Optical quantum effects

A teaching laboratory proposal

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Motivation

Quantum mechanics is a field that enters almost all branches of physics and is an inseparable part of every physics student's training. Over the last two decades, this field experienced major development, primarily associated with the emergence of quantum information science and other quantum technologies. These technologies hinge on our ability to construct complex entangled quantum systems while maintaining control over their individual components – such as photons, ions or photons. Therefore physicists now need to possess not just technical skills to employ quantum mechanics for calculations, but deep understanding of its conceptual logic as well as of fundamental quantum phenomena such as entanglement, nonlocality and measurement. It is our mission as an educational institution to train our students in this spirit.

Quantum physics has been traditionally a purely theoretical discipline. However, the recent progress in quantum technology gave rise to the opportunities of making many of the core quantum phenomena accessible to students for direct experimental observation. Specifically, extensive studies of photonic technology and entanglement resulted in the development of techniques for generating and measuring single photons and entangled pairs thereof that are relatively undemanding in terms of both the equipment costs and experimental skills required. As evidenced by experience at a growing number of schools across the world, these techniques can be successfully implemented in the framework of a university teaching laboratory

Our proposal is to construct a quantum optics teaching experiment that allow the student to prepare polarization entangled photon pairs, as well as manipulate and detect polarization states of single photons. The heart of the experiment consists in a spontaneous parametric down-conversion setup in which a photon of a laser pulse, propagating through a nonlinear optical medium, can spontaneously split into a pair of photons of lower energy. The photons in the pair, under certain circumstances, are in a polarization entangled state. These photons can then be measured in various bases using polarization rotators, polarizing beam splitters and single-photon detectors. This laboratory will enable the student to directly observe the phenomena of quantum measurement, interference, entanglement and nonlocality. It can be used both as a demonstration in a lecture and as an advanced student experiment.

Experiments

The infrastructure requested can be utilized to implement the following experiments:

- Alignment of the parametric down-conversion setup. The student will use mirrors to direct both photons of a pair into multimode optical fibers, which, in turn, will guide the photons into single-photon detectors. The signature of successful alignment consists in observing a high coincidence rate of the two detectors, which is comparable with the individual detector event rate.

- Proof of the indivisibility of photons. While one photon in a pair will be detected directly by a single-photon counter (#1), the other one will be directed onto one of the two photon counters (#2 and #3) via a beam splitter. The student will observe that, whenever detector #1 clicks, only one of the other two detectors will click simultaneously with it.
- Single-photon interference. A demonstration that a single photon, when sent into a Mach-Zehnder interferometer or a two-slit arrangement, will exhibit interference fringes (i.e. interfere with itself in spite of being undivisible). The students will have to align the Mach-Zehnder interferometer and apply minute changes to the path length in one of the arms in order to observe changes in the detector event coincidence rates.
- Hong-Ou-Mandel effect. Prior to sending the photons into the fibers, the student will overlap them on a symmetric beam splitter. The photons will then be expected to stick together at the beam splitter output. The student will observe this by measuring the coincidence event statistics as a function of the photons' temporal overlap, which they will have to control by means of a delay line.
- Quantum state engineering and tomography. Students will prepare of an arbitrary polarization state of the single photon using waveplates. Subsequently, they will send the photon onto a measurement setup consisting of waveplates, polarizing beam splitter, and two detectors in its output channels. Rotating the waveplates to various angles will allow them to perform the polarization measurements in various bases. By recording the event statistics observed in these bases, they will be able to reconstruct the polarization state of the photon and check its consistency with the one they intended to prepare.
- Quantum cryptography. The student will prepare photons in certain polarization states and measure them in certain bases according to the BB84 quantum key distribution protocol, thereby generating a secret cryptographic key. They can then use this key to encrypt a simple message.
- Remote state preparation. The students will prepare a polarization entangled photon pair by means of parametric down-conversion in a pair of nonlinear crystals. They will send one of the photons onto a detector through a polarization filter, consisting of a set of waveplates and a polarizer – so a specific polarization state is detected. The other photon will then be remotely prepared in a correlated polarization state, which the students will be able to check by means of the polarization measurement.
- Quantum nonlocality / Bell inequality. This is an extension of the above procedure, in which the students will measure the correlated detection statistics of the two photons in four sets of polarization bases, thereby refuting local realism.
- Quantum information protocols: Entanglement witness, POVM, quantum eraser, quantum gates, etc.

Costs and implementation

I have set up a similar experiment at my previous home institution (University of Calgary), and hence I will be able to supervise the construction of the Oxford setup. The attached spreadsheet lists the required parts. Given that the most expensive parts (the optical table and the single-photon detector) are already available, the total is about £15k. In addition, at least one summer student position will be required to set up the experiments and write the lab manuals. Additional costs may be required to cover a roundtrip to/from Calgary for consultations.