Single and Entangled Photons

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Abstract: This essay introduces the fundamentals and applications of single and entangled photons. Quantum computing, quantum cryptography and modern communications rely on single photon technologies and their entanglement.
Introduction to Single Photon Sources

A single photon source can be defined as a light source that produces photons that are separated in time. This emission of photons separated in time is also known as photon antibunching. To produce single photons, a coherent laser beam is tightly focused into a sample area containing a very low concentration of emitters, so that only one emitter becomes exited, resulting in the emission of only one photon at a time [1]. Attenuating a laser beam by using filters (attenuators) to only achieve one photon per meter is possible but this is not antibunching. The attenuated laser light is a coherent light and it will contain doublets and triplets of photons making it a bunched source. Photon antibunching is expressed by the value of the second-order correlation function $g^{(2)} = \langle I(\tau)I(t+\tau)\rangle / \langle I(\tau)\rangle \langle I(t+\tau)\rangle$, where $I(\tau)$ is the light intensity, $\tau$ and $t+\tau$ are time intervals and $\langle \rangle$ is the time averaging [2]. For antibunched light $g^{(2)}(0) < 1$ and ideally $g^{(2)}(0) = 0$ & $g^{(2)}_{\text{max}}(t) = 1$, while for bunched light $g^{(2)}(0) > 1$ & $g^{(2)}(0) > g^{(2)}(t)$.

Types of Single Emitters

Multiple materials can be used to behave as single photon emitters such as: quantum dots, nano-diamonds and dye molecules. Quantum dots are nanoparticles of semiconductor materials that have unique electrical and optical properties. When excited, the quantum dots emit photons with their bandwidth as a function of their size allowing scientists to choose the emission spectrum of the frequency [3]. Due to their small size the quantum dots are subject to quantum confinement where the dots diameter is has the same order of magnitude as the wavelength of its electron wavefunction. Quantum confinement also allows for the quantum dots to show the property of fluorescence, where the quantum dot becomes a single photon source and emits various wavelengths based of the size of the dot [3].

Nano-diamonds are another material that can be used as an emitter for single photon sources. Color centers in nano-diamonds are prominent candidates to generate and manipulate quantum states of light, as they are a photostable solid-state source of single photons at room temperature and a very stable molecular configuration [4]. As color centers are spatially separated in a rigid diamond structure and exhibit sufficient brightness, they can be addressed individually by an
excitation laser. Out of more than 500 color centers only 10 have been identified as bright, stable single photon emitters that have demonstrated antibunching characteristics [4].

Dye molecules can also be used in single photon sources. Planar-aligned nematic liquid crystal hosts deterministically align the single dye molecules which produce deterministically polarized single (antibunched) photons [5].

Applications of Single Photon Sources
Single photon sources will revolutionize information data processing with their usage in quantum computing and quantum cryptography [6]. Information is a key component in many fields including: finance, military, media and industry, and with the advancements in technology the integrity and security of this information has become a pressing issue. Encrypted information has been developed since ancient times but became a more complex field during World War I&II and continued to become even more complex in the 21st century. But this complexity and security achieved in time could be compromised due to quantum computing, were the information could be easily deciphered. In quantum computing polarizations states represent either “0” or “1” in the binary code [6]. Quantum computers are capable of simultaneously performing multiple calculations and to be more specific if a quantum computer has n qubits it is possible to perform $2^n$ calculations at the same time, introducing the possibility of factorizing very big numbers. The computational capacity of quantum computing would make obsolete all the current electronic encrypting methods. In order to overcome this problem, researchers have been working on quantum cryptography as a secure way to transmit encrypted information [3]. Quantum key distribution (QKD) uses quantum mechanics to guarantee secure communication and in order to achieve this it uses single photons to transmit the information. It allows two parties to produce, using single photon source, a random secret key known only to the two parties making it possible to encrypt and decrypt the information. This unique ability makes it possible for the two communicating parties to detect any third party that tries to compromise the information [7].
Entangled Photon Source – Christopher Marsh

Introduction
Entanglement is the relationship between particles and their characteristics. If one particle has a characteristic you instantly know the other entangled particle has a certain characteristic. A coin for example has two faces, in this case the faces represent the two particles, and the characteristics are heads or tails. If the coin lands on heads you know the other surface of the coin contains tails. Entanglement differs from this in the fact that one cannot know if the coin is going to be heads or tails until actually observing the coin. A type of particle that could be entangled is an electron. When electrons are entangled, the characteristic that is changed is their spin. If one were to take one electron and move it to the opposite side of the earth and measured its spin we would instantly know the spin of the other electron because they are entangled. In the optics realm photons are the particles that can be entangled through their polarization angles.

Entanglement is a phenomena of quantum mechanics. One way to show particle doesn’t obey classical mechanics but rather quantum mechanics is to have it violate Bell’s Inequality. This inequality is a classical relation, when violated it shows that the particle is obeying quantum mechanical law. This paper shall explore a type of generation of entangled photons and how to prove these photons are entangled through Bell’s inequality.

Generation
Generation of entangled photons are achieved through spontaneous parametric down conversion. This is achieved by using a laser source and two identical Beta Barium Borate (BBO) crystals (one rotated from the other by 90 degrees). When the incident beam hits a crystal it shall be converted into two photons. These daughter photons are called signal photons and idler photons. We would like the magnitude of the angle of these emitted photons to be equal, the photons that satisfy this condition have a wavelength that is twice of the incident beam. This is shown in Figure 1.

![Figure 1](image)

*Figure 1 – This figure represents the spontaneous parametric down conversion of an incident photon into its signal and idler daughter photons as well as the change in polarization. [1]*
Figure 1 also shows that the BBO crystal on the left produces vertically polarized idler and signal photons from a horizontally polarized incident beam. The BBO crystal on the right is rotated 90 degrees from the one on the left and produces horizontally polarized idler and signal photons from a vertically polarized beam. The efficiency of the spontaneous parametric down conversion process is very small, around $10^{-10}$, we need to use a high-power laser e.g. a laser diode or a 100 mW, continuous wave, ion-argon laser beam source as used in Dr. Lukishova’s report [2]. Using a narrowband interference filter (10 nm), we select the specific photons that have twice the wavelength of the incident photons. If we make the incident beam polarized by 45 degrees it can be polarized by either BBO crystal, making the signal and idler photons entangled. There will be two cones of photons, one from each crystal. One cone with horizontal polarization and one vertical as shown in Figure 2.

![Diagram of BBO crystals producing cones of photons](image)

*Figure 2 – This figure represents the cones of signal and idler photons produced by the BBO crystals, and the slight displacement because of the thickness of the crystals. [1]*

We see that the two BBO crystals produce two distinct cones that do not overlap completely. This due to the BBO crystals having a width, this can be compensated using a quartz plate. When the two cones are superimposed one the photons are no longer polarized, however they are still entangled.

**Testing**

Testing the entanglement of photons is relatively simple due to the entanglement property being the polarization of the photons. One test is done by putting polarizers on the signal beam path and the idler beam path as shown in Figure 3. The photons are detected by a pair of single photon counting avalanche photodiodes (APD). There will be a maximum of coincidence counts when the polarizers are oriented at the same angle, this maximum can only occur if the photons are entangled.
One can mathematically calculate the quantum phenomena of entanglement using Bell’s Inequality. When the inequality is violated it means that the system is obeying quantum mechanical law, as opposed to classical law. The maximum possible value of \( S \) in Bell’s Inequality is always less than \(|2|\), for any classical correlation. Getting a value greater than \(|2|\) for \( S \) would confirm the violation of this inequality. The largest values of \( S \) are confirmed when taking 16 measurements of coincidence counts when the polarizers are at various angles. The polarizer angles needed and Bell’s inequality is demonstrated in Equation 1.

\[
S = E(a, b) - E(a, b') + E(a', b) + E(a', b')
\]

\[
E(\alpha, \beta) = \frac{N(\alpha, \beta) + N(\alpha_{\perp}, \beta_{\perp}) - N(\alpha, \beta_{\perp}) - N(\alpha_{\perp}, \beta)}{N(\alpha, \beta) + N(\alpha_{\perp}, \beta_{\perp}) + N(\alpha, \beta_{\perp}) + N(\alpha_{\perp}, \beta)}
\]

Equation 1 – Bell’N(\(\alpha, \beta\)) is the coincidence count of polarizer A at \(a\) degrees and polarizer B at \(\beta\) degrees. [1]

Application
An application for quantum entanglement is information security. Through conventional signal processes anyone can detect a signal, copy it, and send the signal onward to its original destination without the receiving party knowing. By using entangled photons as signals we can have better security. A hacker interfering with the signal will show receiving parties that the signal was compromised. This technique
can be used for many practices ranging from satellite communication, as shown in Figure 4, to terrestrial bank security; we see that security insurance is needed for the future.

With the increase of the popularity of the internet we see how important single photons and photonic entanglement shall become in the future. The applications listed were for mainly organizations and business however this security can be useful for civilians as we see more examples of the NSA employees [9] overstepping their rights. Security insurance will lead to a new age of true confidentiality, and it is being led by optics.
Reference


