Single photon quantum mechanics for undergraduates

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Undergraduate quantum mechanics curricula don't often utilize laboratory experiences to the same degree as other core phenomenological courses, and if they do have labs, they rarely deviate from historical quantum demonstrations, like the photoelectric effect or particle in a box. We implement an experimental investigation for students as a way to develop physical intuition, optical skills, and research practices in the context of cutting edge quantum phenomena that are normally inaccessible to undergraduates. This laboratory will have students utilize single photons, generated via spontaneous parametric down-conversion, to measure interference patterns using research-grade equipment, with potential extensions including concepts like quantum teleportation and quantum computation. We describe the steps taken to prepare the laboratory, as well as how we look to ensure that students are able to engage with the activity in a productive way.

Keywords: Physics education, undergraduate laboratories, single photons, interference

INTRODUCTION

NC State has several initiatives that incorporate research experiences into the classroom, of which, the Education and Research Laboratory (EaRL) is a prominent example in the physics department [1]. This includes experiments for many of the departmental offerings, including three of the qualifying courses: thermal physics, classical mechanics, and electrodynamics. Noticeably absent from this list is an experiment for the qualifying course on quantum mechanics. Quantum phenomena are notoriously unintuitive and are described by formalism that is often entirely novel for undergraduate students [2]; why then, is there not a focus on hands-on experience in this course?

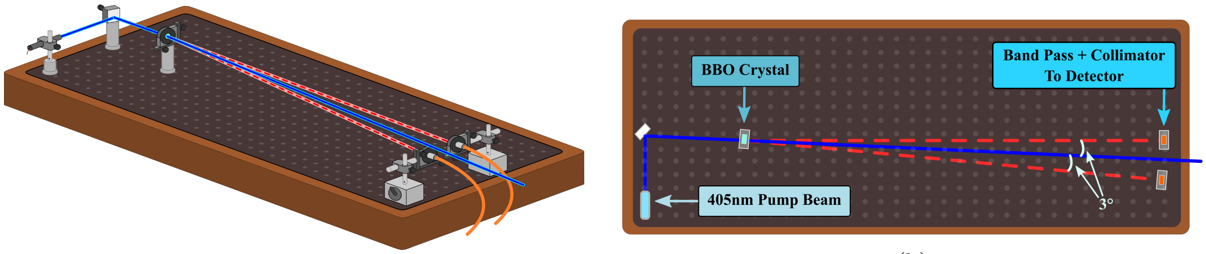
But before answering this question, it should first be established that incorporating experimental opportunities into a taught curriculum has a veritable effect on student learning. Many recent studies (e.g. Refs. [3–5]) have shown quite the opposite: that enrollment in laboratory courses has little to no effect on exam performance in introductory physics courses. However, it is still very possible that, when implemented in the *correct* way – and that stipulation is quite important – laboratory experiences can develop student perspectives and intuition on physical concepts [6]. But what is this mystical, *correct* way to implement a lab that so many curricula seem to fall short of?

The answer lies in what students are encouraged to take away from the experience. The vast majority of the aforementioned studies used exam score differentials as a metric for evaluating laboratory impact, implying that these experiences serve to teach students course concepts. Instead, when the focus of these labs is to develop experimental skills [6], confidence in one's abilities [7], or reflective behaviors [8, 9], they are very effective in attaining these goals. The constituents of a quantum mechanics course are likely well into their undergraduate career, and benefit excellently from developing these skills that often aren't covered in the classroom.

Focusing now only on quantum mechanics, there are several reasons why quantum phenomena are rarely demonstrated in a classroom setting, which tie into the complexity and depth of the subject matter that is needed for a sufficient understanding. The world of quantum mechanics is largely inaccessible without expensive equipment, precise operation, and practiced lab techniques – or at least this was the case two decades ago. Numerous initiatives have sprung up since then to lessen these obstacles, including the ongoing "Photon Quantum Mechanics" collaboration, principally backed by Galvez [10]. We implement and build off these experiments for use in our introductory quantum mechanics curriculum, looking to develop student intuition, conceptual understanding, and laboratory technique.

To simplify the complex quantum phenomena present in any real optical environment, small numbers of photons generated via spontaneous parametric down-conversion (SPDC) [11] are used in entanglement and interference experiments. In this process, the photons from a *pump* beam are incident on a non-linear optical medium, within which a given photon can spontaneously decay into two correlated photons. Even before being used in any experiment, these photons demonstrate the fundamental principles of energy and momentum conservation, as well as the lack of number conservation for light quanta.

In this letter, we describe the techniques and principles utilized to demonstrate quantum phenomena via single photons in a tangible and digestible way to undergraduate students. For a more general discussion of these experiments beyond our implementation at NC State, we defer readers to compiled works such as Galvez [10].



(a)

(b)

FIG. 1: Isometric **(a)** and bird's-eye **(b)** view of the setup used to generate and measure single photons via parametric down-conversion within a non-linear BBO crystal.

METHODS

Single Photon Production

We choose a β-barium borate (BBO) crystal (Newlight NCBBO5300-405(I)-HA3) as our non-linear medium [12], which is pumped by a 45 mW 405 nm GaN diode laser. We restrict our experiments to symmetric photon pairs, such that the energy, wavelength, and polarization of the generated photons are the same – known as *Type-I phase matching*:

$$E_s = E_i = \frac{1}{2}E_p \approx 1.53eV \tag{1}$$

$$\lambda_s = \lambda_i = 2\lambda p \approx 810nm \tag{2}$$

As the down-converted photons, produced via SPDC, travel through the non-linear crystal and into the air, they refract according to the photon pairs' particular wavelengths. For a wavelength of 810 nm, we can calculate the refraction angle from the known properties of BBO crystals [13] to be approximately 3°. It is for this reason that we place our detectors 3° to either side of the pump beam, shown in Fig. 1.

Single Photon Detection

A brief estimate of the number of photons included in the pump beam per second gives

$$N_p/s = (45mW)\left(\frac{1}{1.53eV}\right) \sim 10^{17}, \tag{3}$$

making them vastly more abundant than the $\sim 10^4$ down-converted photons. To accurately and reliably detect these extraordinarily outnumbered, lower energy photons, we utilize a narrow band-pass filter (Newlight NBF810-30), in conjunction with an avalanching photodetector (Excelitas SPCM-AQRH-12). This specialized detector utilizes a silicon-based SLiK plate to register photons via the photoelectric effect, functioning similarly to a photomultiplier [14]. This combination gives a photon detection resolution sufficient for our purposes, allowing us to reproducibly measure as low as 1000 photons/second.

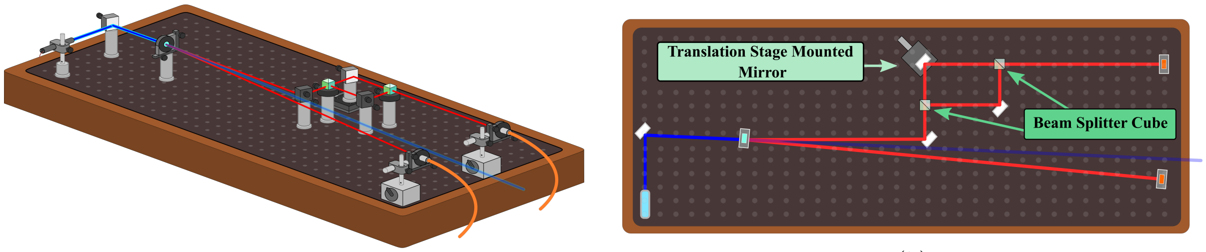
Because this device is extraordinarily sensitive, we have developed a custom power supply that only allows the detector to be activated in sufficiently dark conditions. This is done by utilizing photoresistors placed around the optical bench, controlled by an Arduino microcontroller. This device protects the detectors against accidental exposure to bright light (eg. if the door is opened while the experiment is running) which is especially important for an experiment that will be used by a large number of students.

Beam Alignment

The alignment procedures for the optics are simplified as much as possible, and we have generally found that the following order of operations is suitable (see Fig. 3a):

1. **Pump Beam Polarization:** Conservation of momentum requires that the polarization of the incident beam be aligned with crystal axis of the BBO crystal. This alignment is quite sensitive, even to changes of only a few degrees, and should be fixed first. This can be done either by introducing an optic to rotate the polarization of the pump beam, or by rotating the BBO crystal itself.
2. **Pump Beam Incidence Angle:** Again for the sake of conservation of momentum, the pump beam should be incident perpendicular to the BBO crystal (assuming it is cut along the proper axis). This can be adjusted using the pan knobs on the BBO optic holder.
3. **Collimator Pan and Tilt:** Finally, the fiber inputs should split the pump beam symmetrically by the previously calculated refraction angle of 3°. For the collimators to function properly, the incident light should be perpendicular to the face of the optic. We have found that this adjustment has the largest effect on our measured photo-signal.

In our implementation of this lab in the classroom, we expect that having students align every optic would be far too tedious, and generally would be much more susceptible to running out of time before getting any results.



(a)

(b)

FIG. 2: Isometric **(a)** and bird's-eye **(b)** view of the setup used to conduct interference experiments, implementing a Mach-Zehnder interferometer.

Students will also have varying amounts of optic experience – likely with the majority having never worked with a laser before – and so we pre-align many of the components beforehand. Having the participants only adjust the various alignment knobs on the components, we hope to get to the core lessons and takeaways of the experiment sooner, without depriving students of the opportunity to work with a laser in a realistic setting.

Interference

Having established the source of photons for the experiment, we now describe the interference component that we look to perform, for which a schematic is shown in Fig. 2. We direct one of the single photon paths into a Mach-Zehnder interferometer, where the length of one arm can be adjusted both via a micrometer translation stage (course adjustments) and a piezoelectric unit (fine adjustments). After the beam recombines at the second beam splitting cube, the light is detected by one of the avalanching photodetectors.

During the experiment proper, after having students (partially) align the beam paths, we sweep the piezo across a voltage range, causing that arm to shorten or elongate by a few microns. This is enough to see alternating constructive and destructive interference in the subsequent photons counts, as well as the coincidence counts with the other single photon detector. We expect that for advanced students, it may be reasonable to perform the proper alignment themselves, following the tractable technique described in Price [15].

RESULTS

Shown in Fig. 3a is the count of photons registered by a single avalanching photodetector as the various optics are aligned. While the incidence of the light onto the collimator has the largest impact on how many photons are detected, performing several rounds of alignment of each of these degrees of freedom is recommended. We see a maximum of more than 40000 photons/second, which is certainly sufficient for performing the planned experiments. The interference and entanglement experiments can be performed with much fewer photon counts, though having an abundance gives the students performing the experiment more room for error.

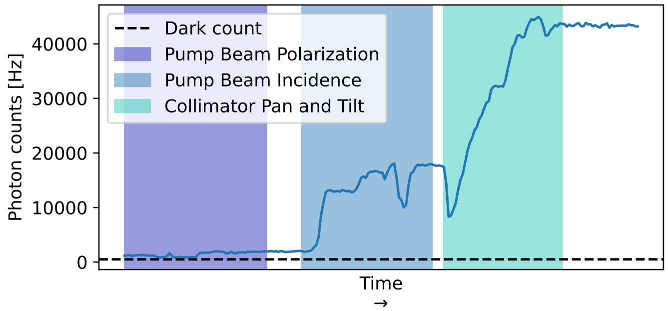
Evidence of the interferometer functionality can be seen in Fig. 3b, which shows spectrometer snapshots of a red laser beam as the relative arm length difference is decreased. When the arms are far from equal, we see the usual spectrum of the beam, but as the arms get closer in length, we begin to see ringing across wavelengths, representing alternating constructive and destructive interference. The period of this ringing indicates the difference in path length of the arms, and when the two arms are exactly equal, we will see consistent constructive or destructive interference across the entire range of visible light.

DISCUSSION

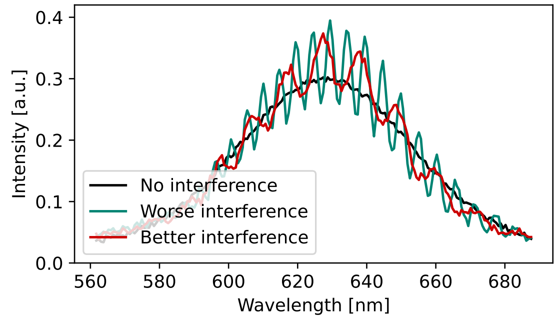
Having successfully established a single photon source, we look now to continue on implementing the interference experiment. Following this, there are several more applications of single photons, including entanglement [16, 17], quantum teleportation [18], and quantum computing [16, 19]. These topics are at the cutting edge of quantum phenomena, and tend to generate significant interest from both experts and non-experts alike. By demonstrating that these concepts are built on the exact same foundations as more traditional introductory material, we look to demystify quantum mechanics, while simultaneously teaching students practical laboratory skills.

SUMMARY AND OUTLOOK

Single photons are fantastically useful in quantum optics experiments, with possible applications including demonstrations of entanglement, quantum teleportation,



(a)



(b)

FIG. 3: **(a)** Typical photon response as the BBO crystal position and angle, as well as the collimator orientation, are adjusted. **(b)** Red alignment laser demonstrating interference as the interferometer arms approach the equal arm condition.

and quantum computing. We have detailed the NC State Physics Department's ongoing implementation of an educational laboratory experience that aims to develop research technique and physical intuition for our undergraduate quantum mechanics students. We use single photons generated through parametric down-conversion as an avenue for students to practice foundational optics techniques in the context of interference or entanglement. We have shown schematic results from the experiment, including alignment procedures for various optics, and discussed the next steps as we move towards integration into our curriculum.

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