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The Hong–Ou–Mandel interferometer in the undergraduate laboratory

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Abstract

The Hong–Ou–Mandel interferometer is an optical device that allows us to prove the quantum nature of light experimentally via the quantum amplitude superposition of two indistinguishable photons. We have implemented this experiment as an advanced undergraduate laboratory experience. We were able to overcome well-known difficulties using techniques reported recently by Thomas *et al* (2009 *Rev. Sci. Instrum.* **80** 036101).

(Some figures may appear in colour only in the online journal)

1. Introduction

Recent advances in quantum information have led to a revival of quantum mechanics and its application in new technologies such as cryptogtraphy, teleportation and computation. New demonstrations with single photons have led to an appreciation of the fundamental properties of quantum mechanics and single-photon experiments are now included in quantum mechanics instruction. A series of these experiments developed for the undergraduate laboratory has successfully emphasized these fundamentals through direct experimentation. Experiments such as proof for the existence of the photon [1], the quantum eraser [2] and quantum non-realism and nonlocality [3] deliver results that embody almost 100 years of discussion on the quantum nature of fundamental particles and light.

This paper presents the implementation of a landmark experiment in quantum optics in the undergraduate laboratory: the Hong–Ou–Mandel (HOM) interference experiment [4]. Many preceding investigations (see Pfleegor and Mandel [5–8]) aimed to show how Dirac's statement [9] about the quantum origin of interference is valid. This says that a photon can interfere only with itself, but two different photons do not produce interference. It is now known that interference of single photons exists [10], and it can be proven even in an undergraduate laboratory [2]. However, Pfleegor and Mandel showed that two photons from different sources

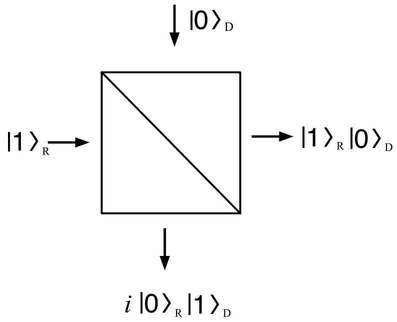

Figure 1. The possible outcomes when an individual photon is incident on a beam splitter. If the beam splitter is 50 : 50, then the probability of the photon being transmitted or reflected is 50%.

can still interfere. The HOM experiment shows that the interference of two photons occurs when they are indistinguishable. Moreover, there is a subtlety that is worth emphasizing: two photons do not interfere in a classical way, but rather it is the quantum mechanical amplitudes for finding them that interfere.

We used this experiment in the context of our graduate and advanced undergraduate quantum optics courses. At the graduate level, it represents one of the possible special projects on a compulsory course (Laboratorio Avanzado) within the Master's degree program, where the student not only treats fundamental quantum principles in an experiment, but also manipulates apparatuses and uses more sophisticated devices and technologies.

This paper is divided into three sections. The first section gives a theoretical description of quantum interference for two photons in a 50 : 50 beam splitter, in particular we indicate that it is dangerous to say that interference occurs 'between' two photons, because it leads to the misconception that in classical interferometers photons would interfere with each other and not with themselves. The second section discusses the experiment and the final section discusses the results and how we used the experiment in the curriculum.

2. Quantum description of a beam splitter and the interference of two photons

We begin by considering a single-photon incident on a 50–50 beam splitter. If initially one photon travels to the right but not 'down', i.e. coming from above in figure 1, it can be described in the photon number representation by the Fock state, or photon occupation state:

$$|\psi_i\rangle = |1\rangle_R |0\rangle_D, \tag{1}$$

where the subindices R and D refer to the mode of the light traveling to the right and down, respectively. In this problem the mode of the light where none is traveling 'down' may appear trivial or unnecessary, but the use of the 'vacuum' state $|0\rangle_D$ is an integral part of the quantized radiation field formalism. After the beam splitter, the quantum state of the light is in a superposition of traveling in two directions

$$|\psi_f\rangle = \frac{1}{\sqrt{2}}(|1\rangle_R |0\rangle_D + i|0\rangle_R |1\rangle_D), \tag{2}$$

A phase of $\pi/2$ is introduced in the state of the reflected light as is necessary to conserve energy [15]. From equation (2) the photon entering has a 50% probability of being transmitted, and a 50% probability of being reflected. If a detector is placed at each of the exits the

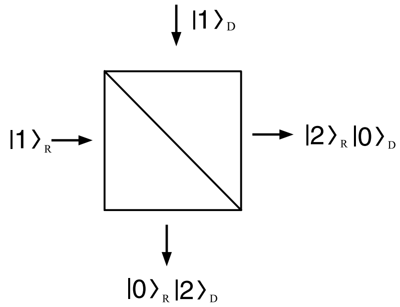

Figure 2. Two indistinguishable photons entering the beam splitter at the same time.

wavefunction collapses and there will be an anticorrelation, which means that either the photon is detected on transmission or the photon is detected on reflection [2, 10–12]. That a photon is in a superposition state of two states is mathematically simple but physically hard to explain to a beginning student. We can also say that the state of the photon is uncertain but balanced because it is equally possible to detect the photon coming out either way. Feynman is particularly insightful in his explanations of this superposition [13].

We have used the more intuitive Shrödinger picture to explain this phenomenon to the beginning student. A more rigorous and commonly used method in quantum optics uses the Heisenberg representation, photon-number creation and anihilation operators [14]. We will continue with our intuitive approach for the next case.

Let us now turn to the case of two photons entering the beam splitter from two separate ports, as shown in figure 2. A critical element of this case is the indistinguishability of the paths taken by the two photons. The pump photon produces two photons that can arrive at the detectors in two possible ways. The indistinguishability of the possibilities makes the quantum mechanical amplitudes interfere.

The state of the light can be represented by $|1\rangle_R|1\rangle_D$. After the beam splitter the state of the light is obtained by applying the beam splitter action to each occupied mode, and the state vector results, $|\psi_f\rangle$:

$$\frac{1}{2}(|1\rangle_R|0\rangle_D + i|0\rangle_R|1\rangle_D)\ (|1\rangle_D|0\rangle_R + i|0\rangle_D|1\rangle_R) \tag{3}$$

$$= \frac{i}{2}(|2\rangle_R|0\rangle_D + |0\rangle_R|2\rangle_D), \tag{4}$$

where we have made the condensation $|1\rangle_R|1\rangle_R = |2\rangle_R$, and similarly for D. The terms with $|1\rangle_R|1\rangle_D$ cancel out when the paths are indistinguishable. Thus, the interference is destructive. Experimentally, if we put detectors at the two output ports of the interferometer we would not get any coincidences because of the destructive interference. Conversely, when the photons arrive at distinguishable times the paths are distinguishable, and so the light is in an incoherent sum of two photons, each incident on the beam splitter, as in the single-photon case. That situation would lead to no interference and photons heading to the two detectors (and hence, coincidences) half of the time.

3. Experiment

The HOM experiment consists of generating a pair of photons and making them converge onto the input ports of a beam splitter. Detectors placed at the output ports of the beam splitter detect coincidences. When the photons are indistinguishable no coincidences are recorded. The photons for the experiment come from a single source: photon pairs produced simultaneously by spontaneous parametric down conversion (SPDC). In order for the photons to be indistinguishable, they have to arrive at the beam splitter at the same time within the coherence time of the light, and be in the same polarization, spatial and momentum modes. The HOM experiment itself is notoriously difficult to recreate, especially in a teaching, non-research setting because of the challenge of making the momentum modes of the photons overlap. That is, the photons after the beam splitter must be collinear. As a consequence, alignment is difficult and tedious. Our efforts benefited from a recent paper that explains a simple way to reach the required alignment [16]. The arrangement also includes a way to vary the time delay between the two photons, so to shift from the case when they are distinguishable to the case when they are indistinguishable. When the latter is achieved one observes a drop in the coincidences, the famous 'HOM dip'. The light is collected by lens collimators attached to multimode fibers, which send the photons to avalanche photo diode (APD) single-photon detectors.

The HOM interferometer (HOMI) has three fundamental parts: the source of the pairs of photons, an interferometer and a photon detection system. The interferometer has a dual use: it is used as an interferometer (HOMI) in the experiments, and as a Mach–Zehnder interferometer (MZI) for the alignment of the optics.

The SPDC source used in the experiment is a type I beta–barium–borate (BBO) crystal, pumped by a 25 mW violet laser with a 405 nm wavelength. SPDC requires conservation of energy and momentum inside the crystal

$$\hbar\omega_p = \hbar\omega_1 + \hbar\omega_2, \tag{5}$$

and

$$\hbar\mathbf{k}_p = \hbar\mathbf{k}_1 + \hbar\mathbf{k}_2. \tag{6}$$

It is very important for the experiment that the laser beam be parallel to the optical table so that the pair of photons is detected in the same horizontal plane. This type of source produces pairs of individual photons with the same polarization and which follow symmetric trajectories about the pump laser beam direction, hereafter called the symmetry axis. In the degenerate case ($\omega_1 = \omega_2$), the two photons come out of the crystal at the same angle $\theta = \cos^{-1}(\mathbf{k}_p \cdot \mathbf{k}_i/(k_p k_i)$, $i = 1, 2$, but on opposite sides of the symmetry axis.

The second important part of the interferometer is the alignment of the two photons through the HOMI with the aid of the MZI. The procedure is described in the next steps. First, we have to identify the angle of the photons, which in this case is 5° from the symmetry axis. To do this, we use the simple procedure for alignment described in [3]. This method is based on mounting the fiber collimators on two rails that pivot just below the nonlinear crystal. This way the collimators always face the crystal as the rail is moved. The rail positions are adjusted roughly to obtain the maximum number of individual photon counts at the detectors. A fine adjustment is made by maximizing the number of coincidences between the two detectors. Once this alignment is complete we know the optimal paths of the down-converted photon pairs. The next step is to define these paths by placing two irises on each path, as shown in figure 3.

This is used so the trajectories of the photons can be followed by a visible laser that sets the mirrors of the HOMI. The initial hardware design should allow the swapping of the nonlinear crystal with a beam splitter. The latter serves as the first beam splitter of the MZI, for use with the visible laser. The positions of the crystal and the beam splitter should be the same, and we should be able to swap both of them without introducing any major misalignment. In our setup we used a vertical translation stage to displace the crystal upwards, and a horizontal

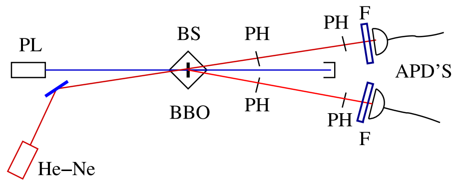

Figure 3. Schematic of the procedure used to define the trajectories of the individual photons using pinholes. Afterward, the helium–neon (He–Ne) laser will follow these trajectories using a beam splitter to simplify the alignment. Pump laser: PL; beam splitter: BS; interference filter at 810 nm: F; and pinhole: PH.

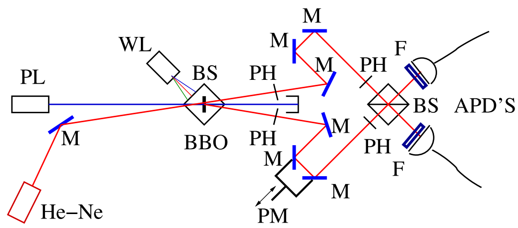

Figure 4. The figure shows the complete alignment where the He–Ne laser helps to align the trajectories that the photons should follow. The use of the mirrors (M) helps to modify the difference in optical path using a stepper-motor (PM). A second beam splitter is placed where the beams intersect to generate the superposition and complete the IMZ interferometer. The balance of the optical path is made by using the interference produced from a white light (WL).

translation stage to displace the beam splitter. The beam splitter was positioned such that the visible laser passed through both sets of irises and thus simulated the trajectories of the two down-converted photons. The alignment was complete when the visible light incident to the collimators fully came out from the ends of the attached fibers. This was of course done with the fibers disconnected from the APD detectors, with the power to the latter switched off.

Once the visible laser is aligned to follow the trajectories of the down-converted photons the collimators and fibers can be removed to set up the hardware for the interferometer. In this setup each trajectory is to be steered by three mirrors. The mirrors are placed such that two of them are mounted in a trombone configuration, on top of a translation stage, as shown in figure 4. This allows the variation of the length of one of the paths (lower in the figure) without altering the alignment. The six mirrors must be placed so that the paths mirror each other about the symmetry axis. The second beam splitter is to be placed at the intersection of the two beams. It must be able to rotate and translate in the horizontal plane so that the reflected beam and transmitted trajectories fully overlap. After the second beam splitter is in position the MZI interferometer should be ready for the next stage of the alignment.

The first step in the alignment is achieved by observing the interference fringes produced by the visible laser going through the MZI. The visible laser we used was a He–Ne. The interference pattern is easy to see because of the long coherence length of the He–Ne laser beam. The alignment should proceed so that the interference fringes are thick. After this is achieved, the next step involves equalizing the two optical paths with the trombone mirror pair. We made this adjustment by driving the stage with a stepper-motor. It is important to use another source of light that has a very short coherence length. In our case we used light from a white fluorescent source, which had a coherence length of a few micrometers. The interferometer path length should then be adjusted carefully until a white-light (WL) interference pattern

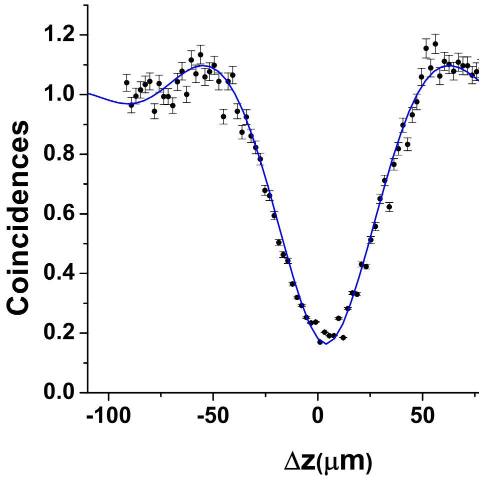

Figure 5. Normalized coincidences versus displacement in optical path (Δz). Each pace produced by the motor modifies the optical path by $2\,\mu$m. The average coincidence count rate outside the zone of interference is around 30^{-1}.

emerges. It is important to note that the observation of a WL interference pattern implies that the difference in optical path is near zero. We note that for the interferometer to be aligned both the WL fringes and the thick guide laser fringes must be present.

After the alignment is complete the fiber collimators are placed in the trajectories of the two beams after the second beam splitter. Finally, the last step is to replace the first beam splitter with the nonlinear crystal, converting the MZI into a HOMI.

In the third stage of our experiment the individual photons went through a wide band filter (810 ± 10 nm) before entering the collimators connected to the APDs by an optical fiber. The detectors generated square pulses that were 25 ns long and 3.5 V in height. These were then sent into a photon counting board. This board can detect coincidences between four inputs [17] within a delay interval that can be adjusted to between 30 to 2500 ns. Before taking any data, the collectors should be aligned as before, so there is a maximum number of counts of individual photons. If the system has been aligned correctly, then the number of coincidences per second in a 30 ns window should be very small. This is because of the destructive HOM interference. If the optical path difference (Δz) is changed by moving the stepper-motor-driven stage, the paths may no longer interfere and the coincidence count will grow. There should be a minimum of coincidence counts when the destructive interference is taking place. The individual photon counts should be almost constant because the number of interfering photons is very small and is only altered by the pairs of photons that interfere. Figure 5 shows the behavior of the photon coincidences at the output ports of the beam splitter. The average count rate of coincidences far from the interference zone is 30 s^{-1}. A Gaussian function multiplied by a sinc function was fitted to the experimental data. The fitting function depends on the bandwidth of the down-converted photons and the difference in optical path [18].

4. Discussion and conclusion

The HOM dip measures the coincidences of photons that come out of the beam splitter. The minimum number of coincidences illustrates the destructive interference of quantum mechanical amplitudes. This interference is not the same as the single-photon, due to the indistinguishability of paths taken by a single photon. This interference is due to the indistinguishability of the paths taken by two photons that are incident on a beam splitter. At this point the two photons travel the same distance between the crystal that generated them and the beam splitter. They enter the beam splitter at right angles, so that after the beam splitter it is not possible to know which way they arrived at the detectors. Interference disappears (i.e. the number of coincidences increases) when the difference in optical path is changed, making the paths distinguishable. For this set of experimental parameters the width of the dip is related to the coherence length of the down-converted photons, which in our case is 40 μm. This compares well with our measurement: 45 $\mu\text{m} \pm 2\,\mu$m.

The HOM interference is one of a broader class of cases involving the interference of two photons. The photons of the pair, sometimes referred to as 'biphotons', can produce constructive interference [19–21] and may depend of a richer variety of paths in which the two photons interfere, where single-photons paths are distinguishable but two-photon paths are not [2, 22, 23].

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Appendix

Here we list the major components used in the experiment, together with their prices and manufacturers. First, the chief optical components.

(1) *Pump laser*. This must satisfy these minimum specifications: the bandwidth must be less than 1 nm, with a beam divergence of less than 0.6×0.3 mrad. Edmund Optics model NT59-562 is a violet laser (405 nm) with an output power of 25 mW; $2, 550.00 USD. A laser with these characteristics can be assembled at an updated cost [1].

(2) *Downconversion crystal*. Nonlinear crystals can be acquired from NewLight Photonics. A crystal with $5 \times 5 \times 2\ \text{mm}^3$, $\theta = 30^\circ$, mounted in a anodized ring costs $499.00 USD.

(3) *Photodetection*. Detectors with high quantum efficiency are of central importance. Two avalanche photodiodes manufactured by Perkin Elmer cost approximately $9000 USD. At almost the same price, Perkin Elmer offers a quartet of these photo-detectors; however, it is necessary to use an associated power supply. Although these detectors are relatively expensive, the use of, for example, lower cost photomultiplier tubes ($400 USD, each) makes our experiment a very complicated enterprise.

(4) *Counting electronics*. Photon counting coincidences can be improved using an ALTERA educational FPGA board DE2 costing $269 USD, with a home made adapter ($50 USD) for sending the signals to the FPGA [1].

(5) *Optics and optical components*. Some of the fundamental components used in this experiments are: two cube non-polarizing beamsplitters 50 : 50, 700–1100 nm, Thorlabs model BS017, $184.60 USD each; seven broadband dielectric mirrors, 750–1100 nm, Thorlabs model BB05-E03,$50.00 USD each; two bandpass filters, Thorlabs model FB810–10, centered at 810 nm, $84.67 USD each; two optical fibers from PACER, opaque jacket with termination FC 62.5 μm, set with four fibers, $600.00 USD each; two

fiber optic collimator lenses FC, Edmund Optics model NT47-225, $150.00 USD each; a white light source, a common white LED.

(6) *Alignment components*. In order to displace one mirror we use a stepper motor (ORIEL 20010) with an interface, but it is possible to use a home-made stepper motor, along with a precision-drive mechanism, properly programmed with commercial software ($250 USD).
The alignment laser used was a 633 nm He–Ne laser from Thorlabs, $800.00 USD. The pinhole used within the alignments process was constructed from black plastic and a fine needle. The mount for this pinhole was made from an aluminum ring, machined as an internal screw.

The experiment was completed using an optical table, though we did not use its dynamical isolation system and an optical breadboard would be sufficient. Other mechanical components of this experiment were realized from home-made parts; for example, the mount used to displace the nonlinear crystal. It is also necessary to use standard optical components, many of them to be found in a typical optics laboratory: posts, mirrors, beamsplitters, etc.

References

[1] Beck M Modern undergraduate quantum mechanics experiments http://marcus.whitman.edu/beckmk/QM/
[2] Galvez E J, Holbrow C H, Pysher M J, Martin J W, Courtemanche N, Heilig L and Spencer J 2005 Interference with correlated photons: five quantum mechanics experiments for undergraduates *Am. J. Phys.* **73** 127–40
[3] Dehlinger D and Mitchell M W 2002 Entangled photons, nonlocality, and Bell inequalities in the undergraduate laboratory *Am. J. Phys.* **70** 903–10
[4] Hong C K, Ou Z Y and Mandel L 1987 *Phys. Rev. Lett.* **59** 2044
[5] Magyar G and Mandel L 1963 *Nature* **198** 255
[6] Pfleegor R L and Mandel L 1967 *Phys. Lett.* A **24** 766
[7] Pfleegor R L and Mandel L 1967 *Phys. Rev.* **159** 1084
[8] Pfleegor R L and Mandel L 1968 *J. Opt. Soc. Am.* **58** 946
[9] Dirac P A M 1930 *The Principles of Quantum Mechanics* 1st edn (Oxford: Clarendon)
[10] Grangier P, Roger G and Aspect A 1986 *Europhys. Lett.* **1** 173–9
[11] Thorn J J, Neel M S, Donato V W, Bergreen G S, Davies R E and Beck M 2004 Observing the quantum behavior of light in an undergraduate laboratory *Am. J. Phys.* **72** 1210–19
[12] Alerigi D S R 2009 La naturaleza cuántica de la luz: anticorrelación experimental *Tesis de Licenciatura* Facultad de Ciencias—UNAM
[13] Feynman R P 1994 *Lectures on Physics* vol 3 (New York: Academic)
[14] Gerry C C and Night P L 2005 *Introductory Quantum Optics* (Cambridge: Cambridge University Press)
[15] Holbrow C H, Galvez E J and Parks M E 2002 Photon quantum mechanics and beam splitters *Am. J. Phys.* **70** 260–5
[16] Thomas P J, Cheung J Y, Chunnilall C J and Dunn M H 2009 The Homg-ou-Mandel intergerometer: a new procedure for alignement *Rev. Sci. Instrum.* **80** 036101
[17] Vergara S and Vargas A 2011 private communication
[18] Jeff Ou Z Y 2006 *Multi-Photon Quantum Interference* (Berlin: Springer)
[19] Mandel L and Wolf E 1995 *Optical Coherence and Quantum Optics* (Cambridge: Cambridge University Press)
[20] Scully M O and Zubairy M S 1997 *Quantum Optics* (Cambridge: Cambridge University Press)
[21] Kwiat P G, Steinberg A M and Chiao R Y 1992 Observation of a 'quantum eraser': a revival of coherence in a two-photon interference experiment *Phys. Rev.* A **45** 7729
[22] Franson J D 1989 Bell inequality for position and time *Phys. Rev. Lett.* **62** 2205–8
[23] Pittman T B, Strekalov D V, Migdall A, Rubin M H, Sergienko A V and Shih Y H 1996 Can two-photon interference be considered the interference of two photons? *Phys. Rev. Lett.* **77** 1917–20