Real-time imaging of quantum entanglement

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Application Note

Introduction

Quantum Entanglement – correlations between at least two systems that are stronger than classically explainable – is widely regarded as one of the most prominent features of quantum mechanics and quantum information science. At the same time, it is one of the most mind-boggling physical effects because it is counterintuitive and not directly accessible for visual observation. We demonstrated that with the help of a modern intensified CCD (ICCD) camera, it is possible to image in real-time the influence of a measurement of one photon on its distant entangled partner photon. Therefore, by using the ICCD camera we made the "spooky action at a distance", to use the words of Einstein, directly observable.

Principle

The basic idea is to generate entangled photon pairs and use the measurement of one photon as a trigger signal for the ICCD camera. The timing of the camera is adjusted such that it only detects the partner photon of the one that created the trigger signal. The important advantage of such a camera is the fast and precise gating (triggering) of the intensifier. Firstly, the signal-to-noise ratio is good enough to image single photon events with nearly perfect distinguishability from the background noise. More importantly, it is possible to only register the partner photons and none of the photons arriving from other pairs at the camera. Additionally, the quantum efficiency is high enough to detect enough single photon events to image the resulting pattern within a short time. Thus if the measurement setting of the trigger photon is altered, the appearing pattern of the imaged partner photons changes as well. Since this is done with a very high visibility of the pattern it can only be explained by the entanglement and not via classical correlation. Hence, the effect of quantum entanglement is imaged in real-time.

Experimental setup

The polarization-entangled photon pairs are created in a spontaneous parametric down conversion (SPDC) process using a nonlinear crystal (periodically poled potassium titanyl phosphate (ppKTP)). A 405 nm continuous-wave diode laser with 20mW power pumps the crystal, thereby creating photon pairs of 810 nm wavelength with 500 kHz rate. One photon is coupled into a single mode fiber, delayed by around 35 m (to account for the delay time of the trigger detector, the travel time of the trigger signal and insertion delay from the ICCD) and brought to an interferometric transfer setup (PBS: polarizing beam splitter / HWP: half wave plates). Here, the photon gets transferred by a spatial light modulator (SLM) to the desired spatial mode depending on its polarization. After erasing the information which path the photon took inside the interferometer with a polarizer at 45°, the generated bi-photon state can be written as

$$|\psi\rangle = \alpha|H\rangle\,|LG_{+1}\rangle + e^{i\varphi}\,\beta|V\rangle\, LG_{-1}\rangle$$

where α, β, and Φ are real and $\alpha^2 + \beta^2 = 1$, H and V denote the horizontal and vertical polarization, $LG_{\pm 1}$ labels the spatial mode (Laguerre Gauss) of the transferred photon and the positions of the ket-vectors label the different photons. The other photon's polarization is measured with a combination of wave plates (quarter-half-quarter- QHQ), a polarizer and a single photon detector. The signal of the detection is used to trigger the ICCD camera, which gates for 5ns and images the spatial mode of the transferred photon. The setup can be seen in figure 1.

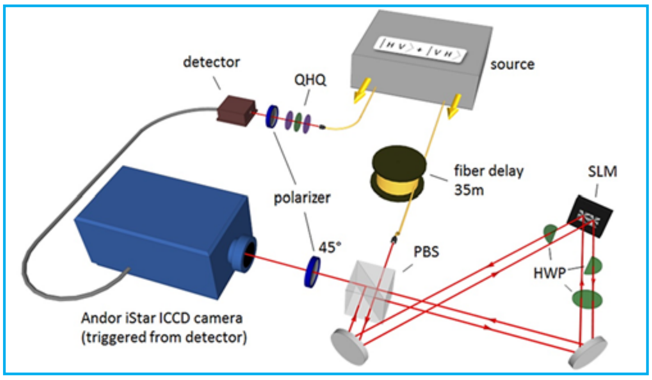

Fig.1: Sketch of the experimental setup.

For the presented measurements, we used an Andor ICCD camera (iStar DH334T-18F-03) with a quantum efficiency of 3% for 810 nm wavelength (other types offer up to 20%), a gating of 5ns and a spatial resolution of 1024x1024 pixels (effective pixel size: 13x13 µm²). With this camera we observe clear single-photon images where the whole spatial information is directly available with very high precision.

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Results

By changing the polarizer setting of the trigger photon different polarization measurements are used to trigger the ICCD. The appearing LG mode structure for the distant partner photon changes accordingly although nothing was changed in the setup of this photon. The visibility of the appearing structure (built by accumulating many single photon events) cannot be explained by classical correlations (see figure 2); hence the images make the effect of entanglement visible.

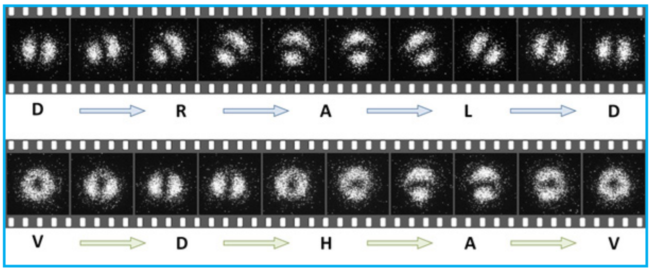

Fig.2: Coincidence images built from many single photon events (accumulation time: 3 seconds). Black letters denote the change of the polarization measurement setting of the trigger photon (H, V, D, A, R and L for horizontal, vertical, diagonal, anti-diagonal, right and left handed circular, respectively)

Why imaging entanglement of spatial light modes?

Spatial modes of light offer many advantages: from encoding more information per single photon to novel tests of higher-dimensional entanglement. However, the spatially encoded information has to be measured efficiently. Compared to scanning or masking of single-pixel detectors, direct imaging with an ICCD shortens the measurement time significantly and increases the spatial resolution. This paves the way to perform novel test of quantum physics and helps with a better intuitive understanding of the effect of entanglement.

Additional information

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Movie of the results on youtube:
http://youtu.be/wGkx1MUw2TU

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