qutools

quEDU - Science Kit

The Science Kit for Quantum Education

Quantum Physics

Quantum theory is probably the most successful physical theory ever, and it is deeply rooted within the heart of modern physics. As such, it is only natural that the subject is part of every physicist's education.

Quantum physics, the branch of physics that studies the behavior of matter and energy at the smallest scales, is of immense importance in our modern world. It provides us with a profound understanding of the fundamental nature of reality and has revolutionized numerous scientific and technological fields.

One of the key aspects that makes quantum physics so important is its ability to challenge and expand our classical intuition. Classical physics, which successfully describes the macroscopic world, cannot explain the behavior of particles at the quantum level. Quantum physics introduces concepts such as superposition, entanglement, and wave-particle duality, forcing us to rethink our understanding of the universe.

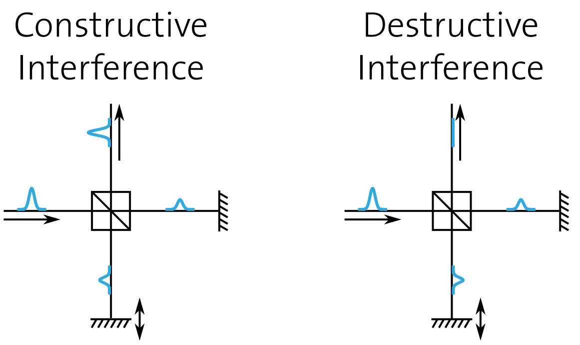
Single Photons and Interference

Single photons and interference play a central role in the field of quantum optics, enabling breakthroughs in various fields. A single photon, as the name implies, is the smallest unit of light. As the fastest quantum object, it excels at exchanging quantum information between other systems. In addition to being seen as a particle, it shows wave-like interference, exhibiting wave-particle duality.

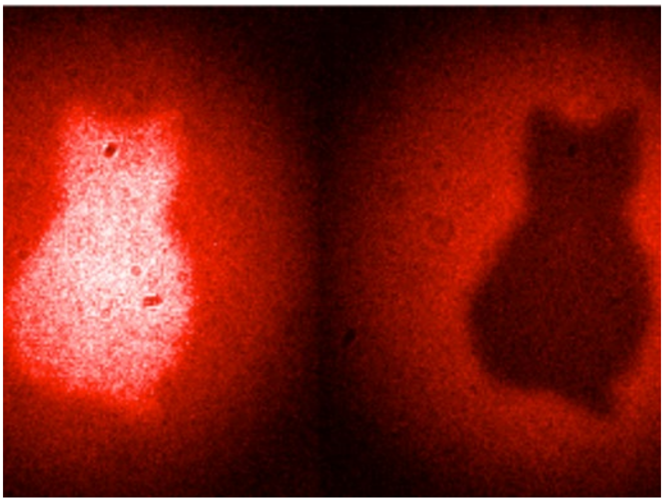
Interference occurs when two or more waves combine. Single photons can undergo interference, creating complex interference patterns of immense scientific significance. By manipulating the path or phase of photons, researchers can control and observe interference effects, paving the way for applications in quantum computing, cryptography, and precision measurement.

Polarization Entanglement

Polarization entanglement, another fascinating concept, involves the correlation of the polarization states of two or more photons. When photons are entangled, their polarization states are intrinsically linked, regardless of their spatial separation. This non-local correlation allows the transfer of quantum information over long distances, even beyond the limits of classical communication.



One of the astounding predictions of quantum physics is that quantum objects can exhibit both wave and particle character. One can demonstrate precisely the interference of a single light quantum with itself by sending single photons through a Michelson interferometer.

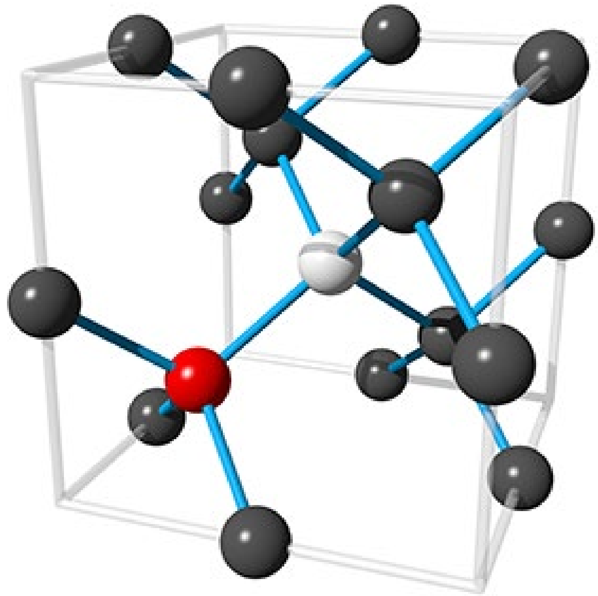


Viennese researchers play on "Schrödingers Cat" with entangled photon pairs and an aperture. The red photons never "interacted" with the object, but they show the cat shape - Patricia Enigl, IQOQI, Vienna.

Spin Manipulation of NV Centers

A prominent example of quantum matter are the NV (nitrogen-vacancy) centers. NV centers are atomic defects in diamond crystals consisting of a nitrogen atom adjacent to an empty lattice site. This quantum systems provides unique spin properties that can be controlled and manipulated with remarkable precision.

By exploiting the spin properties of NV centers, scientists can explore diverse applications in quantum information processing and sensing. For example, the spin of an NV center can serve as a qubit, a unit of quantum information. Through advanced techniques involving laser excitation and microwave manipulation, the spin state of the NV center can be precisely controlled, enabling quantum computing and communication protocols.



The NV center can be used as a quantum sensor for very sensitive magnetic field measurements. NV centers consist of a nitrogen atom (red) next to a vacancy (white) in a carbon (gray) diamond lattice.

quEDU - a Science Kit for Quantum Physics

In summary, quantum physics is of paramount importance because of its ability to challenge our classical understanding, drive technological innovation, and unravel the mysteries of the universe. As we continue to delve deeper into the quantum realm, we can expect transformative breakthroughs that will shape the future of science, technology, and our perception of reality.

qutools' quEDU allows you to experience all of these amazing effects in one unit, with multiple experiments on separate boards. The quEDU itself is the control and detection unit. Its experiment boards, connected by data cables and fiber optics, can be used to observe various quantum effects.

The quEDU frees the hands and brains of anyone trying to explain the complex phenomena of quantum physics. Because that's hard enough.

The quEDU is a platform for various quantum physics experiments. It contains single photon detectors and time tagging electronics for data acquisition and analysis as well as interfaces to control the experiments. One of the experiment boards generates entangled photons, another manipulates electron spins.

quEDU - A Science Kit for Quantum Physics

The quEDU is a platform for various quantum physics experiments. It contains single photon detectors and time tagging electronics for data acquisition and analysis as well as digital interfaces to control the experiments.

The quEDU and its experiment boards combine the latest achievements in quantum optics technology into an easy-to-use system for academic, research and applied purposes with high precision. Advanced models for scientific purposes are also available, with high performance to meet the requirements of state-of-the-art physics experiments.

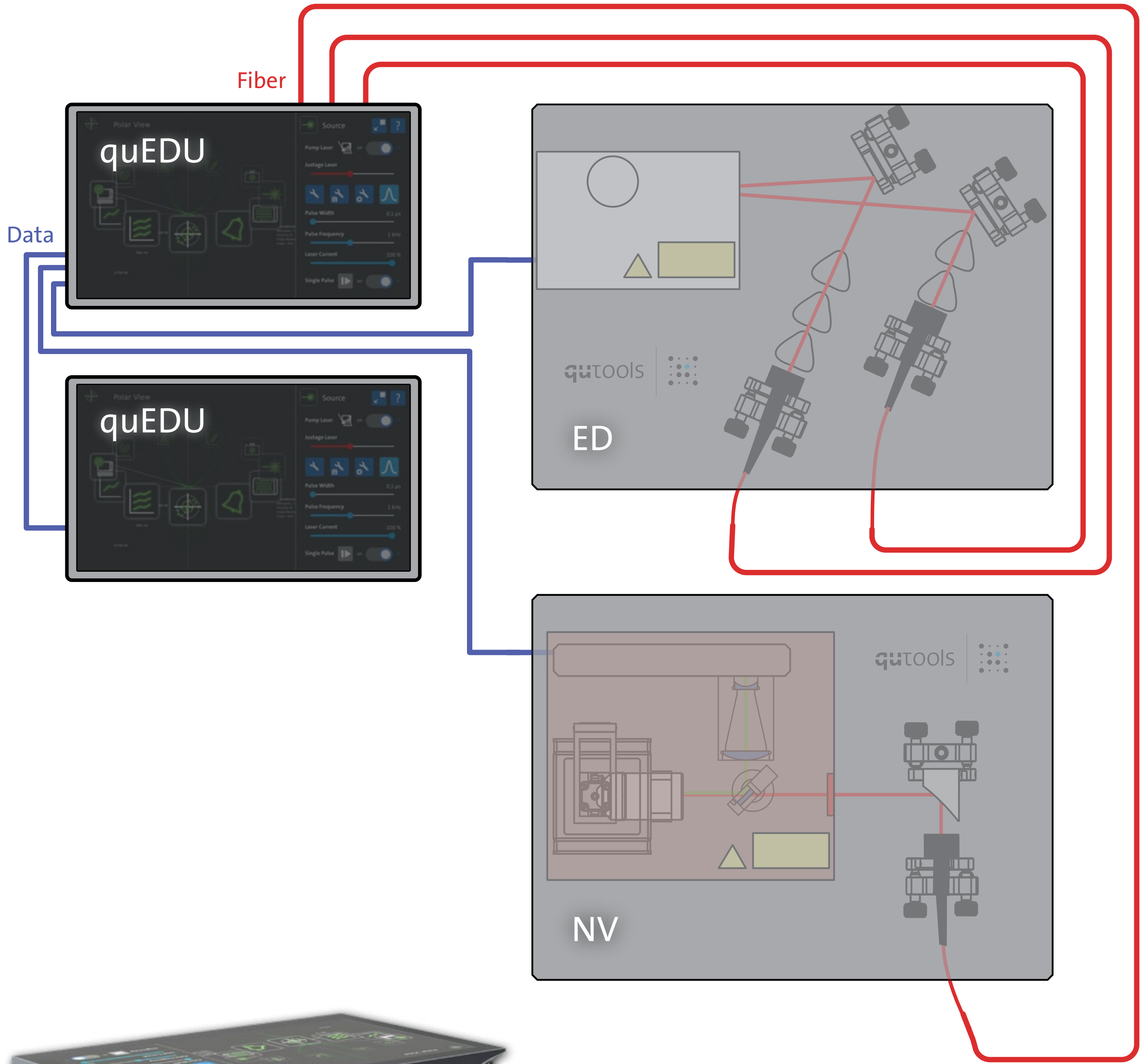
The qutools Quantum Education kit is designed with educators in mind. It's the easiest and most reliable way to explain the complex phenomena of quantum mechanics by generating and analyzing polarization-entangled photon pairs or manipulating electron spins in a diamond.

Key Features

- Hands-on study of quantum physics
- Photon entanglement and spin manipulation
- High modularity for different experiments
- User-friendly operation, complete system
- Add-ons to extend the number of experiments

Specific Applications

- Student lab course experiments
- Violate Bell's inequalities
- Heralded single photon source
- Electron spin manipulation
- Optically detected magnetic resonance



The touch display and the two wheels control the whole experiment, remote access is possible by Ethernet and USB next to the fiber inputs on the rear side.

Control and Usage

- Touchscreen & rotary buttons
- 5 ports for experiment boards
- Pattern generator and pulse streamer
- Control and data export via USB
- Remote desktop via WLAN, Ethernet

Detection and Analysis

- 5 temperature controlled APDs with fiber port
- 1 fast photodiode with fiber port
- Time tagging electronics with picosecond jitter
- Singles & coincidence events counting
- Analysis and processing of measurement data

Experiment Boards

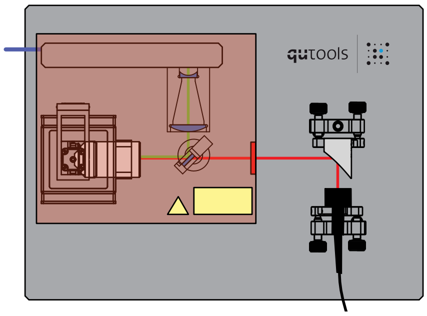
The quEDU can be connected to various photon sources or experimental boards with optical setups like a Michelson Interferometer or a NV center.

NV - Nitrogen Vacancy Centers

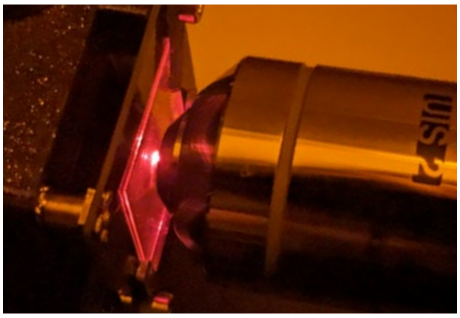
The NV experiment board allows you to experience the properties of nitrogen vacancy centers in diamond, such as NV center fluorescence, electron spin manipulation, optically detected magnetic resonance, and magnetic field sensing of samples.

At the heart of the NV is a green laser focused on the nitrogen-doped diamond through a microscope objective. The diamond begins to fluoresce in the red wavelength range. This light is collected by the objective and, after some filtering, is coupled into a fiber. The fiber is connected to the quEDU and the fluorescence can be analyzed.

The diamond sample itself is in close proximity to a microwave antenna and is surrounded coils producing a user defined homogeneous magnetic field. In addition, the quEDUs included pattern generator is precisely controlling pulse sequences for laser, microwave, and readout, enabling a multitude of spin-control experiments.



The quNV board is connected by a digital data cable to control the laser, the magnetic field and the microwave frequency and power. The fluorescence signal is coupled into a fiber and sent to the quEDU photodiode.

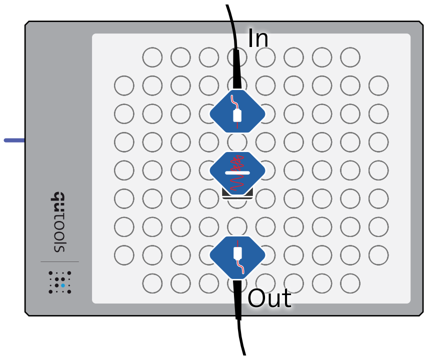


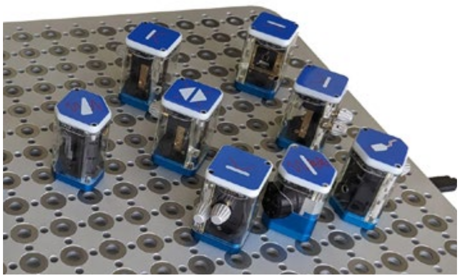
BB - Brick Board

The brick board is an experiment platform on which optical Bricks of the Quantenkoffer® can be assembled to individual optical setups. The board and all bricks can be controlled by the quEDU.

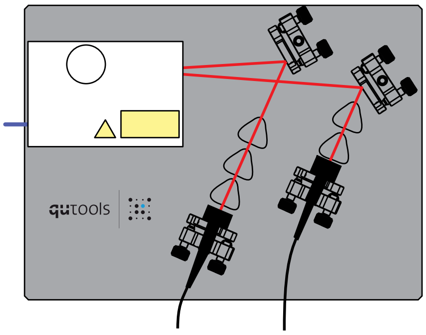
Optical fibers deliver the photons to the BB and the individual setup. After the open beam experiment, optical fibers carry the light back to the photon detectors and time tagging electronics in the quEDU.

The brick board and all the optical tokens are derived from the Quantenkoffer®. All optical and digital interfaces match and both can be combined.



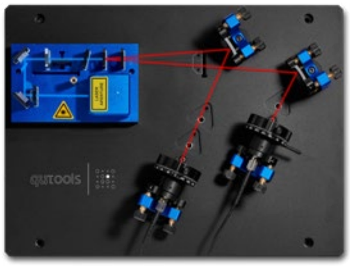


ED - Entanglement Demonstrator



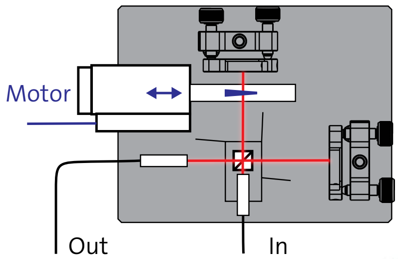
The ED is an experiment for the generation and analysis of polarization-entangled photon pairs. A high-power UV diode laser is focused on a nonlinear crystal. By conservation of energy and momentum, some of these pump photons are transformed into a pair of lower energy near-infrared photons.

Different phenomena can be experienced by optical elements such as polarizers. Finally, the infrared photons are coupled into optical fibers and read by the quEDU with its APDs.



This board can be extended by various optical elements, ether by adding to the board or connecting by fiber.

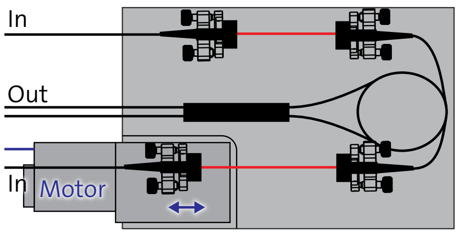
ED-MI - Michelson Interferometer



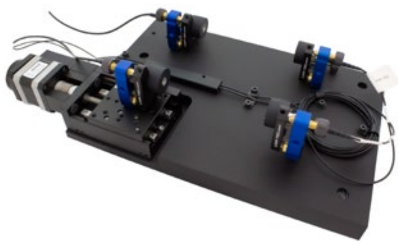
Interference is generally considered to be a wave phenomenon. Curiously, it also works with single quantum objects. The ED-MI Michelson interferometer and the ED as a single photon source are used to show that this is the case.

In addition, polarizers on three sides of the beam splitter can be swung in and out of the interferometer, thus realizing a quantum eraser.

ED-HOM - Hong-Ou-Mandel



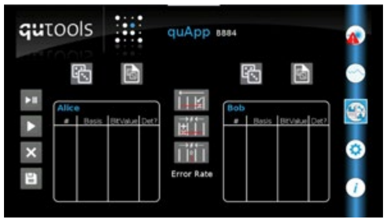
If you have two indistinguishable photons, each of which hits an input of a beam splitter, they will always exit the splitter together at one output port. This is a purely quantum interference effect with no classical analog.

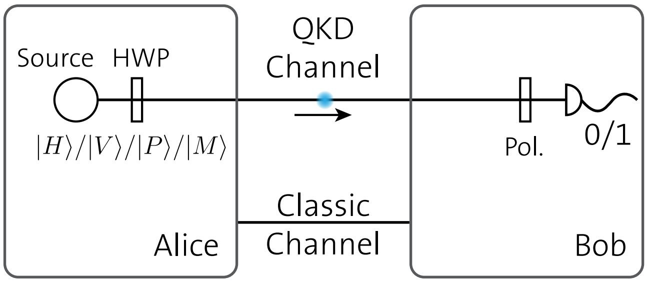


This is usually detected by observing the Hong-Ou-Mandel “dip” in the coincidence count rate of the two output ports of the beam splitter. In combination with the ED-HBT, however, the pairwise bunching of the photons can be observed directly.

Experiment Board Add-Ons

ED-QKD - Quantum Key Distribution

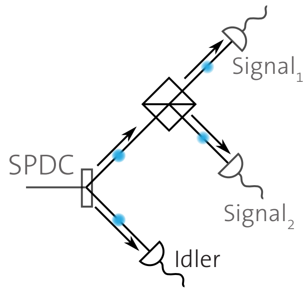




One of the most popular industrial applications of quantum phenomena at the moment is quantum cryptography, or rather quantum key distribution.

With the ED and this add-on, you can realistically demonstrate how secure communication between two parties (Alice and Bob) is made possible by the BB84 protocol. You can also stage an intercept-resend attack and show how it can be detected. The tunable pulsed laser driver provides additional benefits for all experiments and other add-ons.

ED-HBT - Hanbury Brown Twiss

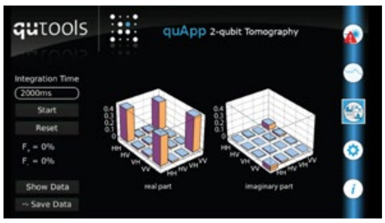


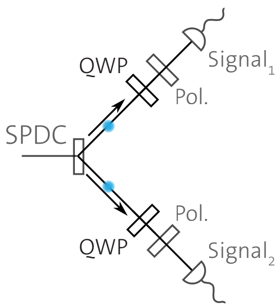
Photons, or more generally quantum objects, sometimes behave like particles. With the ED and this add-on, you can show that individual photons cannot be split.

You can also measure a second order correlation function g(2)(0) to study photon statistics in only one arm of the ED, or use the second arm as a trigger for the announced case, or explore a simple quantum random bit generator.

The ED-HBT can be combined with any other add-on to check the photon number statistics in the experiment and to show the particle-like behavior of photons.

ED-TOM - Tomography





The exact state of one or more quantum objects cannot be determined by a single measurement. However, if one has access to an ensemble of equally prepared states, as is the case with ED's SPDC photon source, there is a way to measure the complete quantum state of this ensemble.

The ED-TOM consists of two additional quarter-wave plates and an easy-to-use software to record the data for an overcomplete tomography scheme.

Experiments

Summary of prepared experiments with boards and add-ons

NV Center experiments

NV Center Fluorescence	NV
ODMR	NV
Zeeman Effect	NV-COIL
Orientation of NV-Centers in Lattice	NV-COIL
Magnetic Field Sensing	NV-COIL
ODMR Microscopy	NV-CAM

with Pattern Generator

Spin Initialization and Readout	NV-PAT
Rabi Oscillations	NV-PAT
Pulse Sequence Development	NV-PAT
Coherence Times T2	NV-PAT
Ramsey sequence	NV-PAT
Dynamical Decoupling, Hahn Echo	NV-PAT

Single Photon Experiments

with Interference

Wave Nature of Photons: Single Photon Michelson Interferometer	ED-MI
Quantum Eraser	ED-MI
Wave-Particle Dualism: Interference & Indifisibility	ED-MI & ED-HBT
Double Michelson Interferometer	ED-MI 2x
Measurement of Central Wavelength of Single Photons	ED-MI
Measurement of Coherence Length of Single Photons	ED-MI
Interaction-Free Measurement (Bomb Test)	ED-MI & ED-QKD

without Interference

Particle Nature of Photons	ED-HBT
Second order correlation function	ED-HBT
Quantum Cryptography / QKD: BB84 Protocol	ED-QKD
Tomographic Single Photon State Reconstruction	ED-TOM
Quantum Zeno Effect	other
Quantum Random Number Generation	ED-HBT
Photon number statistics and the second order correlation function	ED-HBT

Photon Pair Experiments

with Polarization Entanglement

Violation of Bell's Inequality (CHSH)	
"Non-Classical" Polarization	
Tomographic State Reconstruction of an Entangled Photon State	ED-TOM
Quantum Cryptography / QKD: BBM or Ekert Protocol	other

without Polarization Entanglement

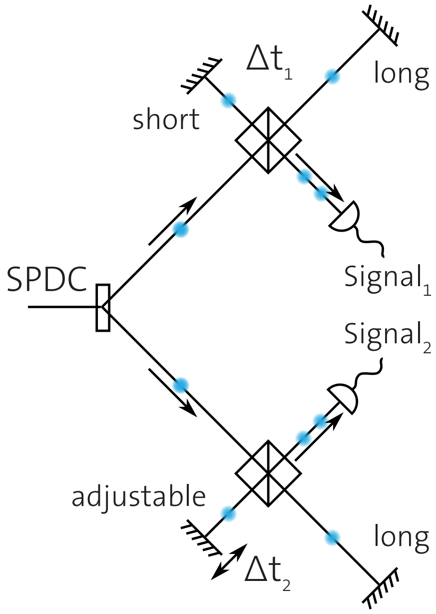
Hong-Ou-Mandel 2-Photon Interference	ED -HOM
Hong-Ou-Mandel Interference + Hanbury Brown & Twiss	ED-HBT & ED-HOM
Franson Interference	ED-MI 2x

Sample Experiments

The Franson Interference is one of the most mind-boggling experiments you can do with the quEDU and its optical boards ED and ED-MI.

Franson Interference

Franson interference is a type of quantum interference where photon pairs, generated by parametric fluorescence, are used to create interference patterns, even when the photons follow different paths.



The ED is used as a source of photon pairs, without using the wave plate. Each pair is sent into an unbalanced Michelson Interferometer, and in one of them the arm length difference can be modulated.

Experiment Setup

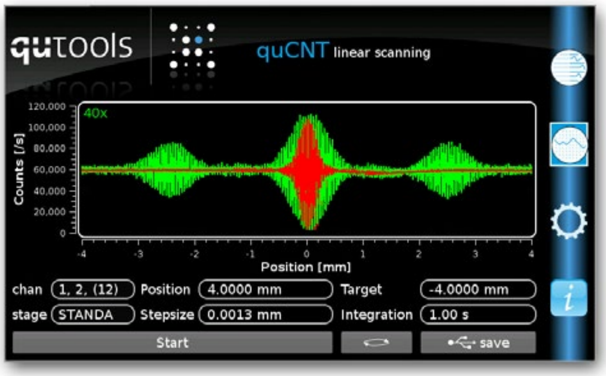
At first, we set up the two ED-MI, one in each arm of the ED output fibers. The ED is set up to produce non-polarization entangled photon pairs. All three boards are connected to the quEDU by data cable and both MI outputs go into the APD inputs.

Changing the optical path length in each arm of an interferometer will show the “standard” single photon interference effect when both arm lengths are nearly equal, red in the screenshot below.

Interference Patterns

Now we change the optical path length difference in one of the interferometers to be far greater than the coherence length, i.e. the envelope of the single photon interference pattern, and scan the other one.

When observing single events in the detectors, the interference pattern again only appears around zero path length difference in the scanning interferometer. This is not so astonishing, since for the events in one arm it does not matter what happens in the other one.



The distinct interference patterns of coincidence counts (green) and singles (red) over displacement.

When measuring coincidence counts, however, we see three distinct interference patterns. Besides the known central interference pattern, two more can be observed, symmetrically distributed around the first one. Each is centered around the corresponding path length difference that is the same as the one present in the static interferometer, with the variable arm being the shorter or longer arm, respectively.

What does that mean? Is this another kind of entanglement (remember we did not use polarization entangled photons)? Is there even a Bell inequality to show that?

Rabi Oscillations are the foundation for every other spin-control experiment, and constitute a show-case experiment for the quEDU and NV.

Rabi Oscillations

When you expose an NV center to an alternating electromagnetic field in the microwave frequency range, the transition between the $m_s = 0$ and the $m_s = \pm 1$ ground states are driven. If you start with an ensemble initialized to the $m_s = 0$ state, the system will begin to oscillate between the different states. This phenomenon is called Rabi oscillation, the cyclic behavior of a two-level quantum system in an oscillatory driving field.

Experiment Setup

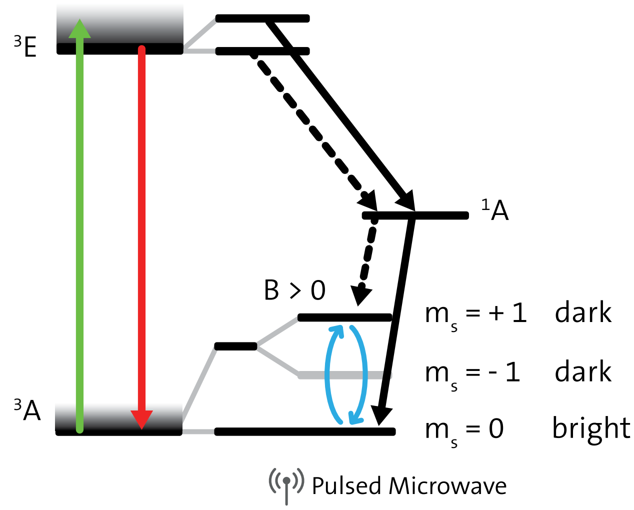
Before the experiment, one needs to determine the exact resonance frequency of the microwave. The goal is to drive the transition as efficient as possible. Therefore, one first performs a standard ODMR measurement sweep.

With the green laser turned on, the photodiode intensity is recorded while the microwave frequency is tuned. The intensity will be lowest at the frequencies that drive the transition most effectively, since the $m_s = \pm 1$ states appear darker than the $m_s = 0$ state.

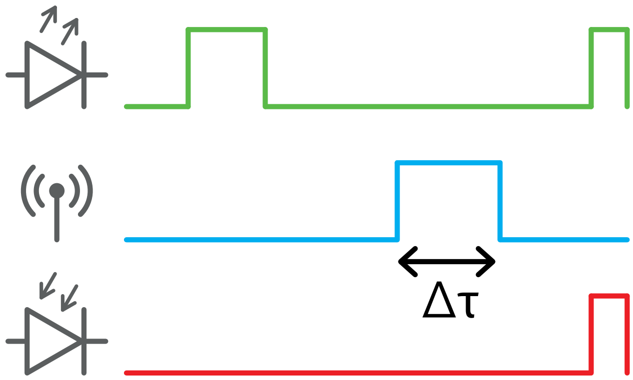
Observing Rabi Oscillation

Of course, the green laser will immediately destroy the state of the NV center we are looking at, so we can't directly observe any time evolution. We can, however, observe the state at any given time and then start over for the next measurement. If we vary the time delays until the state is read out again, and we assume that the state evolution happens in the same way each time, we can "watch" the process unfold!

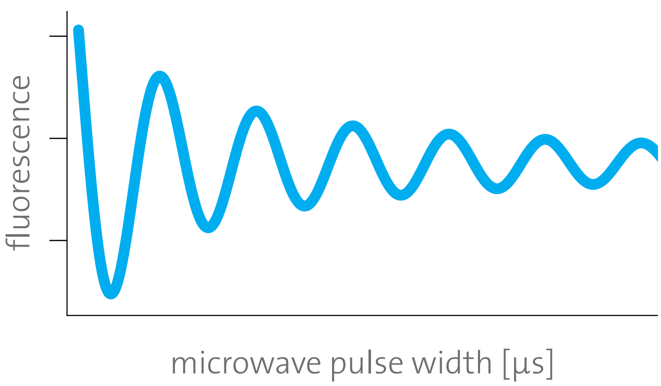
The Rabi experiment also lays the groundwork for other experiments, exploring the quantum nature of NV centers even further. Can this two-state quantum system be used to model a qubit?



Energy-level scheme of the NV center with Rabi oscillations between $m_s = 0$ and $m_s = +1$ state.



Pulse schematic of laser with excitation and read out (green), microwave (blue) at a fixed frequency and the gated read out time of the photodiode (red).



Rabi oscillation measurement with varying pulse length of the microwave. The fluorescence intensity of the NV center is proportional to the population of the $m_s = 0$ state.

Further Products

Quantum physics science kits for education and precision measurement devices for displacement and timing.

Quantum Physics in Teaching

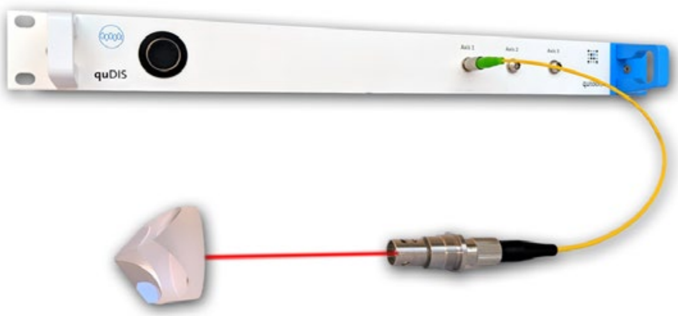
Our Quantenkoffer is a plug and play quantum science kit for schools and universities with single and entangled photon pairs. Multiple tokens with different optical abilities give a huge variety of experiments.

Time tagging for research and industry

quTAG and **qu**TAU are precise time tagging devices with picosecond resolution. Some of its applications are Time Correlated Single Photon Counting (TCSPC), Lidar and characterization of single photon sources. Furthermore the time tagger are applied in time-resolved fluorescence microscopy like FLIM, FCS and FRET.

Sub-nanometer displacement measurement

The quDIS is a confocal displacement sensor, based on a Fabry-Pérot or Michelson interferometer, with highest signal stability of < 0,05 nm and a contrast independent measuring algorithm.



Next to displacement and distance measurement, vibration analysis is possible with a 25 kHz bandwidth in free space or glass rods & fibers as cavities.

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