Foundations of Quantum Physics: An Exploration and Development of A Second-Order Coherence $g^{(2)}(\tau)$ Function Demonstrator

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US Fulbright Marshall STEM Award 2019-20 Final Report

August 2020

Abstract

I will be exploring the background knowledge and necessary setup for building a quantum demonstration setup. This demonstration can be used in future Universität Wien Physics Bachelor level praktikum lab projects. For this project, I learned how to assemble a SPDC single photon source and detect entangled single photons, align optical mirrors for optimized photon counts, how to beamwalk, and properly set up optical elements on a table-top breadboard. From this I worked with Dr. Nikolai Kiesel and Dr. Philip Walther to develop and design a second order correlation coherence out of a Hanbury-Brown-Twiss interferometer with a picosecond resolving time-tagger. The experiment is to be used by students as a part of the Quantum Physics group's bachelor praktikum.

Contents

1 Background

1.1 History of Quantum Physics

With the advent of quantum mechanics in the early 20th century by Albert Einstein, Max Planck and other physicists of the time, a radically different basis for assessing the universe was born. Quantum physics asserts the proposition that on the smallest scale of matter and energy, information is probabilistic instead of deterministic. This is a radically different view from classical physics, which depends on deterministic methods to calculate relevant information.

1.1.1 Black-body radiation problem and the photo-electric effect

Classical physics, often also known as "Newtonian" physics based off of the mathematician and physicist Isaac Newton from the 17th century, is characterized by deterministic methods and calculations. Together with Newton's Laws of Motion, one can determine an object's position and velocity and future path. Newtonian classical mechanics dominated physics for over the next 200 years, with Lord Kelvin famously saying by the end of the 19th century, "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."[3] However, this is not to discredit the advancements made in thermodynamics, statistical mechanics, classical mechanics, and the basis of most analytical physics; much which is still used today for most industrial and engineering purposes. Classical physics along with Newton's Laws of Motion are still widely used and accurate for most real-world applications. It is important to note that classical mechanics holds up well for calculations of matter and energy that are much greater than the atomic level.

By the mid 19th century, there began to be some observed inconsistencies in classical predictions vs. observations. The black-body radiation problem is the observation of when a material undergoes thermal electromagnetic radiation, and changes colour as a result of radiation. A good example of this effect is the coils of an electric stove, which go from black to orange to (hopefully, in this context never observed) white hot. Classical physics predicts the so called "Ultraviolet catastrophe", where the more energy put into the material, the higher the energy is output; infinite, in theory.[1] However, the observed material shows a non-linear output radiation that deviates from this theory.

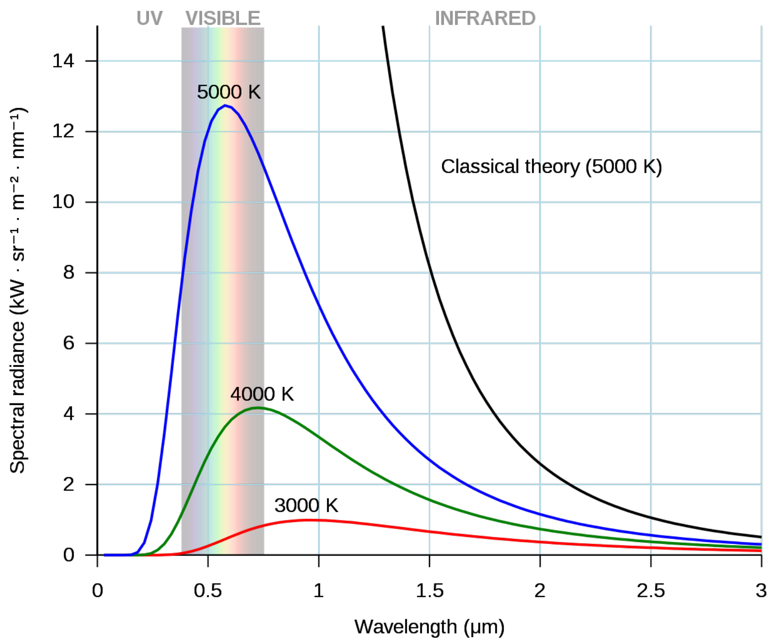


Figure 1: Black-body radiation curves, note classical theory (black curve) predicts the "ultraviolet catastrophe" deviant from the observed radiation. Source: Wikimedia Commons

In 1900, Max Planck offered a solution to this problem. By assuming energy is discretized, and referring to this smallest discrete amount of energy as h the Planck unit, it was possible to see the black-body radiation curves to converge with higher energy. Below is the formula "Planck's Law" for blackbody radiation.

$$I(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

Planck's assumption about the discretization of light was the beginning of our understanding of photons–discrete packets of energy, traveling through space and time.

In 1905, Einstein (his so called "miracle year"–the most prolific year of his career) published a paper[2] hypothesizing an explanation for the photo electric effect via the quantum nature of photons. The photo-electric effect was another puzzling observation that a material (such as a thin sheet of gold) needs a certain amount of energy bombarding the material before releasing an amount of light. Einstein's idea was that these "thresholds" of energy were directly related to the quantization of energy within photons. By 1914, Einstein's theory was confirmed by Robert Millikan's oil-drop experiment, an elegant demonstration of the quantized energy effect on a moving drop of oil between charged metal plates.[4]

1.1.2 Schrödinger's Equation

Einstein's paper brought forth a flurry of activity within the physics community, with many responses to this radical interpretation of energy and matter. In 1925, Erwin Schrödinger formulated a system of equations, known as his wave equations, that describes the propagation of energy on the smallest quantized level. While a full mathematical explanation of the wave equations are beyond the scope of this paper, the most simplified version of the equation is the Time-dependent Schrödinger Wave Equation, which describes the evolution of the wave through time.

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = \hat{H}\Psi(\mathbf{r},t)$$

In these equations, we consider Ψ as the wave function, and holds the information about the "state" of the wave system.[6] What is particularly interesting about Schrödinger's wave equations is the wave function collapse once an observation is made about the system. This is in part the duality of light, as it propagates as a wave but collapses to a particle once enough information is observed about the system. The mechanism of "collapse" stems from the orthogonal basis from which the wave function is represented by, a combination of eigenstates and eigenvalues. [7] The non-intuitive "reality" of quantum mechanics was deeply disruptive to the scientific community, and even Einstein rejected a non-local interpretation of quantum mechanics. In a famous disagreement with Max Born, a scientist who hypothesized that the inherent probability of events happening within quantum mechanical regimes were completely random, Einstein is attributed to retorting, "God doesn't play dice".

Figure 2: The author poses with the bust of Schrödinger and his eponymous equation in the Universität Wien Arkadenhof.

1.1.3 Heisenberg Uncertainty Principle

Classical mechanics is a deterministic set of equations that make it possible to predict the location and energy (kinetic, potential, etc) of the system simultaneously. The set of Newton's Laws of Motion fundamentally shape that process. However, when on such a small level (atomic), that assumption on longer holds. The Uncertainty Principle, that one can know either position (x) or momentum (p), is one of the most colloquially known effects of quantum mechanics (perhaps only after Schrödinger's Cat).

$$\Delta x \Delta p \geq \hbar/2$$

The Uncertainty Principle is non-intuitive with relationship to the physical world mainly because the underlying reason for it is non-intuitive: a "pure" mathematical concept. Heisenberg did not discover this confusing relationship between location and momentum on an accident, the reason for the Uncertainty Principle is due to the fact that momentum and position are conjugate variables and are formed from the canonical commutation relation.[5]

The Uncertainty Principle actually applies to all wave-like systems, but is not observable on the macroscopic scale. The change in momentum multiplied with the change in position must be on a similar order as the Planck constant; for most classical systems this effect is not observed.

1.2 Applications of Quantum Mechanics

1.2.1 Lasers

One of the biggest breakthroughs in the field of optics came with the invention of the laser in 1960. The technology behind the laser exploits the intrinsic nature of light emissions and energy levels. The most fundamentally different attribute of lasers (Light Amplification by Stimulated Emission of Radiation) as opposed to any other light source occuring in the natural world is that it is a coherent source. Coherence does not mean that the light wavelengths are "similar enough", it means they are, by the laws of physics, identical.

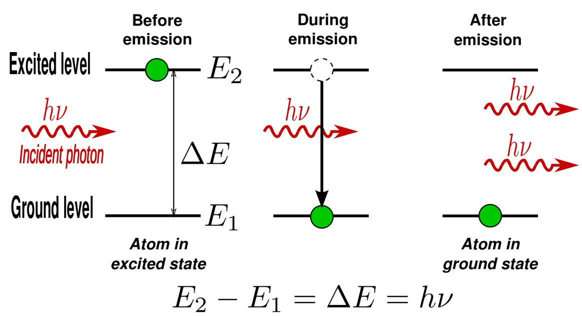


Figure 3: Basic principle how lasers function with stimulated emission. Source:CC BY-SA 4.0

The process of stimulated emission works fundamentally with an energy emission exchange. If the photon is energetic enough, it can "bump" an electron up an orbital and be absorbed by the system. Likewise, an electron can "drop" an energy level and emit a wavelength of light in a process known as spontaneous emission. However, of the photon is exactly matching in energy as the electron in the orbital, it creates a stimulated photon that is exactly alike.

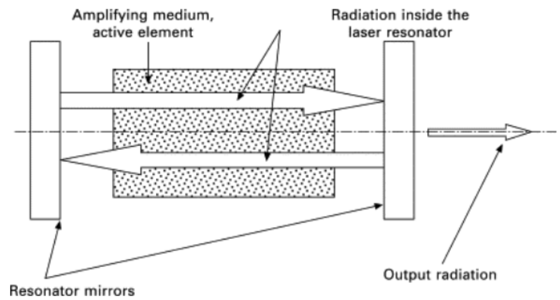


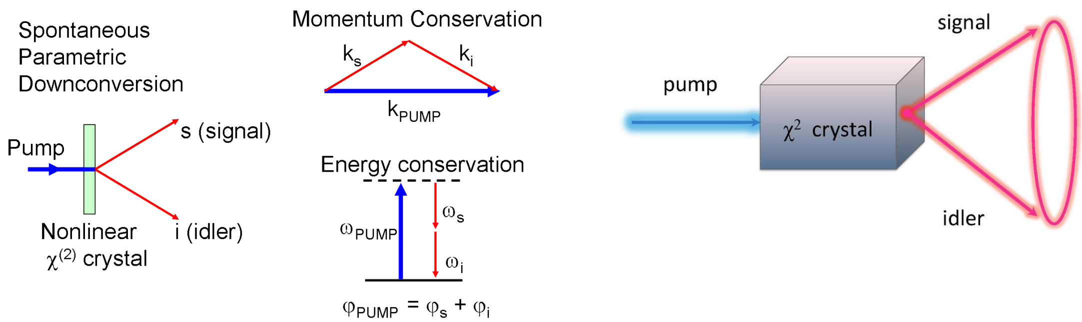
Figure 4: Schematic of laser cavity. Source:N.N. Il'ichev, in Handbook of Solid-State Lasers, 2013

Lasers function by the principle of stimulated emission within an optical cavity. The basic idea is to 1) Create stimulated emission within some medium within an optical cavity 2) the stimulated emission bounces around between the 2 mirrors within the optical cavity, stimulating more emissions from the medium until 3) the light is output as a fully coherent light source.[8] The medium for the stimulated emission can be gas, dye, solid-state crystal(ruby, YAG, etc) and more. Laser pointers, ubiquitous in classrooms and lectures as a pointer, are often made from a solid state doped crystal that are now quite inexpensive to produce.

Lasers are arguably the biggest technological invention from the 20th century, and it is impossible not to interface with some kind of laser technology within daily life. Lasers are used from telecommunication satellites, machining on large scale to microscopic levels, medical procedures, barcode scanning, optical disk drive information transfer, and of course the broad spectrum of uses to experimentally create experiments that test the foundations of quantum physics.

1.2.2 Spontaneous Parametric Down Conversion Sources

In most experiments of quantum photonics and studies of foundations in quantum physics require a single photon source to witness quantum entanglement. Spontaneous Parametric Down Conversion (SPDC) is a process in which an incoming beam of light can be split into photon pairs that are identical (indistinguishable), and lower energy than the incident beam. The photon pairs are generated within a crystal, typically a BBO (beta-barium borate) material due to some interesting effects from its refractive properties.[20] However, BBO SPDC sources are typically not very efficient at



(a) SPDC process

(b) SPDC light cone example

Figure 5: Source: J.S. Lundeen, CC BY-SA 3.0

creating indistinguishable photon pairs, and are typically only used in setups used for demonstration purposes. SPDC is very useful for experimental demonstrations of entangled photons, and what locality can do in those contexts. SPDC is the main effect in the CHSH Bell Inequality Violation, which tests the non-locality of quantum mechanics. [20]

1.2.3 Quantum computing and encryption

In the past few decades, the possibility of vastly accelerating computer processing via quantum mechanics seems evident. Classical computing consists of bits, which can either be in a state of 1 or 0. However, quantum bits, known as qubits, use the power of quantum entanglement and can be in a state of 1, 0, or a combination of the two via the property of superposition. This means that more information can be stored in a qubit than a classical bit.

Creating a qubit can be done a few different ways, for example the solid-state matter route, or by quantum photonics. Quantum photonics look promising because it is less susceptible to the thermal noise from solid-state materials, and can piggy-back off of existing industries to create optical chips (e.g, CMOS).

An advantage that quantum computing offers over classical is the concept of a ”quantum speedup". This speedup is not guaranteed for every algorithm, but for a select few it appears that quantum computing can handle polynomial speedup. [9] Shor's algorithm is a polynomial speed algorithm and can solve prime factorization, while classical computers are still restricted to super polynomial time.

One of the most interesting applications of quantum mechanics is the possibility of a fully encrypted information transfer. The security in the transmission is not simply "very secure", but it is fundamentally secure by the laws of physics and quantum mechanics.[10] Due to the Heisenberg Uncertainty Principle, there is only a certain amount of information that can be known about a system, otherwise the wave function will collapse. The implications of this are that if a data transfer is compromised, the sender and the recipient will be alerted of the hacking as the state of the system will change.

2 An Introduction to Foundations of Quantum Photonics: Quantum Photonics Master's Praktikum

As a part of the preparation into the Walther group at Universitat Wien, I took a Master's level praktikum course with the intention of working through several "foundation" experiments in quantum physics. This was completed with my lab partner Michael Becker, a Masters in Physics Candidate at Universität Wien.

2.1 The Hong Ou Mandel Effect

2.1.1 Introduction

The Hong-Ou-Mandel Effect was discovered in 1987 by the physicists Chung Ki Hong, Zhe Yu Ou, and Leonard Mandel at the University of Rochester. The Hong-Ou-Mandel Effect is a direct observation of the quantum nature of photons, and how entanglement directly affects indistinguishability.

The experiment consists of 2 photons entering a 50:50 beam-splitter. Detectors 1 & 2 detect four possible outcomes: a) Photon 1 & 2 both emerge at Detector 1; b) Photon 1 &2 emerge at

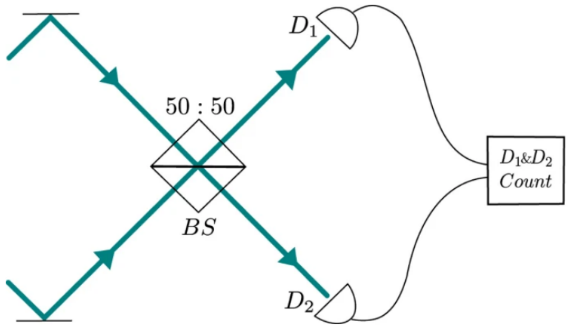


Figure 6: Schematic of the Hong-Ou-Mandel experiment. 2 photons enter 50:50 beamsplitter, detected at either/or Detector 1 and Detector 2. Source: Ralley, K., Lerner, I. & Yurkevich; Nature 2015

Detector 1; c) Photon 1 emerges at Detector 1 and Photon 2 at Detector 2; d) Photon 1 emerges at Detector 2 and Photon 2 at Detector 1. [16]

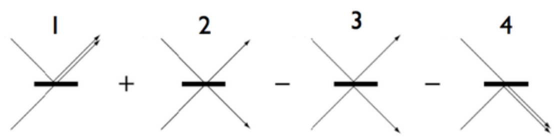


Figure 7: 4 possible outcomes from the Hong-Ou-Mandel experiment. Source: Wikimedia Commons

When the 2 photons arrive at the beam splitter they are subject to quantum entanglement in the form of state mixing. The more "indistinguishable", or the more similar they are in terms of polarization, momentum, etc; the more likely they will "merge", as a result of interference, and be both be detected at Detector 1 or 2. The more "distinguishable" the 2 photons become, the more likely they will be seen at both Detector 1 and 2.

The Hong-Ou-Mandel Effect is also known as a 2 photon NOON state, which is a multi-photon entangled state. In fact, the HOM effect is the "simplest" NOON state, since it is only 2 photons, and can be deterministic. A NOON state is "two possible paths and N photons in one path and 0 in the other—the system being a superposition of “all and nothing” states." [11] NOON state are interesting because of their quantum properties. While on this microscopic of a level, the physical world is probabilistic, in NOON states, the probability of the final state which an N-body system

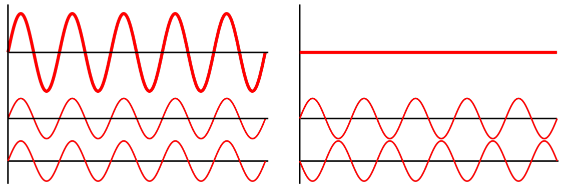


Figure 8: Simple visualization of classical wave interference; (left) is constructive interference, (right) is destructive interference Source: Wikimedia Commons

is "more deterministic" due to the careful selection of entangled outcomes. In the case of the HOM effect, determinism is possible, but N¿3 proves to be probabilistic. The interesting applications of NOON states begin with larger N-body systems, with the promise of higher optical resolution in quantum metrology regimes.[12]

2.1.2 Methods

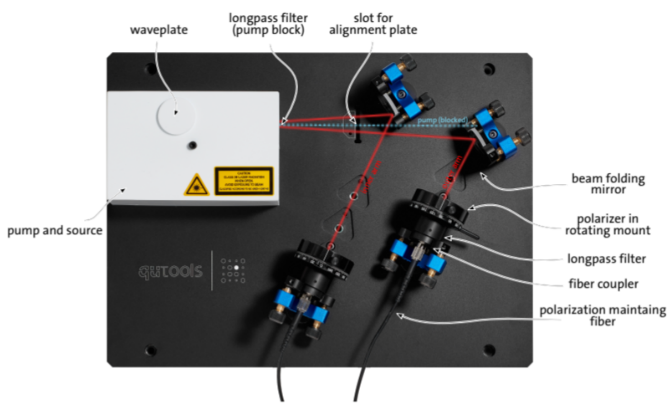


Figure 9: The qutools quED entangled photon source setup. Source: qutools.com

This praktikum lab we used the quED setup from the qutools quantum educational company, who create demonstration equipment for entangled photons, fiber optics, and single photon sources. The quED module consists of: 1) fiber-coupled polarization-entangled photon pairs 2) Two silicon single photon avalanche detectors 3) Alignment help utilities including auxiliary low-power visible laser module 4) Four-channel counter with integrated coincidence logic unit 5)Control and read-out unit. The control main box is the quCR unit, which the quED is connected to via optic fiber. Then the qutools Hong-Ou-Mandel setup is connected to the quED.

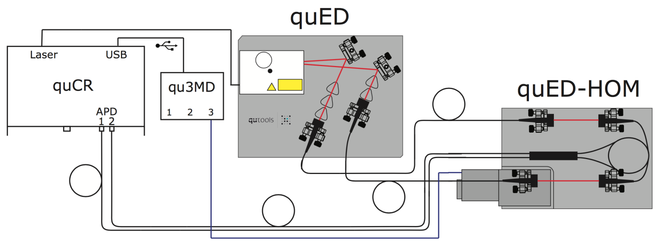


Figure 10: The qutools quED setup for the entangled photons + HOM addon. Source: qutools.com

Each of the quED outputs is connected to one of the inputs of the quED-HOM. We remove the wave plate from the pump beam of the quED, so that we generate indistinguishable non-entangled photon pairs. Now, we can introduce a temporal delay between the two photons by moving one of the fibre collimators in the quED-HOM. This makes the two photons distinguishable (one could say, one photon arrives at the beam splitter "earlier than the other"). We use this to demonstrate the so-called Hong-Ou-Mandel dip in coincidence counts, by tuning the delay between the two photons. [13]

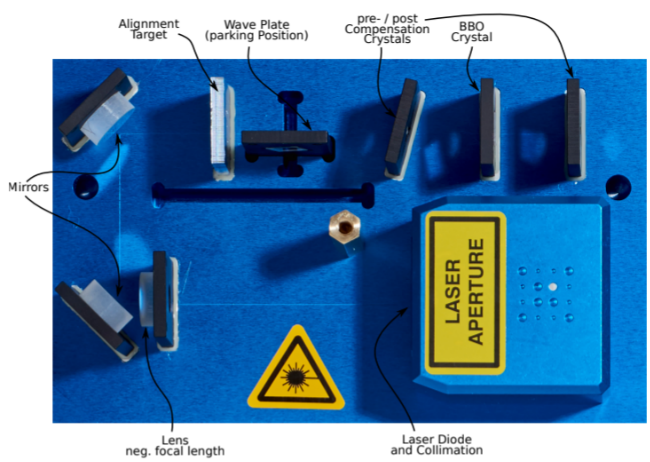


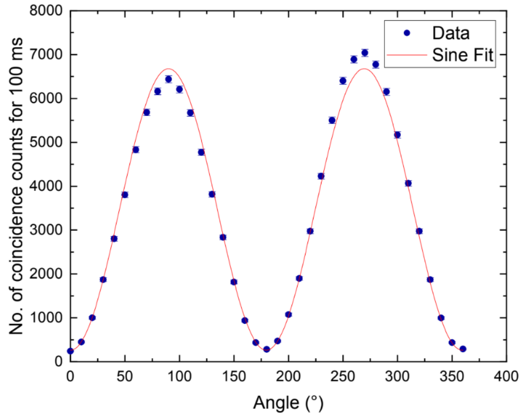
Figure 11: quED "entangled photon" source. Setup uses SPDC (spontaneous parametric down conversion) source with BBO crystal. Source: qutools.com

Our first step was to make sure we were detecting entangled photons with the quED setup.

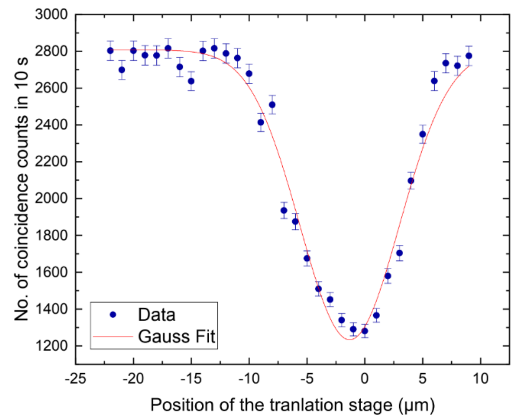
The quED was connected to the quCR via fiber optic cables, and the current on the laser set to I=39.4±1 mA. We then checked that we were seeing enough coincidence counts approximately 10% of the single photon counts. We optimized this number by adjusting the fine-tune screws on the mounts of the mirrors in a process known as "beam walking". Once we received a satisfactory coincidence count rate, we placed the polarizers in front of the detectors on the quED setup. We set the polarizers to H(orizontal)/V(ertical) and the +/- basis and documented the number of counts as a function of changing polarizer angle. Doing so allows us to calculate "how entangled" our setup is. If there is only a small change of coincidence counts, that means that our setup has a low level of entanglement, and if there is a significant percentage increase/decrease within the polarization change, then our system has high entanglement. If the entanglement is low then you know to either realign your setup and check fiber optic cable connections. In our case, we had to exchange one of our fiber optic cables as it was too "noisy".

After we are satisfied with how entangled our system is, we move on to connecting the HOM add-on to the quED. We attach another series of fiber optic cables between the HOM and the quED setup, so that the HOM is using the same entangled photons. At this point we had to make very certain that the fiber optic cable connections were secure and that all the photon counts we were observing on the quCR were not due to a bad cable connection, as detecting the Hong-Ou-Mandel Effect can be hard to determine otherwise.

At this point, the search for the Hong-Ou-Mandel Effect begins. The quED-HOM setup is simply 2 photon source (from the quED) and 2 detectors, but one is on a translation stage. In this case, we will expect to see an interference effect happen when the 2 photon sources become indistinguishable. Indistinguishability occurs when the photons interacting have identical polarizations, momentum, etc. In this case, we will see the HOM interference effect when the arms of the interferometer (path distance of 2 photon sources) are exactly equal and the photon sources are incident to the detectors at the exact same time. In our case, the exact location on the translation stage was hidden, so that we would have to find it and keep alert for any signal fluctuation. However, this was a very long process, and took me and my lab partner close to 2 hours to find, (and we were one of the lucky groups). This time was spent adjusting the micro-meter translation stage and checking the



(a) Visibility curves in H/V basis



(b) Hong-Ou-Mandel "dip" observed with the quED-HOM

Figure 12: Source: M. Becker and K. Sheldon, Praktikum "Hong-Ou-Mandel Interference and Quantum State Tomography"

coincidence counts on the quCR looking for a "dip", or a drop in counts over a specified interval.

2.1.3 Results

The Hong-Ou-Mandel lab had an order of requisite steps: 1) To set up an entangled photon system 2) Determine that system was at a satisfactory level of entanglement 3) Find the HOM dip with the quED-HOM add-on.

For determining the entanglement of our system, we calculated the visibility curves from the H/V and +/- basis function, which was determined with the polarizers in the quED.

The visibility here is a calculation of

$$V = (N_{max} - N_{min})/(N_{max} + N_{min})$$

We found our visibility for H/V basis = 92.42±0.46% [16] and our visibility for +/- basis = 88.16±0.64%.

The Hong-Ou-Mandel "dip" we observed confirmed our hypothesis that we were able to construct and observe an entangled photon interference effect.

2.2 Bell's Inequality Test

2.2.1 Introduction

While the discovery of quantum mechanics rocked the scientific community, there were still many questions raised about how quantum mechanics described reality. Notably, how quantum mechanics dictates reality through entangled systems. In 1935, a paper was published by Einstein, Podolsky, and Rosen from the Institute of Advanced Study in Princeton, New Jersey. The paper, titled "Can Quantum-Mechanical Description of Reality Be Considered Complete?" become colloquially known as the Einstein-Podolsky-Rosen (EPR) Paradox. The EPR paradox suggested that the Heisenberg Uncertainty Principle can be "violated" by two particles that interact at some point. The paradox also asserts the viewpoint that physical reality cannot be fully explained by quantum mechanics as it would thusly be subject to non-locality. [21] Non-locality at this point in history was considered to be "spooky action at a distance", that is, with unsavory implications that quantum mechanical information could move faster than the speed of light and alter reality in a way that violates space-time. Einstein himself questioned whether quantum mechanics could fully explain "reality", and with Podolsky and Rosen created a thought experiment where two particles interact, then separate. The mathematics showed that it would be possible to find the momentum and position of both Particle A and Particle B, which violates the Heisenberg Uncertainty Principle. By this thought experiment; Einstein, Podolsky, and Rosen argued that quantum mechanics is "incomplete" and does not fully represent physical reality as local hidden variables are required to keep quantum mechanics consistent.

The crux of the paradox turned out to be with how locality is defined. Nearly 30 years later, in 1964, John Bell published a paper "On the Einstein-Podolsky-Rosen Paradox" where he raised doubt about the way the EPR paradox handled the correlation between Particle A and Particle B. Mainly, by testing the "hidden variable" theory under the conditions in what is known as a "Bell Inequality". He was able to prove that the 2 photon system from the EPR paradox is consistent with a non-local nature of the quantum mechanical system. [17] Bell's rebuttal was able to address the "incompleteness" issue that the EPR paradox raised about quantum mechanics for nearly 3 decades. By constructing a framework of mathematical systems, it became possible to see if the Bell test experiment either tests "reality" or "locality"; the Bell's Inequality shows that only one of those assumptions can hold true.

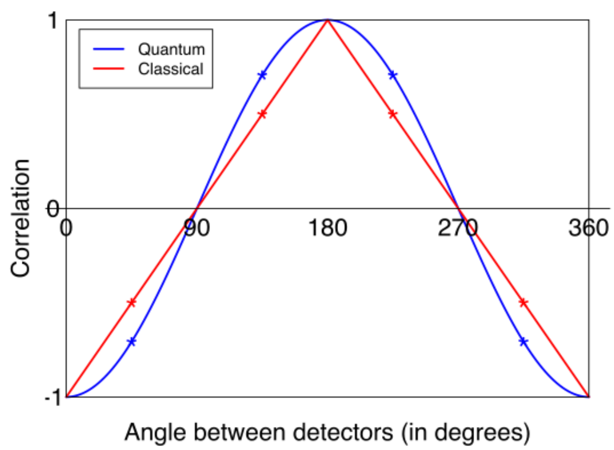


Figure 13: Quantum model vs. Classical: how the correlation in a "singlet" state (pair of particles with net momentum = 0) with respect to changing polarization in the CHSH Bell Inequality test. Source: Wikimedia Commons

For this "Bell Theorem Test" we used the CHSH Inequality test (short for the physicists John Clauser, Michael Horne, Abner Shimony, and Richard Holt). The experiment uses a SPDC (spontaneous parametric down conversion) source to create the paired singlet state, which are then guided through a system of polarizers and waveguides to the photon detectors, where the correlation function is calculated with respect to the polarizer degree orientation.

2.2.2 Methods

Creating the CHSH Bell Test Inequality for this part of the Master's Praktikum course was more challenging; because in essence we were recreating the pre-fixed setup from the qutools quED (see figure from HOM experiment) module from scratch. The reason we built the Bell Test from

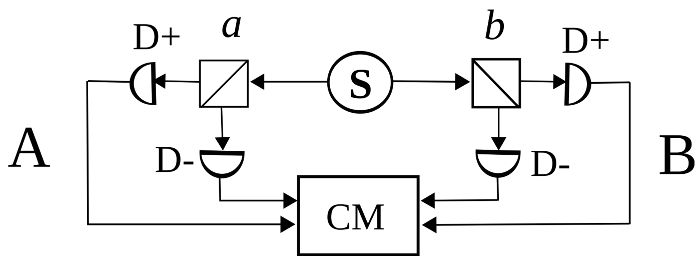


Figure 14: Standard experimental setup for a Bell CHSH Inequality test experiment. Source: Wikimedia Commons

individual optics components instead of with the qutools quED module was mainly to give ourselves the experience of a "real" optics benchwork experiment. If we were to start with the qutools quED module the work required to witness a Bell violation would be trivial.

Materials needed: 1) Mirrors for guiding laser path 2) Pinhole laser beam tool 3) Beam block, for blocking the laser path when not detecting 4) Lens, for focusing the beam 5) BBO (4mm) for the down conversion source 6) Translation stage 7) Prism mirror 8) Laser pointers, for aligning system 9) BBO (2mm) 10) Narrow bandwidth filter 11) Longpass filter 12) Coupler 13) Single mode fiber 14) Photon detector 15) Power Supply 16) Coincidence logic 17) Photon counter

For this lab we had a whole week to complete it, but it was a lengthy multi-step process. Firstly we had to create a laser beam path from the source and reflect it via 2 mirrors at 90 degree angles, and use the pinhole measurement tool to make sure the laser beam (at low power, for safety reasons during alignment) was properly guided through the BBO crystal. A BBO crystal is a material often used as a SPDC source (see Background section), and care had to be done to make sure that the beam was properly focused through the crystal without any "back reflection". This was done by checking for back scattered light behind the lenses.[14]

As a part of the broader alignment process, we used backwards alignment to get the setup optimized for detecting single photons, using the laser pointers plugged into the optic fibers (for easier visibility). Coupling the single photon source took longer, because generally each time we added a new component we would have to check with the pinhole to make sure that the beam was still positioned correctly, as oftentimes perturbations made from screwing in components on the

Figure 15: Required elements for the CHSH Bell Inequality test. Source: Valeria Saggio, "Experimental Violation of Bell Inequality"

breadboard base could sometimes cause things to shift. The 2 prism mirrors were placed between the translation stage and the beam block, and care was taken to ensure that the mirrors were properly reflecting the single photons from the BBO into the coupler.[14]

Once the BBO and prism mirrors were fixed onto the breadboard, the polarizers were set between the coupler and the prism mirror. At this point we had to make sure we had roughly the same number of counts in the H and V basis, which was to ensure that we would have sufficient visibility to witness the Bell's Inequality violation. We then measured the photons in HV to make sure we saw a maximum of photon coincidences, and then to HH and VV to see the minimum. In this way we were able to find the visibility. The same procedure was done for the +- basis, and the ++ and - -. During this process we often found it necessary to realign and finetune the focus for the BBO and the couplers until we were satisfied with the visibility of our setup.

2.2.3 Results and Conclusions

We calculated our visibility with the same sine fit as we did in the Hong-Ou-Mandel lab, and our uncertainty bars came from $1/\sqrt{N}$, the Poisson noise statistic.

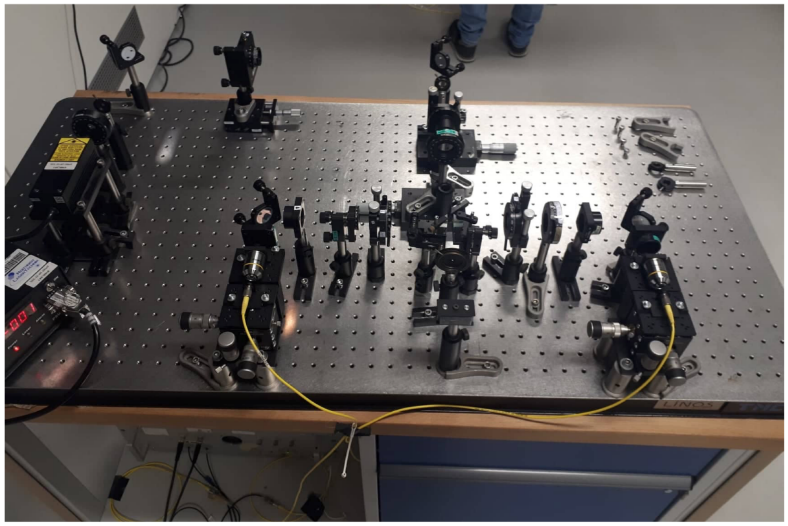


Figure 16: Completed CHSH Bell setup. Source: Valeria Saggio, "Experimental Violation of Bell Inequality"

The visibility in our HV basis matched the sine fit with a value of

$$V = 92.54 \pm 0.98\%$$

The +- basis visibility curve fit the sine function slightly less well than the HV basis, with a visibility of:

$$V = 65.15 \pm 0.02\%$$

We figure this may be coming from a slight asymmetry in the light cones from the SPDC source. See figure for visualization of SPDC light cone. [20]

However, we decided the visibility curves were sufficient enough that a Bell Inequality violation could be witnessed from our setup. The polarizer 1 was set to: 0, 45, 90, 135; and polarizer 2 set to 22.5, 67.5, 112.5, 157.5.

We calculated the expectation value for the angle values with this equation:

$$E = \frac{N(\alpha,\beta) - N(\alpha,\beta\perp) - N(\alpha,\beta\perp) + N(\alpha\perp,\beta)}{N(\alpha,\beta) + N(\alpha\perp,\beta\perp) + N(\alpha,\beta\perp) + N(\alpha\perp,\beta)}$$

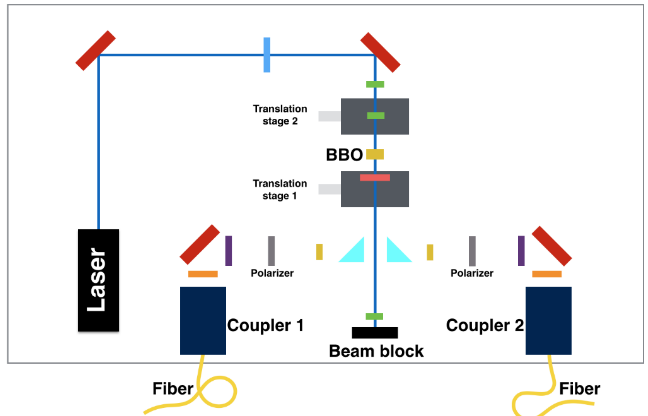
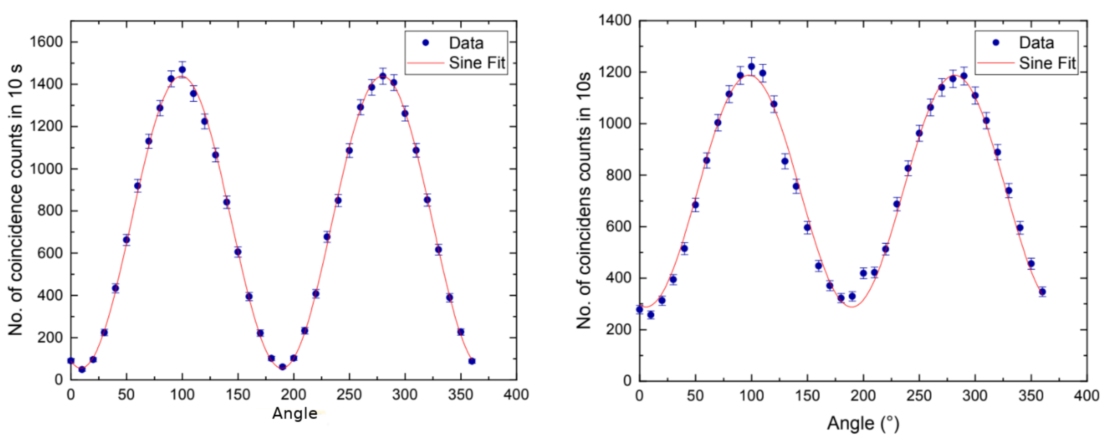


Figure 17: Completed CHSH Bell setup, graphic. Note: we could only fit 1 translation stage onto our breadboard. Source: Valeria Saggio, "Experimental Violation of Bell Inequality"



(a) The calculated HV visbility

(b) Calculated +- visibility

Figure 18: Source: M. Becker and K. Sheldon, "Experimental Violation of Bell Inequality"

Our calculated values for the expectation values for $E(\alpha, \beta) = 0.752 \pm 0.012$, $E(\alpha, \beta\prime) = 0.451 \pm 0.016$, $E(\alpha\prime, \beta) = 0.362 \pm 0.019$,$E(\alpha\prime, \beta\prime) = 0.520 \pm 0.016$

To satisfy the Bell Inequality violation we have to witness a total value of the 4 expectation values to be $E(\alpha, \beta) + E(\alpha\prime, \beta) + E(\alpha, \beta\prime) + E(\alpha\prime, \beta\prime) > 2$.

Our total value is $S = 2.086 \pm 0.032$. Our S value is likely closer to 2 because of the lower

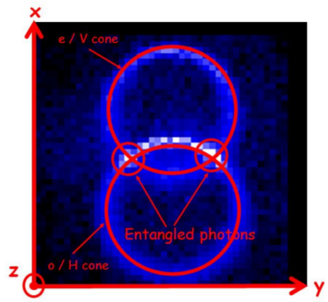


Figure 19: SPDC light cone. Source: Couteau, "Spontaneous Parametric Down Conversion"

	$\alpha = 0°$	$\alpha' = 45°$	$\alpha_{\perp} = 90°$	$\alpha'_{\perp} = 135°$
$\beta = 22.5°$	138.6	919.1	1263	427.5
$\beta' = 67.5°$	965.6	1022	424.1	344.6
$\beta_{\perp} = 112.5°$	1247	381.4	216.6	807.1
$\beta'_{\perp} = 157.5°$	390,5	324.2	1189	1100

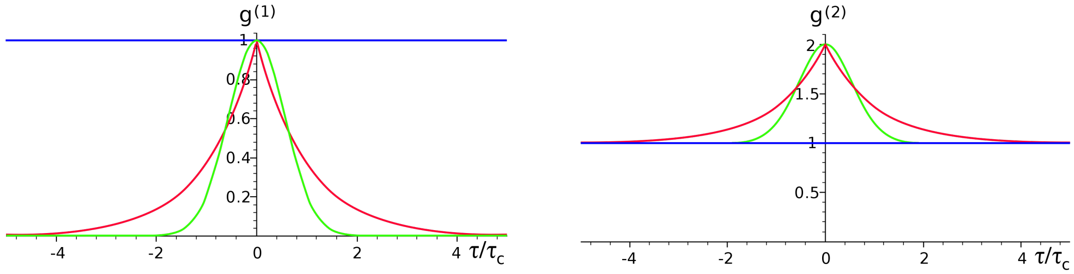
Figure 20: Coincidence counts for polarizer 1 and polarizer 2 angle values. Source: M. Becker and K. Sheldon, "Experimental Violation of Bell Inequality"

visibility in the +- basis, but nonetheless is statistically significant and violates the Bell Inequality.

3 Developing the $g^{(2)}(\tau)$ Quantum Demonstrator

3.0.1 Motivation

The University of Vienna Physics Department has a Bachelor praktikum every year with the purpose of giving bachelor candidates in physics the opportunity to learn and set up foundational quantum physics experiments. With Prof. Dr. Nikolai Kiesel and Mario Ciampini (PhD candidate), I worked with editing curriculum for the bachelor level course. With Dr. Kiesel and Dr. Walther, we also discussed creating another demonstration for the bachelor students to setup and observe for further understanding into the foundations of quantum photonics.



(a) the g(1) first order coherence function

(b) the g(2) second order coherence function

Figure 21: a plot of g(2) as a function of the delay normalized to the coherence length τ/τ c. The blue curve is for a coherent state (an ideal laser or a single frequency). The red curve is for Lorentzian chaotic light (e.g. collision broadened). The green curve is for Gaussian chaotic light (e.g. Doppler broadened. Source: Ajbura, Wikimedia Commons

3.0.2 Background to Second-Order Coherence Function

Light can be in various forms of coherence: coherent (laser) or incoherent (thermal). The difference between coherent and incoherent light sources is profound, and one of the best mathematical ways to distinguish between the two is with the second order correlation function.[19] τ represents $t1 - t2$, the time delay from which the light source evolves. The first order correlation function describes how the light source changes over time, another way of understanding how the coherence of a light source behaves.

$$g^1(\tau) = \frac{< E(t)E(t+\tau) >}{< E(t)^2 >}$$

For the first order coherence function, this time delay can be directly attributed to path length differences between 2 arms of an interferometer such as the Michelson. In this interferometric setup, interference fringes from the light source can be viewed, and the wavelength of the light deduced.

The second order correlation function notes how the intensity of the light source changes over time. A thermal light source will have a different decay time than a laser, and a collision broadened source.

$$g^2(\tau) = \frac{< I(t)I(t+\tau) >}{< I(t)^2 >}$$

The form that is especially important to photonics is the $g^2(0)$, which is the form that essentially is the number of photon counts at an infinitesimal time interval after t.[18] For a bunched light source, $g^2(0) > 1$, for a coherent (laser) light source $g^2(0) = 1$, and antibunched light $g^2(0) < 1$.

3.0.3 Developing and assembling optic elements

The demonstration is intended for use for the quantum photonic's group bachelor student praktikum. So while familiarization with optic elements is an important aspect of the course, we chose to use pre- or partially assembled systems from the qutools company. For the second order coherence function, we chose to use the quED module in addition to a Hanbury-Brown-Twiss interferometer setup. However, to properly resolve the $g^{(2)}(\tau)$ function, our setup has to have a very "fast" resolving time and would require a time-tagger. A time tagger is a module that can "tag" the time that an incoming photon arrives at the detector to a very precise degree. A precise resolution is especially important for giving the single photon coincidence rates a certain amount of accuracy that is needed for resolving the $g^{(2)}(\tau)$ function curve. The qutools website specs sheet for the quED-HBT gave a time coincidence window of $t_c = 30ns$, but we decided that it would give too high of an uncertainty for the $g^{(2)}(\tau)$ curve, after Poisson noise statistics would be taken into account. What this would mean is that collecting data from the lab may take students long data collection times, and not ideal in a praktikum that covers multiple experiments over a few-day period.

After a consultation with a representative from qutools to discuss our options, we considered the following time-taggers from qutools: the quTAG (1 picosec resolution), the quTAU (81 picosec resolution), and the quTAU(H+) (81 picosec resolution, and some more user defined options). The representative advised us to use the quTAU, as the quTAG was likely too excessive for our needs.

4 COVID-19 and Future Work

4.0.1 COVID-19

The COVID-19 global pandemic was a completely unexpected but sobering event that effectively preemptively concluded last 3 months of my grant period, which was when I was just gearing up to start work in the lab to test and develop a project which would be the culmination of my quantum photonics preparation at the University of Vienna. Due to regulations from the University of Vienna, the Ministry of Education and the Austrian government, my lab was effectively closed from March 12, 2020. I was unable to access my lab to assemble and produce a working setup, and was unable to see my project to fruition.

However, I believe that this project is a useful and very educational project for a Master or advanced Bachelor student to work on, which would yield excellent results for future Bachelor praktikum students to engage and learn about the foundations of quantum physics and optics.

4.0.2 Future Work

Whether it be myself or another student, I hope that this $g^{(2)}(\tau)$ demonstrator will able to be made. Current second order correlation function experiments lab protocols exist, one is included in the qutools quED-HBT manual as an exercise, but they tend to only be for the case of t=0 $g^{(2)}(0)$. While an informative way to explore the fundamental mathematical foundations behind the nature of light and coherent light sources, it does not give the student a chance to resolve the coherence correlation as a function of time. What remains for the project is as follows: 1) To assemble optic elements such as the quED, the HBT add-on, and the qutools quTAG time tagger 2) Test the feasibility of the time resolution times with Poisson noise statistics within the time-frame of a bachelor praktikum 3) Do a full test run of the experiment 4) Write protocol for praktikum.

4.0.3 Acknowledgements

I would like to thank the US Fulbright Foundation and the Austrian Marshall Plan Foundation for funding my fellowship this year to live and research in Austria. I would also like to thank my advisors, Dr. Philip Walther, Dr. Nikolai Kiesel, for their assistance and support in developing my project, and to the Giulia Rubino and Mario Ciampini, PhD candidates, for their assistance in answering questions about quantum photonics. Lastly, I would like to thank the other members of my Fulbright cohort 2019-20 for the friendship, community, and solidarity; and particularly to Darrah Lustig and the Fulbright Austria commission for all their unwavering support and guidance through uncertain times. Vielen Dank!

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