ordinary light. It should be noted that we must be able to control the gap within several tens of a nanometer – about one tenth of the wavelength – so that we know tunneling is the wave behavior.

When we perform this experiment in the "single photon states" of light, however, there will be some controversies if we consider that light cannot simultaneously reveal the classical wave and classical particle natures as is generally believed. If a photon should behave strictly like a classical wave, a half of it must be reflected and *at the same time* the other half must tunnel across the gap. On the other hand, if the photon should behave strictly like a classical particle, it should not be able to tunnel across the gap because the tunneling is a wave phenomenon. Both of these possibilities are turned down by quantum optics, however. According to quantum optics the photon either is reflected by or tunnels across the prisms, but *not* at the same time. In this case, light reveals itself as a wave because it tunnels across the gap, while it reveals itself as a particle because it is indivisible. The point is that we can observe both the wave and particle behaviors of light simultaneously, contrary to the conventional interpretation of Bohr's complementarity principle [6].

The above arguments hold only in the single photon states. When one uses a "classical" light source, or even a coherent light source, there always remains a possibility to detect coincidence between signals from the reflected and tunneling beams [7].

In this note we show a first report on the result of the GHA experiment. More details will be reported elsewhere [8]. We adopted the parametric down conversion technique [9] to obtain photon pairs. One of the paired photons served as the single photon

[#1] The historical importance of Bose's double-prism experiment has recently been discussed in ref. [5].

source. The advantage of using the down-converted photons over atomic cascades is in the fact that the former is more controllable and gives higher gain because the converted photons strictly satisfy the momentum conservation law. We measured anticoincidence between the reflected and transmitted light. To compare this "quantum light" with a "classical light" [6] we also performed an experiment with a pulsed laser diode, in which we measured coincidence between reflected and transmitted light.

First we describe the anticoincidence experiment proposed by GHA. Our experimental setup is shown in fig. 1. We used the third harmonic of the pulsed Nd:YAG laser, which has a typical wavelength of 355 nm. The laser generates approximately 20 ps long pulses which are cut off from a train of pulses with the Pockel's cell at a repetition rate of 5 Hz which was electronically controlled. After having been focused with a lens (f=60 cm), the beam was injected into a BBO crystal, where the down-converted photon pairs of 710 nm were generated. One of the photons of a pair was selected with a pinhole and passed through a 640 nm cutoff filter to cut off the 355 nm pump beam. The intensity of the signal light was reduced with neutral density (ND) filters to the single-photon intensity level. Then the light was incident on the prisms. The gap between the prisms was controlled by putting Langmuir–Blodgett films between the prisms leaving the passage of the light untouched. Figure 2 shows the relation between the ratio of tunneling and reflection for various amounts of the gap width. It can be easily seen that as the gap decreases the tunneling light increases. This shows the classical wave nature of light. At a certain amount of the gap, about a half of a light beam is internally reflected off and the remaining half is transmitted through the set of prisms. Both reflected and transmitted light was detected by an avalanche photodiode (APD) single-photon detector (Hamamatsu: C4250), whose detection efficiency was 38%. The electric signals from the single-photon detectors (1.5 V pulse height and 90 ns rectangular pulses) were reshaped to 6 V, 600 ns rectangular pulses with a timing single-channel analyzer unit (EG&G ORTEC: 551 Timing SCA) and then led into the anticoincidence unit (EG&G ORTEC: 414A FAst Coincidence). The resolving time of anticoincidence was determined by the input rectangular pulse duration. therefore the anticoincidence unit gave an output signal, which we call the anticoincidence signal, when no transmitted (reflected) light was detected within 600 ns of detection of reflected (transmitted) light. The anticoincidence signals as well as both of the input signals, reflected and transmitted, were accumulated in counter units (NAIG: E-541). The counter units were gated on for 20 μs synchronized with each laser pulse to minimize the dark counts.

The result is shown in fig. 3. The horizontal axis is the detected signal counts per second at each detector. The vertical axis is the ratio of the anticoincidence counts to the number of signal counts from either the reflected or transmitted light which is preselected. This ratio is unity if there is complete anticoincidence, while it is zero if there is complete coincidence. Our experimental result shows that the

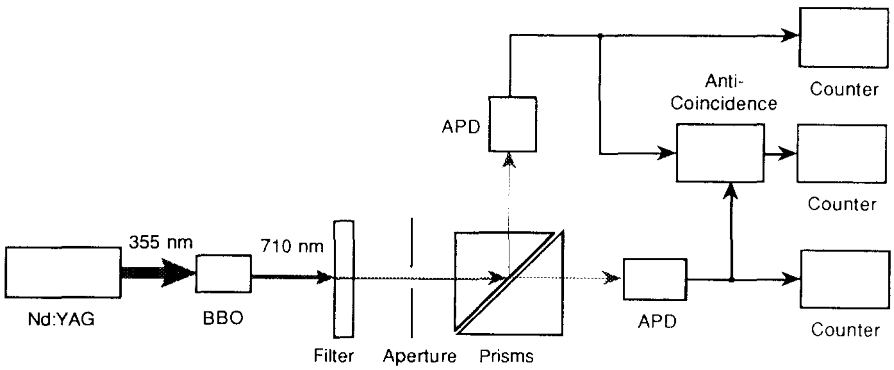

Fig. 1. Experimental setup for the anticoincidence measurement in the single photon states of light.

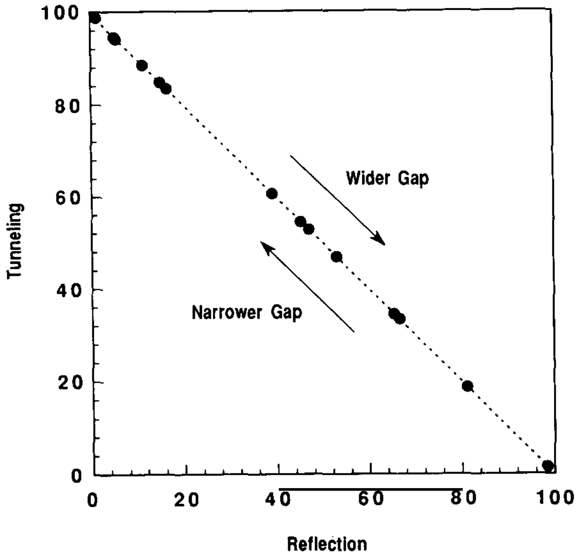

Fig. 2. Relation between the ratio of tunneling and reflection for various gaps.

former is indeed the case, despite the lack of the long time stability of our YAG laser and hence of sufficient statistical accuracy. Therefore in the single photon states, light shows its indivisibility – manifestation of the classical particle property, while still being able to tunnel across the gap between the prisms – manifestation of the classical wave property, at the same time.

Next we discuss briefly the experiment with a classical (or coherent) light source. We used a pulsed laser diode (Hamamatsu: PLP-01) to make a coincidence measurement. The experimental apparatus is shown in fig. 4. The wavelength of the light source is 410 nm, therefore we used photomultiplier tubes (Hamamatsu: R1617) as detectors, which had the highest detection efficiency (18%) around that wavelength. Reducing the light with ND filters to as low as 10^4 photons/s, a small enough figure for our purpose comparing with the size of our apparatus (less than one meter), we measured the coincidence at several incident light intensities and compared it with the semiclassical calculation. If the light source is a semiclassical one, the second order correlation function is unity. Therefore in our experiment, where tunneling and reflection probabilities are nearly equal, the following relation should hold [10]:

$$\frac{\langle n_1 n_2 \rangle}{\langle n \rangle} = \tfrac{1}{4}\langle n \rangle ,$$

where $n = n_1 + n_2$ is the total number of incident photons in a state, and $\langle\ \rangle$ denotes the ensemble average. Therefore the ratio of coincidence with singles

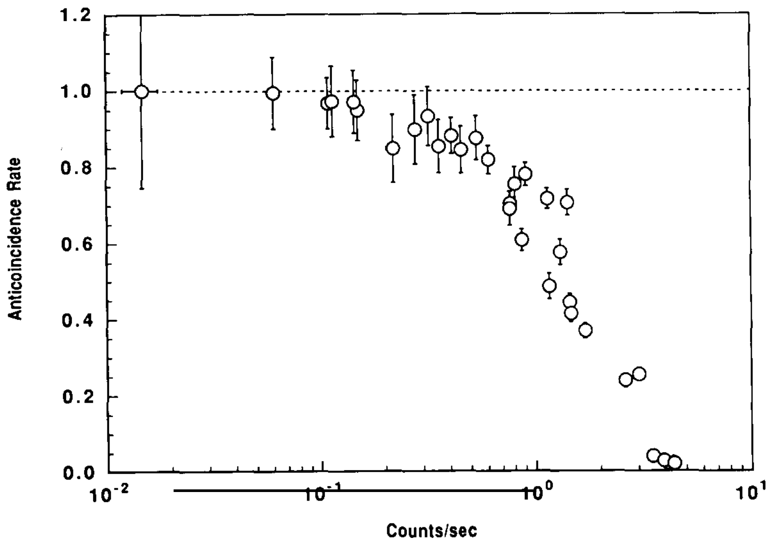

Fig. 3. Result of the anticoincidence measurement. The dashed line represents the complete anticoincidence.

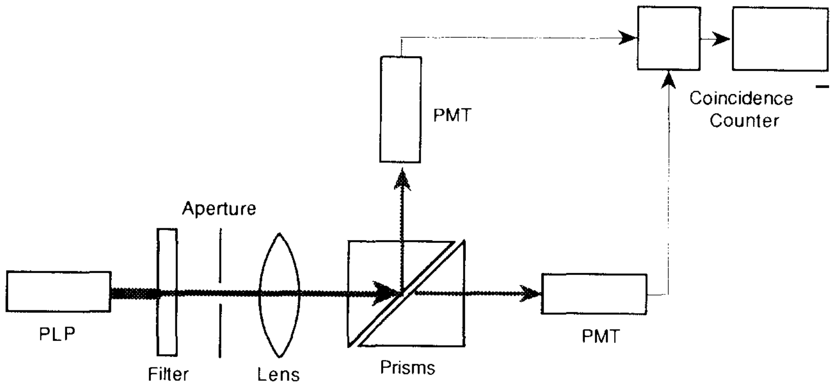

Fig. 4. Experimental setup for the coincide measurement with a pulsed laser diode.

is proportional to the count of singles. If one uses the single photon states, on the other hand, the second order correlation becomes zero [7]. As is shown in fig. 5, the ratio is nearly proportional to the count of singles. Therefore though the incident light intensity was taken such that there was never more than one photon inside the apparatus at any given instant, still non-classical wave-like or single-particle-like behavior was not observed because of the characteristics of the light source.

In summary our anticoincidence experiment supported the prediction of quantum optics, namely, light showed both the classical wave-like and particle-like pictures simultaneously. This is in contrast to the conventional interpretation of the duality principle [6]. In this first report, however, we could not verify the statistical properties of the single photon states due to the rather low stability of our Nd:YAG laser. This will be done in a next report.

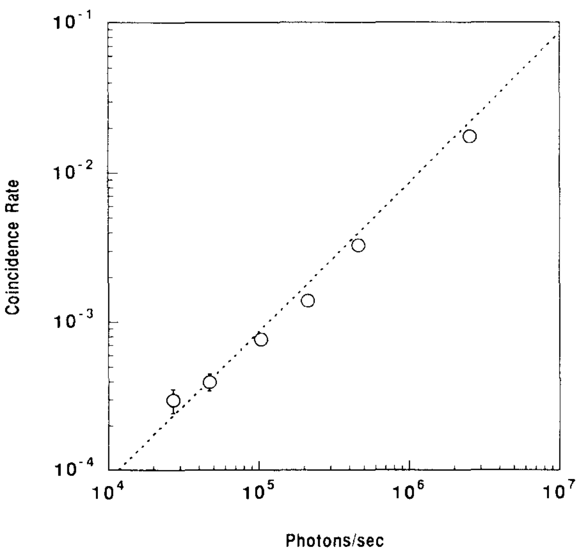

Fig. 5. Result of the coincidence measurement. The dashed line represents the semiclassical calculation.

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