Undergraduate Laboratories Using Correlated Photons: Experiments on the Fundamentals of Quantum Mechanics

Enrique J. Galvez, Colgate University, Hamilton, NY

Advances in several technologies have created an educational opportunity for curricular innovation in physics. Experiments with correlated photons can be used in the upper-level physics curriculum to complement the teaching of an otherwise theoretical topic: quantum mechanics. Undergraduates can now recreate, on a tabletop setup, experiments with correlated photons that not too long ago were used in research to make dramatic demonstrations of fundamental principles of quantum mechanics. Here we present the results of a project to develop a new set of laboratories with correlated photons adapted to the undergraduate setting where affordability and simplicity are primary concerns.

Introduction

Quantum mechanics has been labeled as the most successful physical theory ever invented. It has explained an unspecified number of physical situations and measurements and has never been found incorrect. But for all its effectiveness, quantum mechanics challenges our classical view of the world and hence our intuition. Superposition, the cornerstone of quantum mechanics, has some striking consequences. Feynman et al. (1) referred to it as "the only mystery" of quantum mechanics.

Consider the simplest case: a physical system with two possible states, labeled 1 and 2. These states may denote physical situations where the system has different measurable properties (e.g., energy, momentum). Measurements of a physical property of the system in each of the two states can give distinctly different results. So far, this situation may refer to one that is easy to understand with our own classical physical intuition. For example, the system could be a particle and the states could be two different paths that the particle can take in going from one place to another. Quantum superposition, however, allows a classically nonintuitive possibility: the system can be in a superposition of two states. That is, the system can be in both states 1 and 2 at the same time. There is a caveat: the system is in the superposition of two states at once as long as there is no possible way for us to tell in which state the particle could be.

At this point, let's be more specific about our system. Let the particle be a "quantum" of light, i.e., a photon. Our physical situation is the photon going through a Mach-Zehnder interferometer, shown in Figure 1. This interferometer has four elements: two beam-splitters and two mirrors. When a photon is incident on the first beam-splitter, there is a 50%

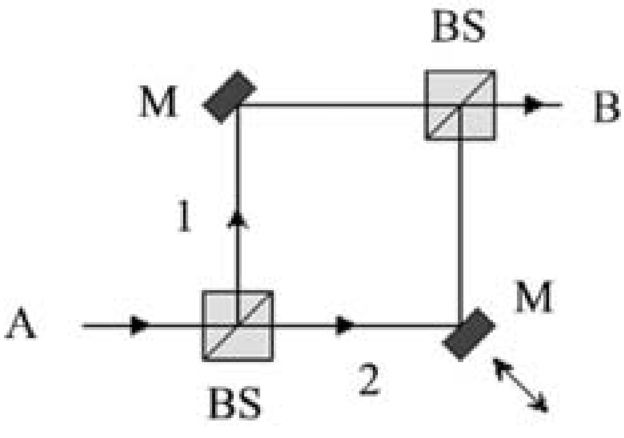

Figure 1. The Mach-Zehnder interferometer has two beam splitters (BS) and two mirrors (M). A photon going from A to B can take either path 1 or 2.

chance that it will be reflected and a 50% chance that it will be transmitted. Past the beam splitter, the mirrors steer the light toward a second beam splitter, where again they can be reflected or transmitted. Because this is the case for both paths, the arrangement of Figure 1 allows a photon that is incident on the interferometer to take either path 1 or path 2 in going from A to B.

If the interferometer is set up so that we cannot tell which path the photon takes, then the paths are said to be "indistinguishable." Quantum mechanics tells us that if the paths are indistinguishable, then the state of the photon going through the interferometer is a superposition of the photon going through the two paths. At this point, our classical intuition would lead us to think that a given incoming photon may randomly pick any one of the two paths in going through the interferometer. However, quantum mechanics says that the photon takes both paths. One may ask, "How do we know the difference?" Quantum mechanics explains that if the paths are indistinguishable, then a measurement of the photon reaching the other side of the interferometer will exhibit "interference." If the paths are "distinguishable," there will be no interference.

Below we will get to more details of this specific experiment, but returning to the more fundamental issue, quantum mechanics predicts that a system can be in two physically distinct states at the same time as long as we cannot tell in which state it could be. When a measurement is made, we will find the system in one of the two states with a corresponding probability. However, there is no way to know beforehand in which state we will find the system when we do the measurement.

This fundamental issue has troubled physicists since quantum mechanics was first formulated. Of all doubters, Einstein had serious concerns about it, and his discussions with Bohr, who advocated quantum mechanics, are legendary. In a landmark publication in 1935, Einstein, Podolsky, and Rosen (2) presented a "thought experiment" to show that quantum mechanics predicts "non-local" behavior. Einstein reasoned that because of this prediction, quantum mechanics must be wrong or incomplete. The debate generated by this argument was the birth of a striking quantum property of multiparticle systems: entanglement. Quantum mechanics allows a physical situation (e.g., atomic decay) to result in the emission of two particles that are said to be entangled. This is a general concept, so we will define it in terms of optical experiments. The optical process of spontaneous parametric down-conversion can result in the simultaneous creation of pairs of photons that are entangled in polarization. As is well known, light possesses polarization. It can be described in terms of two states of linear polarization that are mutually independent of each other (e.g., vertical and horizontal polarization). The entanglement could be, for example, that the linear polarizations of the two photons are mutually orthogonal. Polarization entanglement may imply, for example, that photons 1 and 2 of a given pair will be in the superposition of the case where photon 1 is vertically polarized and photon 2 is horizontally polarized with the case where photon 1 is horizontally polarized and photon 2 is vertically polarized. For this situation, superposition means that the polarizations of the pair of photons are in the two cases simultaneously.

The two photons in this entangled state will be in the superposition of both cases until a measurement is made. If we make a measurement of the polarization of photon 1 with a polarizer oriented either vertically or horizontally, it will give only one answer: vertical or horizontal polarization, not both. Thus, when a measurement of the polarization is done on one particle resulting in horizontal polarization, the two particles will no longer be in the entangled state but in one of the two product states (cases) that form the entangled state. For example, when the measurement on photon 1 is made giving horizontal polarization, we will instantaneously know that the polarization state of particle 2 is vertical.

Quantum mechanics predicts that the pair can be in a state where their polarizations are undefined but correlated as long as we cannot tell which case it is. Moreover, if at any time we measure the polarization of one, then we will immediately know the polarization of the other one. Incredulously, Einstein referred to this strange prediction of quantum mechanics as "spooky action at a distance." Quantum mechanics forbids us to think "locally," or to say that superposition is our inability to know the polarization of the photons, which was defined when they were created. Instead, quantum mechanics tells us that we must think that the polarizations of the two particles are in reality undefined until they are measured.

In the case of the Einstein, Podolsky, and Rosen experiment, the two particles were entangled in their momentum. This thought experiment remained an un-testable paradox until 1964, when Bell (3) formulated a set of experimentally measurable conditions that would prove or disprove quantum mechanics' non-local properties. Bell formulated a set of inequalities, now known as "Bell's inequalities," that would test non-locality. Should an experiment verify these inequalities, then nature would be demonstrated to be local and quantum mechanics incorrect. Conversely, a measurement of a violation of the inequalities would vindicate quantum mechanics' non-local properties. In a series of landmark experiments (see the article by Dehlinger and Mitchell [4] for a historical account), a number of investigators demonstrated the violation of Bell's inequalities, proving that quantum mechanics is indeed correct and that nature is non-local.

In recent years, technological advances have allowed substantial progress in the investigation of these non-local properties of nature. This has lead to striking results, such as quantum teleportation (5), where entanglement is used to recreate the quantum state of a particle remotely without having to actually send the particle in that state. More development on this topic has led to the rise of the new field of quantum information (6).

These technological advances have allowed a reduction in the size and cost of the experimental infrastructure to conduct experiments. The cost reduction has been of such magnitude that the apparatus now fits on a 2′ × 4′ optical breadboard. This has allowed us (7,8) and others (4,9,10) to design and implement experiments for undergraduates. Students now get a chance to do experiments that verify these startling predictions of quantum mechanics. In this chapter, we present an overview of the experiments that undergraduates can now perform, giving a specific example of the work that we have done.

Experimental Method

The experiments use a novel source of light: photon pairs created by the process of spontaneous parametric down conversion. High-efficiency photon detectors detect the partner photons. Recording only the coincident detections of the two photons ensures that the data represent events that involved both photons.

Photons from a blue/UV-wavelength laser beam incident on a nonlinear crystal produce pairs of photons via parametric down conversion. Conservation of energy requires that the sum of the energies of the daughter photons be equal to the energy of the incident photon. For convenience, we chose the pairs that have the same energy, although other pairs of complementary but unequal energies are also produced. Because momentum is also conserved in this process, the directions in which the two photons emerge from the crystal are correlated. The direction of the photons is controlled by the orientation of the crystal. Thus, one can design experiments where the two photons are either non-collinear, as shown in Figure 2, or collinear. We have used both kinds of setups for doing interference experiments.

Figure 2 shows the layout of a Mach-Zehnder interferometer. It is used to understand the quantum mechanical concepts of distinguishability and superposition. By sending one photon of a pair through the interferometer, we can perform measurements of the interference of this photon with itself. After the interferometer, the photons are directed to light-tight boxes, where they are detected by very sensitive high-efficiency photon detectors. The high efficiency of the detectors is needed because the detection of events in coincidence is the product of the efficiencies in detecting each photon. The use of inefficient detectors may quickly lead to signals that are below the noise level of the detectors. The electronic signals that are generated by the detectors go to coincidence electronics and are recorded by a PC. The degree of interference is changed by slightly changing the length of one of the arms of the interferometer.

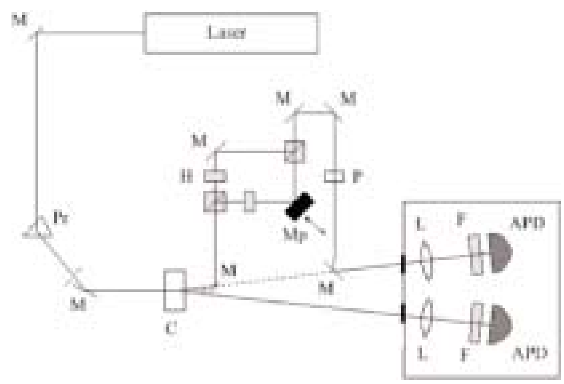

Figure 2. Experimental layout for the experiment on the quantum eraser. The laser beam is steered onto the down conversion crystal (C) by a set of mirrors (M) and a prism (Pr). The interferometer has a half-wave plate (H) to rotate the polarization and a movable mirror (Mp) to change the degree of interference. The erasing effect is provided by a polarizer (P) oriented 45 degrees with the horizontal. The photon detector assemblies have a lens (L), energy filter (F), and avalanche photodiodes (APD).

Experiments

The layout of Figure 1 allows us to understand the principles of the "quantum eraser" experiment. The photon entering the interferometer has a set polarization (e.g., vertical). As it goes through the interferometer, it has two possible paths to take. If we align the interferometer so that the lengths of the two arms are the same, then the paths are indistinguishable. By varying the length of one of the arms, we can have this photon interfere with itself. For example, if the arm-length difference is a multiple of the wavelength of the light, then the interference is constructive and the probability of detecting the photon is $P = 1$. If the arm-length difference is an odd multiple of half-wavelengths, then interference is destructive and $P = 0$. A continuous change in the arm-length difference will result in oscillations in the probability that the photon passes through the interferometer. This manifests experimentally by oscillations in the detected number of coincidence counts as a function of the difference in the length of the two arms. The results of our experiments are shown by the square symbols in Figure 3.

We now insert a "half-wave" plate in the top arm [1] that rotates the polarization of the light from vertical to horizontal. Under these circumstances, the paths will be labeled, or distinguishable. The photon going through the top arm will exit the interferometer horizontally polarized. Conversely, the photon following the lower arm [2] will exit

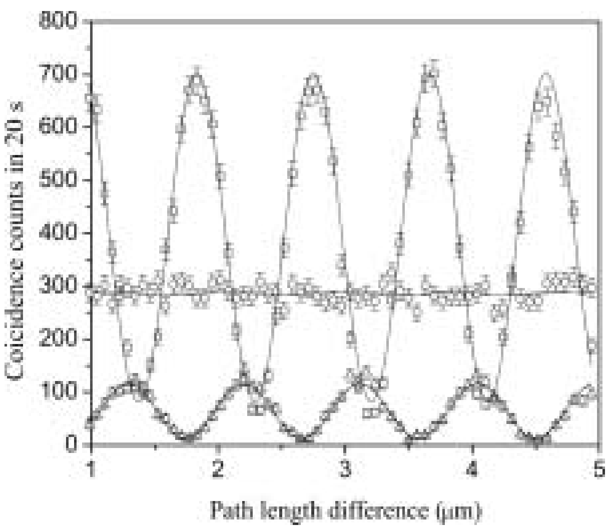

Figure 3. Data for the experiment on the quantum eraser as a function of the difference in length between the two arms of the interferometer. The solid lines are fits to the data.

the interferometer vertically polarized. The predicted probability is $P = 1/2$, independent of the arm-length difference. There is no interference. This is because the paths are now distinguishable. The circles in Figure 3 represent our measurements for this case. We note that we did not measure the polarization of the photon leaving the interferometer and thus were not able to distinguish which path the photon took. However, quantum mechanics predicts that there will be no interference even if, in principle, we can distinguish between the two paths.

Finally, we do a clever trick to erase the distinguishable information reaching the detector. After the interferometer, we use a polarizer with its transmission axis forming an angle of 45 degrees with the horizontal. In this setting, photons of both polarizations have a 50% chance of going through. The polarization direction of the photons after the polarizer is oriented at 45 degrees with the horizontal. Thus, the photons reaching the detector will not have the path information. The distinguishing information will be erased, and the interference will be recovered. The triangles in Figure 3 show the data for this case, which exhibit interference.

The experiment given above is only one example of the types of experiments that can be done by undergraduates. We have recently demonstrated experiments that illustrate other fundamental aspects of quantum mechanics. These include the energy correlation in interference (11), shown in Figure 4A (8), where the degree of interference is controlled by the photon that does not go through the interferometer. This is implemented by the use of unequal energy filters (F1 and F2) in front of the detectors. The remote filter, with narrower energy bandwidth, determines whether the paths are indistinguishable or not. In Figure 4B, we show an experiment where the issues of quantum superposition get more elaborate (12). In that experiment, we send both photons through a Michelson interferometer (8). After the interferometer, there is a beam splitter that on the average splits half of the photon pairs into the two detectors for the recording of coincidences. The experiment gives an unusual interference pattern because of the two photons going through the interferometer. A different version of this experiment with non-collinear photons produces a type of interference known as the "Hong-Ou-Mandel dip" (13). It can be recreated with the setup shown in Figure 4C (7).

The experiment in Figure 4D involves measuring the correlations between outputs of the three detectors. The

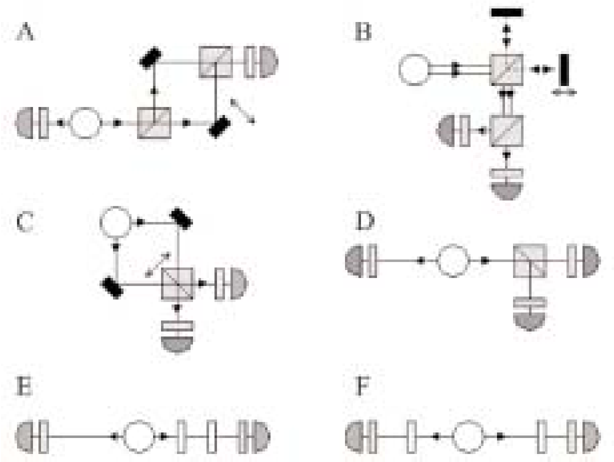

Figure 4. Six experiments with single photons that can be used for understanding quantum mechanics. The circles represent the source of photon pairs, the squares with a diagonal line are beam splitters, the dark rectangles are mirrors, the light rectangles are either energy filters or polarizers, and the half-circle symbols represent the photon detectors.

analysis of the results demonstrates that quantum mechanics prevails over classical mechanics (9,14). Briefly, if light is exclusively a wave, then the wave splits at the beam splitter. If it is made of indivisible photons, it will not. A null in the detection of triple coincidences settles the issue in favor of the photon picture (9).

Even the more quantum mechanical topics of "basis change" can be recreated in experiments, as shown in Figure 4E, where one of the photons is sent through two polarizers (8). Measurements of the polarization correlations of photons that are entangled in polarization can be done with the polarizers P1 and P2 in the setup of Figure 4F. These correlations can be extended for a measurement of the cornerstone of the locality argument: a violation of Bell's inequalities (4).

Conclusions

In closing, technological advances have opened a new door to educational innovation and improvement that affect the upper-level physics curriculum. It involves the introduction of laboratory experiments on a topic that is currently taught with an almost exclusive theoretical emphasis. We have developed a core of experiments that illustrate quantum mechanical concepts that are otherwise theoretical, abstract, and even counterintuitive. Through experimentation, students will learn the reality of the striking predictions of quantum mechanics, but more importantly, have a better understanding of the fundamentals of quantum mechanics. As we enter the era of quantum information, this will be an increasingly important component of our undergraduate education. Advances in the technology of these experiments will bring the cost of implementing them to the point where they may become an integral component of the upper laboratory in the physics curriculum.

Acknowledgments

This project was developed in collaboration with Charles H. Holbrow. A number of Colgate University students participated in the development of these experiments. We acknowledge Matthew Pysher, Justin Spencer, James Martin, Naomi Courtemanche, and Lauren Heilig for their important contributions. We are indebted to many investigators who have lent us their expertise in carrying through this project. In particular, we thank Paul Kwiat and Anton Zeilinger for their advice and inspiration and Beth Parks, Shimon Malin, William Wooters, and Joseph Eberly for important discussions. This work was funded by NSF grant DUE 9952626.

REFERENCES

1. Feynman, R. P., R. B. Leighton, and M. Sands. 1965. *The Feynman Lectures in Physics*. Vol. 3. Reading, MA: Addison-Wesley.

2. Einstein, A., B. Podolsky, and N. Rosen. 1935. Can quantum mechanical description of physical reality be considered complete? *Phys Rev* 47: 777–780.

3. Bell, J. S. 1964. On the Einstein-Podolsky-Rosen paradox. Long Island City, NY. *Physics* 1: 195–200.

4. Dehlinger, D., and M. W. Mitchell. 2002. Entangled photons, nonlocality, and bell inequalities in the undergraduate laboratory. *Am J Phys* 70: 903–910.

5. Bouwmeester, D., J.-W. Pan, K. Mattle, M. Eibl, H. Weinfurter, and A. Zeilinger. 1997. Experimental quantum teleportation. *Nature* 390: 575–579.

6. Bowmeester, D., A. Ekert, and A. Zeilinger (Eds.). 2000. *The Physics of Quantum Information*. Berlin: Springer.

7. Holbrow, C. H., E. J. Galvez, and M. E. Parks. 2002. Photon quantum mechanics and beam splitters. *Am J Phys* 70: 260–265.

8. Galvez, E. J., C. H. Holbrow, M. J. Pysher, J. W. Martin, N. Courtemanche, L. Heilig, and J. Spencer. Interference with correlated photons: five quantum mechanics experiments for undergraduates. *Am J Phys*. In press (see also http://departments.colgate.edu/physics/pql.htm)

9. Dehlinger, D., and M. W. Mitchell. 2002. Entangled photon apparatus for the undergraduate laboratory. *Am J Phys* 70: 898–902.

10. Thorn, J. J., M. S. Neel, V. W. Donato, G. S. Bergreen, R. E. Davies, and M. Beck. 2004. Observing the quantum behavior of light in an undergraduate laboratory. *Am. J. Phys* 72; 1210-1226.

11. Kwiat, P. G., and R. Y. Chiao. 1991. Observation of nonclassical Berry's phase for the photon. *Phys Rev Lett* 66: 588–591.

12. Brendel, J., E. Mohler, and W. Martienssen. 1991. Time-resolved dual-beam two-photon interferences with high visibility. *Phys Rev Lett* 66: 1142–1145.

13. Hong, C. K., Z. Y. Ou, and L. Mandel. 1987. Measurement of subpicosecond time intervals between two photons by interference. *Phys Rev Lett* 59: 2044–2046.

14. Grangier, P., G. Roger, and A. Aspect. 1986. Experimental evidence for a photon anticorrelation effect on a beam splitter: a new light on single photon interferences. *Europhys Lett* 1: 173–179.