Spatial characterization of photonic polarization entanglement using an intensified Tpx3Cam fast camera

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Abstract

Scalable technologies to characterize the performance of quantum devices are crucial to creating large quantum networks and quantum processing units. Chief among the resources of quantum information processing is entanglement. Here we describe the full temporal and spatial characterization of polarization-entangled photons produced by Spontaneous Parametric Down Conversions using an intensified high-speed optical camera, Tpx3Cam. This novel technique allows for precise determination of Bell inequality parameters with minimal technical overhead, as well as novel characterization methods of the spatial distribution of entangled quantum information. This could lead to multiple applications in Quantum Information Science, opening new perspectives for the scalability of quantum experiments.
INTRODUCTION

Ever since the original experiments with entangled photons [1], photonic entanglement has become a remarkable resource in the development of quantum technologies, including entanglement over long-distance for quantum communication [2], entanglement swapping [3], teleportation between a photon and an atomic ensemble [4], violation of the CHSH (Clauser-Horne-Shimony-Holt) inequality measured over long distances [5, 6] and entanglement of spin waves among four quantum memories [7].

The creation of quantum networks of many such quantum devices in which entanglement is shared among multiple network nodes is the next technological frontier for the successful development of these applications. Easy-to-use, scalable, and compact characterization devices, providing all the information regarding entanglement in near-real-time are fundamental for further large-scale network developments.

Recent developments have shown that spatial characterization of entangled states with single-photon sensitive cameras provides access to a myriad of new possibilities, such as imaging high-dimensional entanglement [8], generalized Bell inequalities [9] and the study of Einstein-Podolsky-Rosen non-localities [10, 11]. However, these measurements used resource-intensive methods, such as sequential scanning or multiple standalone detectors. Early studies of entanglement with modern imagers used an electron-multiplying CCD (EMCCD) camera with an effective area of $201 \times 201$ pixels and frame readout-rate of $5\text{Hz}$ [8]. Albeit the EMCCD quantum efficiency was up to 90%, prolonged exposure time of about $1\text{ms}$, requires this device to operate at very small photon-rates to avoid multiple photons in the same frame. Furthermore, to achieve single-photon level sensitivity the EMCCD camera operated at a low temperature of $-85^\circ\text{C}$.

Further progression on quantum imaging with cameras was achieved using intensified CMOS and CCD cameras [12–17]. Flexible readout architectures allow $kHz$ continuous framing rates in CMOS cameras. Additionally, nano-second scale time resolution for single photons can be achieved by gating image intensifiers. For example, an intensified sCMOS camera was used to observe Hong-Ou-Mandel interference [18], where the photons were collected on
a 700 × 22 pixel area at a framing rate of 7kHz. The photon acquisition statistics can also be enhanced by using multiple triggers during a single frame, so the camera integrates multiple photons within a single acquired image. This approach was employed in [15], where an idler photon from an entangled pair was used to trigger an intensified CCD camera. Although many thousands of photons were imaged in a single frame of the camera, allowing the spatial characterization of the photon’s angular momentum, the framing-rate was only 4Hz.

This low throughput is a severe limitation to resolve spatial characterization of entanglement in real-time. Here we show how a development from the high-energy physics community, the intensified Tpx3Cam camera [19] can be converted into a quantum characterization device of photonic polarization entanglement. This setup allows for imaging and time-stamping of a continuous stream of entangled photons with an excellent spatial and temporal resolution (55 × 55 µm², 1.5 ns), providing a high signal-to-background ratio. We emphasize that the Tpx3Cam readout is data-driven, with a high throughput of ≈ 10⁷ photons per second, which is several orders of magnitude higher than the conventional cameras discussed above.

**EXPERIMENTAL SETUP**

In this collaboration experiment between Stony Brook University and Brookhaven National Laboratory, we study the characterization of SPDC-based quantum polarization entanglement using fast 2D imaging with a Tpx3Cam. The experimental layout is shown in Figure 1.

**Entangled-photon source**

Our entanglement source (QuTools QuED [20]) utilizes a blue pump laser diode tuned to wavelength λ = 405 nm, and a pair of Type I non-collinear BBO crystals with optical axes perpendicular to one another to generate signal and idler photons at wavelength λ = 810 nm. The first crystal optical axis and the pump beam define the vertical plane. Owing to Type-I phase matching, an incoming photon which is vertically polarized gets down-converted and produces two horizontally polarized photons in the first crystal, whereas a horizontally-polarized photon going through these crystals would get down-converted in the second crystal.
Figure 1: **Experimental layout for entanglement generation (1; left) and characterization (2; right):** 1) The source utilizes a blue pump laser diode tuned to a wavelength of $\lambda = 405$ nm and a pair of Type I BBO crystals with optical axes perpendicular to one another to generate signal and idler photons entangled in polarization at a wavelength of $\lambda = 810$ nm. The entangled photons undergo individual transformations using polarizers to evaluate Bell’s inequality parameters and are then fiber coupled. 2) Exiting from the fibers photons are mode-matched and detected by an image intensifier before registration with the Tpx3Cam camera.

producing two vertical photons. An additional pair of birefringent crystals ensures maximum spatial overlap of the down-converted photons by pre- and post- compensating for differences in effective optical path lengths of signal and idler. The produced state has the form:

$$|\phi^\pm\rangle = \frac{(|HH\rangle \pm |VV\rangle)}{\sqrt{2}}$$

Signal and idler photons are spatially separated and collected using single-mode, polarization non-maintaining fibers, with a linear polarizer, used for projective measurements, before each coupler.

**Intensified fast-camera: Tpx3Cam**

An intensified camera, Tpx3Cam [19], achieves imaging with single-photon sensitivity, which allows time-stamping of incident photons with 1.5 ns time granulation when coupled to an
image intensifier. The Tpx3Cam consists of a light-sensitive silicon sensor bump-bonded to Timepix3, a time-stamping readout chip [21]. The sensor-chip assembly has \( 256 \times 256 \) pixels of \( 55 \times 55 \, \mu m^2 \) each. The silicon sensor in the camera has a thin entrance window with an anti-reflective coating providing excellent quantum efficiency [22]. The sensor is optimized for emission spectrum of the \( P47 \) scintillator [23]. The non-intensified version of Tpx3Cam has been used before for the velocity mapped ion imaging [24] while the intensified version of its predecessor, TimepixCam, has been used for fluorescent lifetime imaging, which required single photon sensitivity, similar to this application [25].

The Timepix3 processing electronics in each pixel records the time-of-arrival (TOA) of hits that cross a preset threshold and stores it as a time-code in a memory inside the pixel. The time-over-threshold (TOT) is also recorded serving as an estimate of the light flux seen by the pixel. The individual pixel dead time is of the order of 1 \( \mu s \). The readout is data-driven, and only the pixels with signals above the threshold are recorded. The camera can operate continuously and does not require a trigger as the pixels transfer the data asynchronously within microseconds after being hit. The maximum camera throughput is 80 Mpix/s [19, 26].

The intensifier in front of the camera is an off-the-shelf vacuum device [27] with a photocathode followed by a chevron micro-channel plate (MCP) and fast \( P47 \) scintillator with a signal rise time of \( \sim 7 \, ns \) [28]. Photons are first converted to photoelectrons in the photocathode and then amplified in the MCP before producing a flash of light in the scintillator. The 18 mm diameter scintillator screen is projected on to the \( 14 \times 14 \, mm^2 \) sensor with a relay lens with no magnification [29]. The photocathode used for the experiments had a quantum efficiency attaining \( \approx 18\% \) for the used wavelength of 810 nm.

The camera was calibrated to equalize the response of all pixels by adjusting the individual pixel thresholds. After this procedure, the effective threshold to fast light flashes from the intensifier is 700-800 photons per pixel depending on the wavelength. A small (\( \approx 0.1\% \)) number of hot pixels was masked to prevent logging large rates of meaningless data to the disk.
EXPERIMENTAL RESULTS

Benchmarking: entanglement characterization.

Our procedure starts by evaluating the entangled state produced by the source. We assume the state to be in a superposition of two Bell-states of the form:

\[ |\psi\rangle = \cos \theta |\phi^+\rangle + e^{i\delta} \sin \theta |\phi^-\rangle = \frac{\cos \theta + e^{i\delta} \sin \theta}{\sqrt{2}} |HH\rangle + \frac{\cos \theta - e^{i\delta} \sin \theta}{\sqrt{2}} |VV\rangle \] (1)

Using a density matrix \( \rho = |\psi\rangle \langle \psi | \), after projection of the two photons by polarizers with angles \( \alpha \) and \( \beta \), we obtain an expectation value for the measurements of coincidences:

\[ P_{VV}(\alpha, \beta) = \text{Tr}\{ \rho \hat{M}_{\alpha\beta} \} = c_0 + c_1 \cos 2\beta + c_2 \sin 2\beta \] (2)

Here, the operator \( \hat{M}_{\alpha\beta} = |V_\alpha V_\beta\rangle \langle V_\alpha V_\beta| \) denotes the projection onto a vertical polarization state. In the basis of BBO crystal we have:

\[ |V_\alpha V_\beta\rangle = \sin \alpha \sin \beta |HH\rangle - \sin \alpha \cos \beta |HV\rangle - \cos \alpha \sin \beta |VH\rangle + \cos \alpha \cos \beta |VV\rangle \] (3)

with \( c_0 = \frac{1 - \sin 2\theta \cos 2\alpha}{4} \), \( c_1 = \frac{\cos (2\alpha) - \cos \delta \sin 2\theta}{4} \) and \( c_2 = \frac{\cos 2\theta \sin 2\alpha}{4} \).

The incoming photon pairs from BBO crystal and background are denoted as \( N_0 \) and \( N_d \) respectively. Then the total coincidence can be fitted as the equation:

\[ N(\alpha, \beta) = N_0 P_{VV}(\alpha, \beta) + N_d = C_0 + C_1 \cos (2\beta) + C_2 \sin (2\beta) \] (4)

where \( C_0 = -\frac{N_0 \cos \delta \sin 2\theta}{4} \cos 2\alpha + \frac{N_0 + 4N_d}{4}, \) \( C_1 = \frac{N_0}{4} \cos 2\alpha - \frac{N_0 \cos \delta \sin 2\theta}{4} \) and \( C_2 = \frac{N_0 \cos 2\theta}{4} \sin 2\alpha \).

Experimentally, we evaluate the rate of coincidences using two single-photon counting modules, as a dependence of the polarization angles \( \alpha \) and \( \beta \), which are set by rotating two polarizers (cf. Fig. 1). The coincidence data for different settings of the polarizers and the respective fitting curves are shown in Fig. 2, where we see the oscillation predicted by the simple theory described above. We numerically fit the parameters \( N_0, \theta, \delta \) and \( N_d \) to the experimental data, obtaining the following results: \( N_0 \pm \Delta N_0 = 47640 \pm 2800, \) \( N_d \pm \Delta N_d = 380 \pm 830, \) \( \theta \pm \Delta \theta = -0.15 \pm 0.10 \) and \( \delta \pm \Delta \delta = 2.10 \pm 0.48 \). Hence, the produced entangled state is: \( |\psi\rangle = 0.989 |\phi^+\rangle + (0.076 - 0.130i) |\phi^-\rangle \).
Figure 2: Coincidence for all four linear polarizer angles $\alpha = 0^\circ$ (blue), $45^\circ$ (green), $90^\circ$ (red), $135^\circ$ (orange) using quTools [30]. Polarizer angle $\beta$ was varied over full $360^\circ$ at a step of $10^\circ$ for each of four $\alpha$’s. Five data points were taken and averaged at each polarizer combination. The uncertainty of polarizer angles is $1^\circ$. Curves are fitted with sine functions predicted from pure state model as discussed in entanglement characterization. The pure quantum state is fitted to be $|\psi\rangle = 0.989 |\phi^+\rangle + (0.076 - 0.130i) |\phi^-\rangle$. Notice that the colors are chosen to be consistent with the following measurement in Fig. 6.

**Benchmarking: Bell inequality violation using SPCM.**

Our next step is to calculate the Clauser-Horne-Shimony-Holt (CHSH) inequality violation [31, 32] using SPCM (Single Photon Counting Module). The inequality can be written as

$$S = E(\alpha, \beta) + E(\alpha', \beta) - E(\alpha, \beta') + E(\alpha', \beta') \leq 2$$

where $E(\alpha, \beta) = \frac{N_{VV}(\alpha, \beta) + N_{HH}(\alpha, \beta) - N_{VH}(\alpha, \beta) - N_{HV}(\alpha, \beta)}{N_{VV}(\alpha, \beta) + N_{HH}(\alpha, \beta) + N_{VH}(\alpha, \beta) + N_{HV}(\alpha, \beta)}$ from the fitted curves in Fig. 2. We obtain the values shown in Table I.

Using these values, we calculate the $S$ parameter $S = 2.679 \pm 0.007 > 2$, clearly showing the violation of the CHSH inequality. The uncertainty is calculated using $\Delta S = \ldots$
Table I: The number of coincidences used to calculate the S-value.

| (α, β)° | N_{VV} | N_{HV} | N_{VH} | N_{HH} | E(α, β) |
|---------|--------|--------|--------|--------|---------|
| (0,22.5) | 17656  | 4393   | 3344   | 23767  | 0.685243|
| (0,67.5) | 3344   | 23767  | 17656  | 4393   | -0.685243|
| (45,22.5)| 19064  | 2984   | 5516   | 21596  | 0.654174|
| (45,67.5)| 21596  | 5516   | 2984   | 19064  | 0.654174|

\[ \sqrt{\sum_{\alpha,\beta} \Delta E(\alpha, \beta)^2} \quad \text{and} \]

\[ \Delta E = \frac{2[N_{VV}(\alpha, \beta) + N_{HH}(\alpha, \beta)][N_{HV}(\alpha, \beta) + N_{HV}(\alpha, \beta)]}{(N_{VV}(\alpha, \beta) + N_{HH}(\alpha, \beta) + N_{HV}(\alpha, \beta) + N_{HV}(\alpha, \beta))^2} \]

\[ \times \sqrt{\frac{1}{N_{VV}(\alpha, \beta) + N_{HH}(\alpha, \beta)}} + \frac{1}{N_{HV}(\alpha, \beta) + N_{VH}(\alpha, \beta)} \]  

(6)

ENTANGLEMENT CHARACTERIZATION WITH TPX3CAM

Having set a benchmark for the measurements, we now proceed to characterize the entanglement source using the Tpx3Cam. Instead of being measured in the single-photon detectors, we now send the entangled pairs to another experimental setup where they are converted to photoelectrons, amplified in different regions of the intensifier and sub-sequentially time-stamped in the fast camera.

The photon pairs were recorded continuously by the camera for a given period of time, 5 minutes for each combination of polarizations. Figure 3 shows single photon hits recorded by the camera in a time slice of 5 ms, examples of the hits registered in the camera and the pixel occupancy map. Note that photons can be recorded by the same pixel multiple times during the 5ms time period as the pixel deadtime is only 1µs. If this is the case the latest pixel information is shown Figures 3a) and 3b). The two fiber-modes are clearly visible, corresponding to the areas of highest occupancy. The intensity distributions in the fibers follow the Gaussian modes as expected. The rate of photons in these regions was \( \approx 30 \text{ kHz} \), determined primarily by the output rate of the photon source at the fiber end (typically
Figure 3: a) Single photon hits recorded by the camera in a time slice of 5ms. The color encodes the time-over-threshold (TOT) in ns. b) same single photon hits recorded by the camera in a time slice of 5ms. However this time, the color encodes the time-of-arrival (TOA) in ns. c) Examples of zoomed-in photon hits. The left column shows TOT in ns; the right column shows relative TOA from the first hit pixel in ns. d) 2D occupancy map of the sensor (256 × 256 pixels) showing the photon hits for the full statistics of a five-minute run. The color encodes the number of times a particular pixel was hit in log scale.

≈ 150 kHz ) and the intensifier quantum efficiency.

The background, uniformly distributed over the photocathode surface in the occupancy map in Figure 3d), is caused by spurious dark counts from the photocathode. This rate is ≈ 50
times smaller than the measured single photon rate and could be further reduced by cooling the intensifier, which in our measurements was operated at room temperature. We also note that the background photo-electrons arrive at random times and thus will be suppressed by requiring coincidence between the two photons, as shown below.

Data processing

To perform a Bell’s inequality measurement using data from the fast camera, we gathered 72 five-minute long datasets corresponding to different settings of the polarizers. The raw data is processed following several steps: i) time-ordering of the hit pixels, ii) identification of the pixel clusters corresponding to the single photon hits, iii) centroiding of the pixel clusters, iv) TOT corrections to improve the time resolution, v) calculating the number of coincidences and vi) Bell analysis.

I. Time-ordering: Tpx3Cam reads out the hit pixels asynchronously, which might alter the time order, especially at high rates. Thus, the first step of the data processing, is to time-order them to prepare the data for the cluster finding.

II. Clustering: Clusters are groups of pixels adjacent to each other and within a preset time window. We used a recursive algorithm to look for the clusters: for a pixel, a 1 $\mu$s time window is applied to select other pixels close in space and time to the first one. Each pixel in a cluster should have a neighboring pixel separated not more than 300ns. The algorithm then chooses another pixel, not contained in a cluster, shifting the time window and starting the process anew.

III. Centroiding: A photon hit in the camera comprises on average $\approx 4$ pixels with measured TOA and TOT, which allows applying a centroiding algorithm. The TOT information is used as a weighting factor, helping to define the geometrical center of the cluster, yielding an estimate of the coordinates $x, y$ of the incoming single photon. The arrival time of the photon is estimated by using TOA of the pixel with the largest TOT in the cluster. The above TOA is corrected as described below.
IV. TOT correction: Photons in the entangled pairs are simultaneous. Therefore, they will have the same time-stamps, within the time resolution. Precise timing is a powerful handle to reduce the random background, thus improving the camera time resolution and the signal-to-background ratio. For this, the timing information must be corrected to account for the so-called time walk. In the Timepix3 front-end electronics, within each pixel, the discriminator has a constant threshold, so larger signals cross the threshold earlier producing smaller TOA and larger TOT values. The correlation of ToA and ToT allows to calibrate the constant threshold effect and, hence, to improve the time resolution.

Typically, the correction requires a time reference, for example from a laser, to determine the shift, as in the ion imaging experiments [24]. However, in these experiments, the entangled pairs are generated continuously, so a different procedure, which does not rely on an external time reference had to be developed. This was done as follows: the zero reference time of each cluster was defined as the TOA of the earliest pixel in the cluster, TOA\textsubscript{centroid}, so a time difference (dTOA = TOA - TOA\textsubscript{centroid}) can be calculated for each pixel in the cluster and associated with the pixel TOT value. Using a range of large TOT values where the dTOA was stable (typically for TOT\textsubscript{centroid} greater than 1500ns there is no change in dTOA) as a global time reference, a lookup table of dTOA shifts for different TOT values was obtained, shown in the top graph of Figure 4. This procedure reduces the time difference between entries within a given cluster from $\sim 100$ ns to a few ns correcting the time walk for individual pixels.

The time resolution after the TOT correction is shown in the top graph of Figure 4 as a function of TOT. The time resolution is determined from the distribution of time difference between two entangled photons. The distribution is fit with a Gaussian function, and the resolution is defined as the sigma of the fit divided by $\sqrt{2}$. This accounts for the fact that variance of the time difference between two photons is larger than the resolution per photon. Therefore the cited time resolution is per photon assuming equal resolution for each of two photons. To determine the dependence of the resolution on TOT we required that both photons have TOT greater than a certain value on the TOT axis. The bottom graph shows the distribution of the TOT values.
Figure 4: Time correction and time resolution as a function of TOT (top) and TOT distribution (bottom). In the top figure, the red dots show the TOA shift due to the TOT correction. The green dots show the time resolution as function of TOT.

V. Time coincidences: to identify pairs of simultaneous photons we selected areas of the sensor corresponding to regions illuminated by the fibers. The corresponding square areas were $42 \times 42$ pixels for the right fiber and $30 \times 30$ pixels for the left fiber as they are shown in Figure 3(d). Then, for each photon detected in one region, we looked for its associated pair at the closest time in the second region. The time difference distribution for these detected pairs is shown in Figure 5 for several settings of the polarizers, as defined in the Bell measurement above. The prominent peaks correspond to the pairs of entangled photons, while the small flat background corresponds to random coincidences of uncorrelated photons. Due to the finite quantum efficiency and other losses, not each photon from the source will have a detected synchronous partner in the other fiber. In this case, it will be paired with a random photon, either from the photon source (more likely) or from the spurious photocathode counts, giving rise to the flat background.

Each distribution was fit to a function consisting of two Gaussians and a constant accounting for the flat background of random coincidences. The number of coincidences was estimated as the area under the Gaussian functions. The dependence of the number of coincidences
on the polarizer settings indicates that the operation of the camera detection setup closely resembles the SPCM operation, despite the use of an entirely different registration scheme for single photons.

Figure 5: Distribution of time difference between two photons in different fibers for selected pairs of polarization settings combinations: $\alpha = 0^\circ$ (blue), $\alpha = 40^\circ$ (orange), $\alpha = 80^\circ$ (red) and $\alpha = 120^\circ$ (green) with $\beta = 90^\circ$. The amplitudes for different polarization combinations are determined by the entangled state projection. Flat background is the result of uncorrelated photon background. The total number of coincidences is calculated by integration over the Gaussian curves.

Bell’s inequality violation with a fast camera.

Our next step is to study the dependence of the coincidence measurements on the polarization projective measurements of the two-photon state. In the measurements, one polarizer was varied in $20^\circ$ steps for four fixed values of the other polarizer: $0^\circ$, $45^\circ$, $90^\circ$ and $135^\circ$. The dependence of the number of coincidences versus the polarizer angle is shown in Figure 6. The data points were fitted with a sine function with the period, phase, amplitude and
offset as free parameters. The fit results are shown in Table II.

Figure 6: **Coincidences as a function of polarization:** showing the dependence of the signal amplitude (number of coincidences) for different settings of a Clauser-Horne-Shimony-Holt type Bell inequality test. We use the same color regulation as Figure 2, with fix polarization $\beta = 0^\circ$ (blue), $\beta = 45^\circ$ (green), $\beta = 90^\circ$ (red) and $\beta = 135^\circ$ (orange). The uncertainty in polarization is $1^\circ$. Fitting parameters can be found in Table II.

With these experimental parameters, we follow the procedure outlined in the benchmarking section, to obtain a Bell-state inequality S-value with the Tpx3Cam setup. The obtained value is $2.78 \pm 0.02$, well above the classical limit of 2, and closer to the Tsirelson Bound of $2\sqrt{2}$ (2.82) than the SPCM measurements. We attribute this improvement to the better rejection of random background enabled by the fast camera.
Table II: The parameters of the sin functions used to fit the polarization function. The function $A \sin\left(\frac{2\pi}{T}(x + \phi)\right) + D$ is used to fit the values. Here amplitude is defined as $A$, $T$ is period, phase shift is $\phi$, and offset is $D$.

| Polarization $\beta$ | Amplitude $A$ | Period $T$ [deg] | Phase shift $\phi$ [deg] | Offset $D$   |
|----------------------|---------------|-------------------|--------------------------|-------------|
| 0                    | 1.000         | 180.2 ± 0.2       | −44.0 ± 0.2              | 0.999 ± 0.005 |
| 45                   | 0.851 ± 0.005 | 180.8 ± 0.2       | −3.8 ± 0.2               | 0.877 ± 0.004 |
| 90                   | 0.735 ± 0.004 | 180.5 ± 0.2       | 46.5 ± 0.2               | 0.732 ± 0.004 |
| 135                  | 0.822 ± 0.005 | 180.2 ± 0.2       | 94.2 ± 0.2               | 0.853 ± 0.004 |

Position dependent Bell analysis.

One of the clear advantages of using high-speed cameras for quantum state characterization is the capacity to analyze multiple processes simultaneously. In our last experiment, we probe the capacity of the fast camera to analyze 81 entangled pairs in parallel. To simulate the latter, we divided the areas illuminated by the fiber’s output into nine subareas, forming a $3 \times 3$ matrix as shown in the two fiber regions in Figure 3. We then analyze each pair-wise combination (81 total combinations) independently and reproduce the Bell analysis presented above for each of them. In order to accumulate enough statistics for these spatially resolved measurements, we took one-hour-long extended datasets, corresponding to the 16 combinations of the polarizers settings, which are needed to calculate the Bell’s inequality violation. The total number of recorded photons was considerable, about $10^9$, and required efforts to implement parallel processing of the data. The data analysis was performed within the modular scientific software framework root developed at CERN [33]. Figure 7 shows the results of the parallel evaluation of 81 Bell’s inequalities. Each box represents a specific spatial combination of subareas. The corresponding S-value is color-coded with the corresponding uncertainty shown in the center of the box. The results show that the S-value is uniform within the experimental errors with no position dependence visible.
DISCUSSION AND OUTLOOK

We have demonstrated that the spatial characterization of photonic entanglement can be performed employing the intensified Tpx3Cam camera. The camera can simultaneously time-stamp multiple single optical photons with nanosecond timing resolution while also capturing their spatial information. The S-value results confirm that the fast camera spatial characterization of quantum-states in parallel is a viable alternative to be used in scaled up quantum systems.

The photon rate in these experiments was limited by the photon source to about 100 kHz. This is a factor of 100 lower than the maximum rate allowed by the camera, which should be capable of working with much brighter sources of entangled photons. Another specification of the fast camera, the quantum efficiency (QE) of the image intensifier, is another critical parameter for the efficient detection of entangled photons. New photocathodes based on GaAs offer QE of $\sim 35\%$ in the same wavelength range as used for these studies [34].

New imaging technologies based on monolithic silicon devices, such as SPADs (Single Photon Avalanche Devices) are rapidly improving and could become competitive soon. Since the devices have internal amplification, the image intensifier is not required, which is a considerable simplification. In addition, SPADs could have better time resolution and, potentially, higher QE, compared to the intensified cameras. The SPAD imagers started to appear on the market, and first applications for QIS have been reported [35]. Currently, the main limitation of the devices is the high dark count rate in the tens of MHz/cm$^2$ range, which may saturate the readout and lead to low signal-to-background ratio. Another difficulty is the integration of the photon sensing SPAD pixels and complex readout electronics in a monolithic device, which has many technical challenges. Also, in a SPAD, a single photon fires only one pixel producing a standard pulse so no centroiding is possible and, therefore, it is also impossible to distinguish a noise hit from useful signal.

From the QIS perspective, we have showcased the possibility of parallel processing of tens of entangled states in parallel by analyzing independent combinations of subareas illuminated by the two fibers, which is an unprecedented capability for quantum information processing.
As all pixels of the Tpx3Cm sensor act independently of each other, the dimensionality of this processing can be scaled up many-fold, for example, employing the same camera setup with brighter photon sources and/or multiple photon beams. We estimate that Tpx3Cam can successfully process at least $10 \times 10 = 100$ photon beams, each with a photon rate similar to the one used in these experiments. This technique may become a crucial tool for the real-time characterization of the performance for large entanglement-based quantum networks or circuits.

The camera also has the ability to count the number of spontaneous photons in the same fiber, given sufficient spatial separation. This offers the possibility of discerning an event with more than one photon pairs, an effect of the statistical distribution of the number of photons at the output of the SPDC process. This information was not used in the present analysis.

We also envision that our characterization setup can prove effective in other quantum information processing tasks, such as Hong-Ou-Mandel interference \[18\] and the characterization of entanglement encoded in orbital angular momentum modes \[36\]. Furthermore, it is well suited for the real-time benchmarking of quantum memories using OAM states \[37, 38\], and for the parallel processing of the information in many memories systems \[39\]. Lastly, it could also find a niche as a feedback tool in the positioning of long-distance free-space quantum communication channels forming intra-city quantum cryptographic networks \[40\].

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[1] Paul G. Kwiat, Klaus Mattle, Harald Weinfurter, Anton Zeilinger, Alexander V. Sergienko, and Yanhua Shih. New high-intensity source of polarization-entangled photon pairs. Phys. Rev. Lett., 75:4337–4341, Dec 1995.

[2] W. Tittel, J. Brendel, H. Zbinden, and N. Gisin. Violation of bell inequalities by photons more than 10 km apart. Phys. Rev. Lett., 81:3563–3566, Oct 1998.

[3] Jian-Wei Pan, Dik Bouwmeester, Harald Weinfurter, and Anton Zeilinger. Experimental entanglement swapping: Entangling photons that never interacted. Phys. Rev. Lett., 80:3891–3894, May 1998.

[4] Jacob F. Sherson, Hanna Krauter, Rasmus K. Olsson, Brian Julsgaard, Klemens Hammerer, Ignacio Cirac, and Eugene S. Polzik. Quantum teleportation between light and matter. Nature, 443(7111):557–560, Oct 2006.

[5] R. Ursin, F. Tiefenbacher, T. Schmitt-Manderbach, H. Weier, T. Scheidl, M. Lindenthal, B. Blauensteiner, T. Jennewein, J. Perdigues, P. Trojek, B. Omer, M. Furst, M. Meyenburg, J. Rarity, Z. Sodnik, C. Barbieri, H. Weinfurter, and A. Zeilinger. Entanglement-based quantum communication over 144 km. Nat Phys, 3(7):481–486, Jul 2007.

[6] B. Hensen, H. Bernien, A. E. Dréau, A. Reiserer, N. Kalb, M. S. Blok, J. Ruitenberg, R. F. L. Vermeulen, R. N. Schouten, C. Abellán, W. Amaya, V. Pruneri, M. W. Mitchell, M. Markham, D. J. Twitchen, D. Elkouss, S. Wehner, T. H. Taminiau, and R. Hanson. Loophole-free bell inequality violation using electron spins separated by 1.3 kilometres. Nature, 526:682, Oct 2015.

[7] K. S. Choi, A. Goban, S. B. Papp, S. J. van Enk, and H. J. Kimble. Entanglement of spin waves among four quantum memories. Nature, 468(7322):412–416, Nov 2010.

[8] M. P. Edgar, D. S. Tasca, F. Izdebski, R. E. Warburton, J. Leach, M. Agnew, G. S. Buller, R. W. Boyd, and M. J. Padgett. Imaging high-dimensional spatial entanglement with a camera. Nature Communications, 3:984, Aug 2012.

[9] Adetunmise C. Dada, Jonathan Leach, Gerald S. Buller, Miles J. Padgett, and Erika Andersson. Experimental high-dimensional two-photon entanglement and violations of generalized
bell inequalities. *Nature Physics*, 7:677, May 2011.

[10] John C. Howell, Ryan S. Bennink, Sean J. Bentley, and R. W. Boyd. Realization of the einstein-podolsky-rosen paradox using momentum- and position-entangled photons from spontaneous parametric down conversion. *Phys. Rev. Lett.*, 92:210403, May 2004.

[11] S. P. Walborn, A. Salles, R. M. Gomes, F. Toscano, and P. H. Souto Ribeiro. Revealing hidden einstein-podolsky-rosen nonlocality. *Phys. Rev. Lett.*, 106:130402, Mar 2011.

[12] Manuel Unternährer, Bänz Bessire, Leonardo Gasparini, David Stoppa, and André Stefanov. Coincidence detection of spatially correlated photon pairs with a monolithic time-resolving detector array. *Opt. Express*, 24(25):28829–28841, Dec 2016.

[13] Bradley M. Jost, Alexander V. Sergienko, Ayman F. Abouraddy, Bahaa E. A. Saleh, and Malvin C. Teich. Spatial correlations of spontaneously down-converted photon pairs detected with a single-photon-sensitive ccd camera. *Opt. Express*, 3(2):81–88, Jul 1998.

[14] Felix Just, Mykhaylo Filipenko, Andrea Cavanna, Thilo Michel, Thomas Gleixner, Michael Taheri, John Vallerga, Michael Campbell, Timo Tick, Gisela Anton, Maria V. Chekhova, and Gerd Leuchs. Detection of non-classical space-time correlations with a novel type of single-photon camera. *Opt. Express*, 22(14):17561–17572, Jul 2014.

[15] Robert Fickler, Mario Krenn, Radek Lapkiewicz, Sven Ramelow, and Anton Zeilinger. Real-time imaging of quantum entanglement. *Scientific Reports*, 3:1914, May 2013.

[16] Matthew Reichert, Xiaohang Sun, and Jason W. Fleischer. Quality of spatial entanglement propagation. *Phys. Rev. A*, 95:063836, Jun 2017.

[17] Matthew Reichert, Hugo Defienne, and Jason W. Fleischer. Massively parallel coincidence counting of high-dimensional entangled states, 2017.

[18] Michał Jachura and Radosław Chrapkiewicz. Shot-by-shot imaging of hong–ou–mandel interference with an intensified scmos camera. *Opt. Lett.*, 40(7):1540–1543, Apr 2015.

[19] www.amsdcins.com/tpx3cam.

[20] Enrico Pomarico, Jean-Daniel Bancal, Bruno Sanguinetti, Anas Rochdi, and Nicolas Gisin. Various quantum nonlocality tests with a commercial two-photon entanglement source. *Phys. Rev. A*, 83:052104, May 2011.

[21] T. Poikela, J. Plosila, T. Westerlund, M. Campbell, M. De Gaspari, X. Llopart, V. Gromov, R. Kluit, M. van Beuzekom, F. Zappon, et al. Timepix3: a 65k channel hybrid pixel readout chip with simultaneous toa/tot and sparse readout. *Journal of instrumentation*, 9(05):C05013,
[22] M. Fisher-Levine and A. Nomerotski. Timepixcam: a fast optical imager with time-stamping. *Journal of Instrumentation*, 11(03):C03016, 2016.

[23] A. Nomerotski, I. Chakaberia, M. Fisher-Levine, Z. Janoska, P. Takacs, and T. Tsang. Characterization of timepixcam, a fast imager for the time-stamping of optical photons. *Journal of Instrumentation*, 12(01):C01017, 2017.

[24] A. Zhao, M. van Beuzekom, B. Bouwens, D. Byelov, I. Chakaberia, C. Cheng, E. Maddox, A. Nomerotski, P. Sviha, J. Visser, V. Vrba, and T. Weinacht. Coincidence velocity map imaging using tpx3cam, a time stamping optical camera with 1.5 ns timing resolution. *Review of Scientific Instruments*, 88(9):113104, November 2017.

[25] Liisa M. Hirvonen, Merlin Fisher-Levine, Klaus Suhling, and Andrei Nomerotski. Photon counting phosphorescence lifetime imaging with timepixcam. *Review of Scientific Instruments*, 88(1):013104, 2017.

[26] B. van der Heijden, J. Visser, M. van Beuzekom, H. Boterenbrood, S. Kulis, B. Munneke, and F. Schreuder. Spidr, a general-purpose readout system for pixel asics. *Journal of Instrumentation*, 12(02):C02040, 2017.

[27] Photonis hi-qe red intensifier, www.photonis.com.

[28] B. Winter, S. J. King, M. Brouard, and C. Vallance. A fast microchannel plate-scintillator detector for velocity map imaging and imaging mass spectrometry. *Review of Scientific Instruments*, 85(2):023306, 2014.

[29] Photonis cricket advanced image intensifier adapter, www.photonis.com.

[30] www.qutools.com.

[31] Alain Aspect, Philippe Grangier, and Gérard Roger. Experimental tests of realistic local theories via bell’s theorem. *Phys. Rev. Lett.*, 47:460–463, Aug 1981.

[32] Alain Aspect, Philippe Grangier, and Gérard Roger. Experimental realization of einstein-podolsky-rosen-bohm gedankenexperiment: A new violation of bell’s inequalities. *Phys. Rev. Lett.*, 49:91–94, Jul 1982.

[33] root.cern.ch.

[34] Rene Glazenborg, James Marr, Adrian Martin, Raquel Ortega, Emile Schyns, Oswald Siegmund, and John Vallerga. Imaging photon camera with high spatiotemporal resolution. european microscopy congress 2016: Proceedings. pages 471–472, 2016.
[35] Manuel Unternährer André Stefanov Dmitri Boiko Matteo Perenzoni David Stoppa Leonardo Gasparini, Bänz Bessire. Supertwin: towards 100kpixel cmos quantum image sensors for quantum optics applications. *Proc.SPIE*, 10111:10111 – 10111 – 11, 2017.

[36] Robert Fickler, Radek Lapkiewicz, William N. Plick, Mario Krenn, Christoph Schaeff, Sven Ramelow, and Anton Zeilinger. Quantum entanglement of high angular momenta. *Science*, 338(6107):640–643, 2012.

[37] A. Nicolas, L. Veissier, L. Giner, E. Giacobino, D. Maxein, and J. Laurat. A quantum memory for orbital angular momentum photonic qubits. *Nature Photonics*, 8:234, Jan 2014.

[38] Dong-Sheng Ding, Wei Zhang, Zhi-Yuan Zhou, Shuai Shi, Guo-Yong Xiang, Xi-Shi Wang, Yun-Kun Jiang, Bao-Sen Shi, and Guang-Can Guo. Quantum storage of orbital angular momentum entanglement in an atomic ensemble. *Phys. Rev. Lett.*, 114:050502, Feb 2015.

[39] Michal Parniak, Michal Dabrowski, Mateusz Mazelanik, Adam Leszczynski, Michal Lipka, and Wojciech Wasilewski. Wavevector multiplexed atomic quantum memory via spatially-resolved single-photon detection. *Nature Communications*, 8(1):2140, 2017.

[40] Fabian Steinlechner, Sebastian Ecker, Matthias Fink, Bo Liu, Jessica Bavaresco, Marcus Huber, Thomas Scheidl, and Rupert Ursin. Distribution of high-dimensional entanglement via an intra-city free-space link. *Nature Communications*, 8:15971, Jul 2017.
Figure 7: Table of S-values for subarea matrices. In this configuration the two areas on the fast camera that are illuminated by photons from the fibers are divided into subareas, forming two $3 \times 3$ matrices. The coincidence thus decomposes into that of 81 possible pairs of a combination of subareas. Using these coincidences, we calculated the CHSH inequality violation and plotted the resulted S values in the form of 81 blocks in nine $3 \times 3$ matrices. The S-values are color coded with the corresponding uncertainty shown in the center of the box. This gives an intuitive illustration of the spatial distribution of entangled photon pairs. The black digits above each matrix give the position of the photon in the first fiber: $0 \times 0$ corresponds to the top left corner, $0 \times 2$ to the top right corner, $1 \times 1$ to the center.