1-2: A single photon is not just a particle of light

What is a Photon?

Introduction

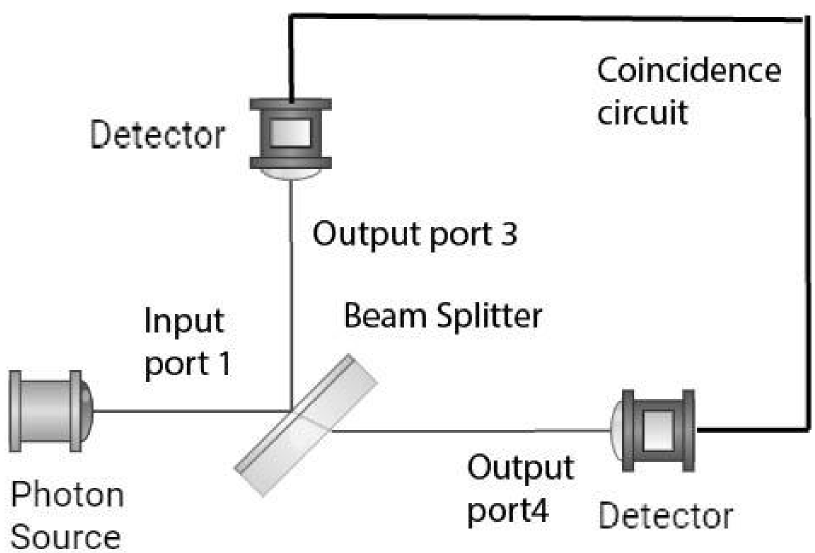
One of the key properties of a photon is that it can be measured once and only once. Photons have other weird properties, like they bunch together. So, creating a single photon is hard. It is not just dim light from a laser, even if your textbook or someone else told you this. The key way to determine that you have a single photon is to show it can be measured once and only once. This was first done in the mid-1980s. Before then, we never really knew we could create single photons. In this worksheet, we explore this remarkable discovery.

Counting Coincidences

The experiment to certify that you have a single-photon source was first completed by Nobel Laureate Alain Aspect and his colleague Philippe Grangier through a clever measurement using a beam splitter with a single-photon light source (the calcium cascade light source). A schematic is shown below. Take a photon, create a superposition, and measure it on its two possible paths. Then count how often you see coincidences. Before the modern-day understanding of quantum optics, physicists thought that they could create a single-photon source by just using very dim light from a classical laser. In this worksheet, we will go over the so-called G2 experiments that verify that dim light is not a single-photon source.

The G2 Experimental Setup

Here is a figure of a photon source directed onto a 50-50 beam splitter, along with its two possible trajectories: a reflected path and a transmitted path. In quantum mechanics, we now know that the beam splitter does not perform a measurement on the photon, but instead it creates what we call a *superposition*. This is a fancy way of saying that we do not know whether we will observe the photon on one path or the other. The technical way we describe this is that the photon path after passing through the beam splitter is *indeterminate*.



Photomultiplier tubes (PMT) are used to convert the incoming light into an electrical signal with single-photon sensitivity. Hence, the number of times the photon is detected can be tracked. We know we have a single photon when we see only one PMT go off in a short interval after the single photon was heralded by detecting the first photon of the calcium cascade. The superposition tells us we cannot predict which detector goes off, and on average, we will find that each goes off half of the time. By counting the coincidences, which can occur due to multiple photons entering the beam splitter at the same time, from dark counts, or from single photons being measured twice, we can test to see whether the source is dim classical light (such as from a laser) or a true quantum single-photon source (such as from the calcium atom cascade transition).

Think carefully about how you might use this data, knowing that any real detector will have dark counts; that is, spurious counts when there are no photons.

Why is this important: Having a way to certify a single-photon source allows one to use it for single-photon-based experiments, which is a hallmark of the second quantum revolution.

To do: Since the photon source will randomly emit photons, think about how you can set up an experiment by activating the PMTs only after a heralded photon is detected, and for how long you keep them active to see whether there are coincidences.

Record your results: Describe an experimental plan for how to make this G2 experiment work.

Probability: Experimentally, to determine the probability for a single count at either detector, we also need to know the number of times that a photon is sent towards the beam splitter. This is possible from the calcium cascade source because a heralded photon is emitted before a second photon (with about 10 ns of delay time between the two photons). The number of heralded photons detected is labeled N_H or the number in the LED beam is N_I. Based on a variety of experimental factors such as beam alignment, precision of optics, striking the PMT adequately, etc., the N_H will be much larger than even the combination of the single counts at either PMT (N_3 or N_4), as well as, the rate of coincidences, N_C (when *both* PMT 3 and PMT 4 "fire" in the allowed time window). To get probabilities, divide the number of counts (N_3, N_4, or N_C) by the number of total counts ($N_{H,I}$).

Event	Counts	Probability
Hit PMT 3	N_3	$P_3=N_3/N_H$
Hit PMT 4	N_4	$P_4=N_4/N_H$
Hit Both PMT 3 and PMT 4	N_C	$P_C=N_C/N_H$

For a classical wave description of light, without photon bunching, we would expect that the probability for coincidences should be *the product* of the probabilities to be measured in each PMT. Think carefully about why this is so. Because we have photon bunching and dark counts, one might expect the measured coincidences to be a bit higher, so we have

$$P_c \geq P_3 P_4 \quad \text{or equivalently} \quad \alpha = \frac{P_C}{P_3 P_4} = \frac{N_C N_{H,I}}{N_3 N_4} \geq 1$$

For dim classical light, since a single photon can be measured once and only once, a single-photon source should have no coincidences, so α=0. Of course, dark counts and random occurrences of two atoms emitting photons in the same measurement window can make it higher. On the other hand, perfect classical light sources always have α=1. Accounting for experimental error, dark counts, and spontaneous emissions, it is expected that $\alpha_{classical} \geq 1$ and a light source can be verified as "single-photon" if α<1. However, much less than 1 is preferred, to be sure.

Let's explore some examples with real experimental data!

Experimental Data

We will compare two sets of experimental data: set 1 is from a very dim LED, which is a classical photon source due to its low attenuation of photons at 0.01 photons per pulse, and set 2 is from a calcium cascade source, where single-photon pulses are produced and heralded through an atomic emission process.

Set 1: Dim LED Light Source				
Experiment	**Number of Input Photons**	**Single PMT 3 Counts**	**Single PMT 4 Counts**	**Calculated Classical Coincidence Counts**
1	148,512,000	94,224	117,312	
2	457,000,000	337,920	423,680	
3	955,040,000	832,840	913,680	

Set 2: Radiative Calcium Cascade Source				
Experiment	**Heralded Photon Counts**	**Single PMT 3 Counts**	**Single PMT 4 Counts**	**Calculated Classical Coincidence Counts**
1	152,564,000	78,260	98,900	
2	391,680,000	241,920	326,400	
3	422,520,000	399,840	519,960	

From this data and the measured coincidences in the given measurement window, one can compute α for each run of the experiment. Do this, and fill in your results in the table below.

Experiment	Calculated Coincidence Classical Counts	Measured Coincidence Counts	GR Coefficient, α
Set 1, Experiment 1		82	
Set 1, Experiment 2		329	
Set 1, Experiment 3		840	
Set 2, Experiment 1		9	
Set 2, Experiment 2		86	
Set 2, Experiment 3		314	

Note: Experimental data obtained from *Aspect, Alain, and Philippe Grangier. "Wave-particle duality for single photons." Hyperfine Interactions* ***37*** *(1987): 1-17.*

Which source is a classical source, and which is a single-photon source? Explain why you came to this conclusion. Does this experiment prove that photons can be measured one and only once.

Why is this important? This simple measurement allows us to determine whether photons really can be measured once and only once, because their detection via the photoelectric effect destroys them.

To do: Think about what needs to be adjusted in the experiment to make it work efficiently. By changing the density of calcium atoms that the lasers are directed at, we adjust the number of atoms that can create single photons. How often, on average, do we want photons emitted? How does the geometry of how we measure heralded photons and the secondary single photon affect the measurement? Why does it not matter that many heralded photons do not result in a final measured photon in the PMT?

Record your results: Write your thoughts on these ideas related to how such an experiment would work.

Deep dive: Since the 1980s, better ways of making heralded and unheralded single-photon sources have been created, and we are getting close to having single photons available on demand. That would mean pushing a button, and a photon comes out. Go and research what these modern sources are and see if you can predict how soon we will have single photons on demand. Terms to look for include “parametric down conversion” and “quantum dot single-photon sources.”

Take-home message: Often, you may ask whether an experiment can just be described classically, and then we do not need to use quantum mechanics to understand it. Because of the fundamental property of a photon, that it can be measured once and only once, we can now have a class of truly quantum experiments. This is the realm of quantum optics. It forms a cornerstone of the second quantum revolution and is part of the pathway towards quantum devices that we will see in the near future. Don’t ever think about a photon as just a particle of light anymore. Now you understand just a bit more about its mystery and its splendor!