

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

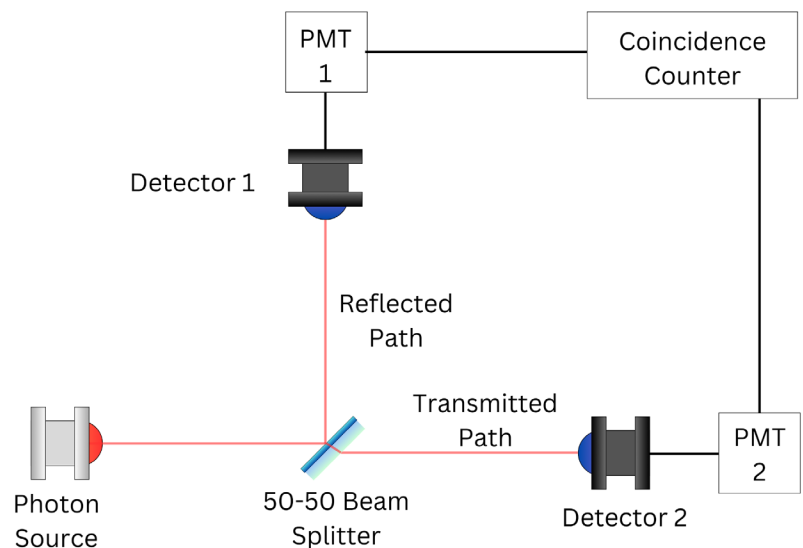
The experiment to certify that you have a single photon source was first completed by Nobel Laureate Alain Aspect and his colleague Philippe Grangier through a clever measurement using a beam splitter with a single photon light source (the



calcium cascade light source). A schematic is shown below, and the idea is fairly simple. Take a photon, create a superposition, and measure it on its two possible paths. Then count how often you see coincidences. Before 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 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 an *indeterminate* one.



Photomultiplier tubes (PMT) are used to convert the incoming light into an electrical signal with single-photon sensitivity, as we discussed previously. 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 half the time each goes off. 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 a laser) or a true quantum single photon sources, 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.

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 the 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 rate of the triggering event, or in other words, the number of times we measure a photon to be sent towards the beam splitter. This is possible from the calcium cascade source because a photon is emitted before a second photon (with about 1 ns of delay time between the two photons). The number of heralded photons detected is labeled N_H . 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 rates of the single counts at either PMT (N_1 or N_2), as well as, the rate of coincidences, N_C (when *both* PMT 1 and PMT 2 “fire”). To obtain probabilities, divide the number of counts (N_1 , N_2 , or N_C) by the total number of heralded counts (N_H).

Event	Rate	Probability
Hit PMT 1	N_1	$P_1 = N_1/N_H$
Hit PMT 2	N_2	$P_2 = N_2/N_H$
Hit Both PMT 1 and PMT 2	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

$$P_C \geq P_1 P_2$$

Or equivalently,

$$\alpha = \frac{P_C}{P_1 P_2} = \frac{N_C N_H}{N_1 N_2} \geq 1,$$

For dim classical light. Because a single photon can be measured once and only once, a single-photon source should have no coincidences, so $\alpha=0$. 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 $\alpha=1$. Accounting for experimental error, dark counts, and spontaneous emissions, it is expected that $\alpha_{\text{classical}} \geq 1$ and a light source can be verified as “single-photon” if $\alpha < 1$, although much less than 1 is preferred.

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	Heralded Photon Rate	Single PMT 1 Photon Rate	Single PMT 2 Photon Rate	Duration
	P_H (photon/s)	P_1 (photon/s)	P_2 (photon/s)	T (s)
1	4760	3.02	3.76	31200
2	35750	26.4	33.1	12800
3	50800	44.3	48.6	18800

Set 2: Radiative Cascade Source				
Experiment	Heralded Photon Rate	Single PMT 1 Photon Rate	Single PMT 2 Photon Rate	Duration
	P_H (photon/s)	P_1 (photon/s)	P_2 (photon/s)	T (s)
1	4720	2.45	3.23	12000
2	8870	4.55	5.75	17200
3	50300	47.6	61.9	8400

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. Use your computation for the numbers of heralded, PMT, and coincidence counts by multiplying rates by the measurement times.

Experiment	Coincidence Rate	GR Coefficient, α
	P_C (pairs/s)	
Set 1, Experiment 1	1.20	
Set 1, Experiment 2	1.05	
Set 1, Experiment 3	1.05	
Set 2, Experiment 1	0.30	
Set 2, Experiment 2	0.17	
Set 2, Experiment 3	0.64	

Experimental data 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?

Why is this important? This simple measurement allows us to determine whether photons really can be measured once and only once, because 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 we shine the lasers onto, 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 1980's 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 experiments that are truly quantum. 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!