

Generation and Detection of Hyperentangled Bell States at an Ultra-High Flux

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Abstract: We demonstrate both the generation and detection of an ultra-high flux of polarization Bell states using broadband hyper-entangled bi-photons that are quantum-correlated in both polarization and time-energy. Bell states of polarization embody the most basic form of two-state entanglement, and are a key component of quantum protocols of communication and sensing. High-speed generation, processing and detection of polarization Bell-states is therefore critical for quantum technology. However, all current protocols that employ polarization entangled photons are inherently slow, primarily due to the photo-detectors (Photomultiplier tubes, avalanche photodiodes, etc.) that can handle only 10^{6-7} photons/s, whereas sources may easily produce 10^{10-13} photons/s or more (if properly designed). We fully alleviate this detection bottleneck by resorting to physical detection of the bi-photons with nonlinear interferometry. We harness a generalized, dual polarization SU1,1 interferometer to generate, manipulate *and measure* all the triplet Bell-states at a flux of $\sim 5 \times 10^{11}$ photons/s, enhancing the speed of quantum processing by ~ 5 orders of magnitude compared to standard methods.

The Bell states of two particles, which are the maximally-entangled states of light polarization / atomic spins, are a cornerstone of quantum science and technology[1–4].

$$\begin{aligned}\Phi^\pm &= \frac{1}{\sqrt{2}} (|HH\rangle \pm |VV\rangle) \\ \Psi^\pm &= \frac{1}{\sqrt{2}} (|HV\rangle \pm |VH\rangle)\end{aligned}\quad (1)$$

(For light, H/V represents the horizontal/vertical polarization and $|XY\rangle$ denotes the two-photon state of polarizations X and Y) On the one hand, Bell states demonstrate the fundamental properties of quantum mechanics[5], while on the other hand Bell states are key to major applications in quantum technology[6], particularly for quantum communications. Consequently, methods for the generation of Bell states and their measurement are of great importance in experimental quantum optics, and a critical challenge is to process them at a high flux. While sources of high fluxes of entangled photons are readily available through broadband parametric down-conversion (PDC), generating up to 10^{10-13} photon-pairs/s [7], measurement is a major bottleneck: Current methods of measurement can handle only fluxes of 10^{6-7} bi-photons/s, primarily due to the limited electronic bandwidth of standard photo-detectors [8–10]. Thus, new methods to generate and measure Bell states at high flux are desired.

For this purpose of mass generation and processing, time-energy entanglement is a major tool. Time-energy entangled photons are simultaneously correlated in both

energy sum (or frequency sum $\omega_1 + \omega_2 = \Omega$) and time-difference $t_1 - t_2 \rightarrow 0$ [11], while the individual energy / time of each photon is not defined. Since the time-correlation between the photons is very short ($\sim 100fs$ in our experiment, limited only by the frequency uncertainty of each photon), a high flux of *single* pairs can be generated [12]. These states are typically produced via spontaneous parametric down-conversion (PDC) under broad phase-matching conditions.

Normally, the simplest method for generating polarization-entangled Bell states is to rely on type-II down conversion in a nonlinear χ_2 crystal, which generates bi-photons of crossed polarizations, and naturally produces the $\Psi^\pm$ Bell states[13]. However, the phase-matching bandwidth of type-II PDC is considerably lower than that of type-0 (or type-I) and the nonlinear coefficient is generally lower, which in turn limits the photon flux[14]considerably. Thus, for the generation of hyperentangled photons, we harness a type-0 configuration, which offers much higher conversion efficiency and broader phase-matching bandwidths (typically 10-100THz), eventually translating to a very high flux of entangled pairs ($\sim 5 \times 10^{11}$).

In our experiment, we employ two type-0 periodically-poled KTP crystals in a crossed configuration (see figure 1), such that the pump polarization dictates the amplitude-ratio and relative phase between the polarizations of the generated bi-photon state. Specifically, when the pump is polarized at $\pm 45^\circ$ (as shown in figure 1), it generates an equal amplitude in each of the crystals with equal/opposite phase, thereby producing the $\Phi^\pm$ Bell states[15]:

$$\begin{aligned}|\Phi^\pm\rangle &= \frac{1}{\sqrt{2}} (a_H^{\dagger 2} \pm e^{i\theta} a_V^{\dagger 2})|0\rangle \\ &= \frac{1}{\sqrt{2}} (|HH\rangle \pm |VV\rangle),\end{aligned}\quad (2)$$

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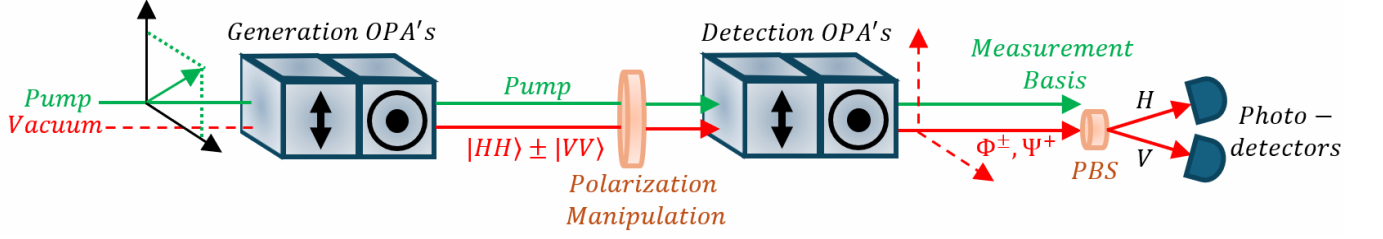


FIG. 1. Concept for the generation and detection of hyper-entangled photons: Polarization entangled bi-photons are generated by a pair of crossed type-0 nonlinear crystals, where each crystal acts as an OPA for one polarization (generating the $\Phi^\pm$ states) via SPDC over a broad bandwidth (limited by phase matching). Phase and polarization manipulations allow complete manipulation of the polarization Bell-state and selection of the detection basis. Another identical pair of crossed crystals detects the quantum state of the light by further amplification or annihilation of the bi-photons from the first pair, depending on the relative phase between the pair and the pump in each polarization (forming a dual-polarization SU(1,1) interferometer).

where $a_{H(V)}^\dagger$ is the creation operator for the horizontal (vertical) polarizations.

This configuration has already been used to generate entangled pairs in a polarization Sagnac interferometer [16]. In that experiment they achieved a photon rate of 10^7 photons/s, which, while very high for the input power (about $100\mu W$) is still several orders of magnitude below what we can generate, as well as fully process in our experiment ($\sim 5 \times 10^{11}$ bi-photons/s).

Due to the nature of type-0 crystals it also generates time-energy entanglement [7]. In addition, the correlation time of time-energy entangled photons is very short (inversely proportional to their bandwidth), indicating that the probability of multiple photon-pair emissions is dramatically reduced, allowing us to generate a photon flux of 10^{10-11} bi-photons/s, into a single spatial mode.

To generate the third triplet state (Ψ^+) one can apply the time-reversed Hong-Ou-Mandel effect by taking the state generated $\Phi^\pm$ and applying polarization manipulations. We do this by rotating the polarization of both photons by 45° using a $\lambda/2$ waveplate, which relates to the original HV basis as: $a_H^\dagger = \frac{1}{\sqrt{2}}(a_D^\dagger + a_A^\dagger)$, $a_V^\dagger = \frac{1}{\sqrt{2}}(a_D^\dagger - a_A^\dagger)$ where $a_{D(A)}^\dagger$ is the creation operator of the diagonal (anti-diagonal) polarization. Plugging these into equation 2 yields:

$$\begin{aligned} |\Phi^+\rangle_{HV} &= \frac{1}{\sqrt{2}}(a_H^{\dagger 2} + a_V^{\dagger 2})|0\rangle \\ &= \frac{1}{\sqrt{2}}(|D^{(s)}A^{(i)}\rangle + |A^{(s)}D^{(i)}\rangle) \\ &= |\Psi^+\rangle_{AD} \end{aligned} \quad (3)$$

indicating that Φ^+ can be transformed into Ψ^+ simply by rotating the polarization by 45° thereby completing all the triplet states. Since our photons were generated by broadband OPAs (with type-0 phase matching conditions), the signal and idler photons are also entangled in time-energy, indicating that we now have a pair of hyperentangled bi-photons.

The reversed Hong-Ou-Mandel is a two-photon interference effect, where two identical photons anti-bunch after meeting on a 50:50 beam splitter [17, 18]. This is possible due to the linear nature of beam splitters, we can run the standard Hong-Ou-Mandel “backwards” to separate pairs of photons. Using the time-reversed Hong-Ou-Mandel effect, it is possible to generate polarization entanglement between bi-photons, and due to our use of broadband type-0 PDC, the photons are entangled also in time-energy, thereby hyperentangled [19].

In order to measure the high flux of photons, we utilize an SU(1,1) interferometer [10, 20, 21]. In SU(1,1) interferometry, the traditional beam splitters of a standard Mach-Zehnder interferometer are replaced with parametric amplifiers, where the passage through the first crystal generates bi-photons, and when passed through the second crystal a bi-photon can be either annihilated or amplified (stimulate more pairs), depending on the phase ϕ relative to the pump. Thus, for destructive interference ($\phi = \pi$) the 2nd crystal annihilates photons only in pairs, thereby acting as a physical coincidence detector that operates at any photon-flux. This enables complete measurements of time-energy entangled states while enhancing signal-to-noise ratio and phase sensitivity [22, 23].

It has also been demonstrated that SU(1,1) interferometers can operate at high gain and bandwidth, making them suitable for high-throughput quantum state characterization and real-time processing of broadband entangled states [10, 23]. This approach has already proven useful for quantum sensing and communication protocols, including homodyne detection, stimulated Raman processes, and quantum key distribution (QKD) [24–26]. By combining polarization entanglement with time-energy entanglement, thereby achieving hyperentanglement [19], and using expanded SU(1,1) schemes, we can extend mass-processing capabilities to polarization based applications. The SU(1,1) interferometer is highly useful for sensing applications also beyond the regime of single bi-photons and effective coincidence, where it can gen-

erate squeezed light and demonstrate better-than-shot noise sensitivity [27, 28].

The experimental design, shown in figure 2 is constructed as an SU(1,1) interferometer in a folded configuration, where a pair of crossed OPA crystals both generates the hyperentangled bi-photons (in the forward direction) and measures them (in the backwards direction). This configuration acts as a double SU(1,1) interferometer - one for each polarization (if the polarization state is not manipulated between the passes). When the crossed-crystal SU(1,1) is pumped with a CW laser (532nm), which is linearly polarized at 45° relative to the crystal axes, we will generate (and measure) the $HH + VV$ state. In order to independently manipulate the polarization state and to control the measurement basis, we separate the down-converted bi-photons beam from the main pump beam using a dichroic filter and independently manipulate the polarization of the pump and the bi-photons with separate $\lambda/2$ plates ($\lambda/4$ double-passed), before returning back into the OPAs to be measured. This allows us to either transform the measurement basis (dictated by the pump polarization) or to transform the bi-photon's state (by manipulating the polarization of the bi-photons beam). The output bi-photons (after the 2nd pass through the OPAs) are directed to a double-spectrometer (home-built from a pair of dispersive prisms, a Wollaston PBS and a CCD camera) which measures the spectrum of each polarization separately, allowing us to observe the SU(1,1) interference fringes of both polarizations simultaneously.

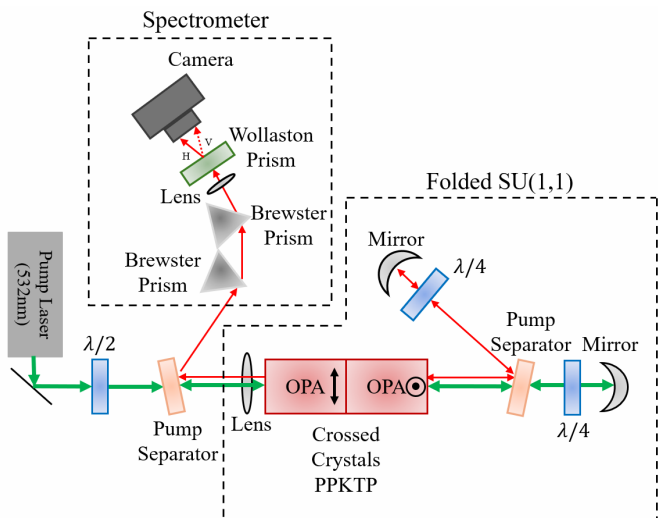


FIG. 2. Experimental layout

To explain the expected performance of this interferometer configuration and how the different Bell states are generated and detected at a high photon-flux, let us consider a simple example: When this interferometer is pumped by a laser with a diagonal polarization at 45° relative to the crystal axes the Φ^+ Bell state is generated,

and if no polarization manipulations are applied within the interferometer, it is also measured, causing SU(1,1) fringes of high-contrast to appear on the spectra of both polarizations *in phase* (see figures 4A, D), identifying Φ^+ .

If between the passes we rotate the pump polarization by 90° , we will shift the measurement basis to the Φ^- state. Thus, when we generate the Φ^+ state but measure Φ^- , the spectra of the two polarizations will still show high-contrast fringes, but now they will be π *out of phase* (figures 4B, E) which will identify Φ^- . Finally, to generate Ψ^+ , we rotate the polarization of the *bi-photons* by 45° to the A, D basis, as explained above. However, since the measurement remains in the H, V basis, the classification of Ψ^+ is indirect, by identifying that the polarization rotation erases the spectral fringes from the output of both polarizations (figures 4C, F), but further rotation to 90° revives them again. To illustrate how these principles are reflected in the actual experiment, Figure 3 shows the raw output images from our CCD camera (in the home-built spectrometer) for the different Bell states. The top/bottom line in each image shows the spectrum of the horizontal/vertical polarization, with the dashed lines representing the analyzed portion of the spectrum shown below in figure 4.

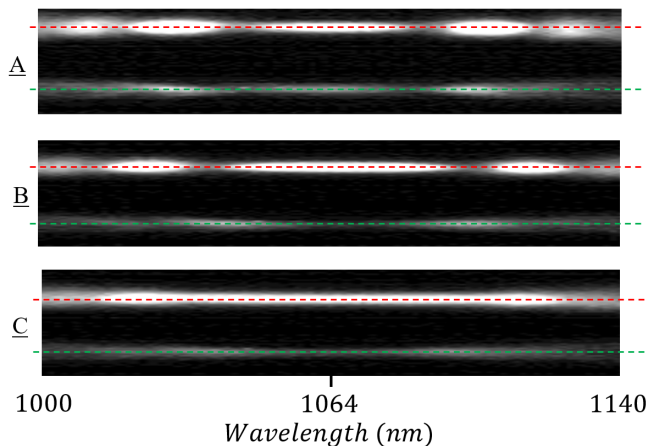


FIG. 3. Raw Camera Images; A – C show $HH + VV$, $HH - VV$, $HV + VH$ accordingly.

The configuration shown in figure 2 was constructed, and all the triplet Bell states were generated and measured. The measurements were performed by recording a continuous video (at 50 frames/s) of the free-running spectral interference pattern (fringes) for both horizontal and vertical polarizations simultaneously (figure 3). Evidently, the integration time of each video frame was sufficiently short compared to the typical time of phase fluctuations in the free-running SU(1,1) interferometer, indicating that every frame extracts the instantaneous spectral phases of both polarizations *simultaneously*, allowing to deduce the relative phase between them. To evaluate the interference contrast of each polarization we

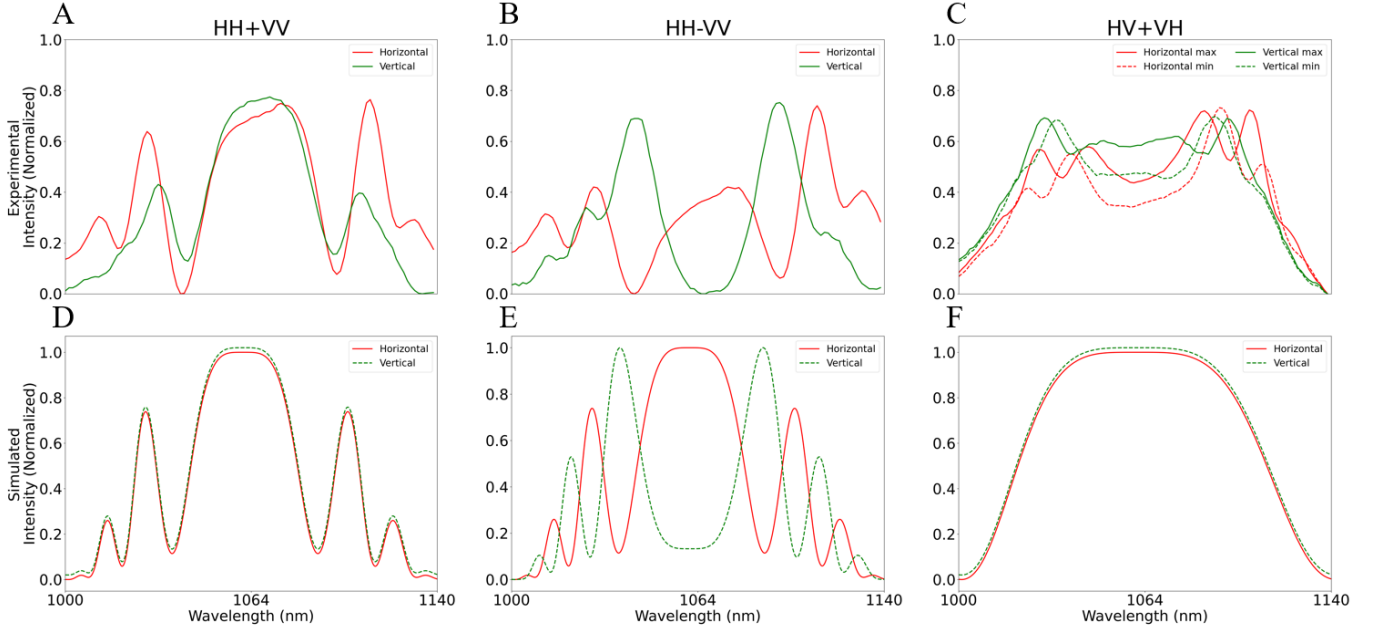


FIG. 4. Simulated and experimental results: *A – C* show the measured spectra of $HH + VV$, $HH - VV$, $HV + VH$ accordingly; *D – F* depict the simulated spectra of $HH + VV$, $HH - VV$, $HV + VH$ accordingly.

TABLE I. Summary of which wave plate rotations generate which Bell state

Rotation Angle of the Pump Plate	Rotation Angle of the SPDC Plate	Generated Bell State
0°	90° ^a	Φ^+
90°	90° ^a	Φ^-
90°	45°	Ψ^+

^a The relation between the generated Bell states and the setting angles of the various wave-plates (detailed explanation can be found in the experimental methodology). Note that to symmetrize the observed spectra of the two polarizations, we rotate the angle of the SPDC by 90° , for both $HH + VV$ and $HH - VV$. When rotated 90° the horizontally and vertically polarized photons swap (horizontal becoming vertical and vice versa), indicating that photons generated in the 1st crystal are measured in the 2nd and vice versa.

post-selected the frames with the maximum (constructive, $\phi = 0$) and minimum (destructive, $\phi = \pi$) intensity at 1064nm . The entanglement between the polarization states is directly indicated by the fact that despite the inherent instability of the phase of each polarization (that was randomly drifting and fluctuating), the relative phase between the two polarizations remained stable at all times. Specifically, when generating $HH + VV$ (or $HH - VV$), we selected frames where the horizontal polarization was at a maximum at 1064nm and compared to the spectral fringes of the vertical polarization in the same frame (same time), showing the phase alignment (or anti-alignment) between the polarizations (figures 4A, D and 4B, E). When generating $HV + VH$ the interference should ideally vanish, indicating that we can

infer the fidelity of the generated state from the residual interference contrast we observe. We therefore extracted the residual interference contrast by selecting the frames with the maximum and minimum intensity of the horizontal/vertical polarization at 1064nm ($\text{contrast} = 100 * (I_{\text{max}} - I_{\text{min}}) / (I_{\text{max}} + I_{\text{min}})$), where $I_{\text{max/min}}$ is the maximum/minimum intensity at 1064nm . Again, both polarizations were always evaluated from the same frame.

The measurement settings for the various polarization states are outlined in table I, and the results are presented in figure 4, where the top row of graphs shows the measured spectra at the interferometer output for the two polarizations and the bottom row illustrates the corresponding calculated theoretical spectra, which show a rather good match between the experiment and theory. Specifically, for the Φ^+ state (Figure 4A, D) the spectral fringes of the two polarizations are in phase, and for the Φ^- state (Figure 4B, E) they are π out of phase, as expected and calculated. For the Ψ^+ state, which is projected by the measurement onto the mutually unbiased pair of $\Phi^\pm$, one expects the contrast to vanish when rotating the polarization of the SPDC by 45° . Indeed, Figure 4C, shows a dramatic reduction of the fringe contrast for both polarizations (from $\sim 80\%$ for $HH \pm VV$ down to $\sim 10\%$ for $HV - VH$). The residual interference is likely due to fact that the crystal lengths are not exactly identical, which causes an undesired residual birefringence that is not compensated in our setup.

Since we observe the fringe pattern with a CCD camera, our measurement speed is low relative to the rate at which the photons arrive, indicating that we measure the

(rather large) *average* number of photons per pixel, which basically reflects the probability to detect a photon at a given wavelength. Note however, that even with this long integration time the experiment is performed well within the regime of single bi-photons, since the parametric gain of both crystals is very low, indicating that the average number of photons *per coherence time* is far less than one. In addition, the "coincidence" measurement is performed physically within the 2nd crystal pair of the SU(1,1) interferometer, which is inherently ultra-fast, and therefore detects the pairs "one by one", as reflected by the full utilization of the broadband spectrum.

In conclusion, we demonstrated both the generation and complete quantum measurement of an ultra-high flux of hyperentangled bi-photons in both polarization and time-energy. The ultra-fast measurement of the entire flux is made possible by harnessing the nonlinear SU(1,1) interference as a physical two-photon detector. In the future, our concept can be used for applications in quantum metrology [29] as well as quantum computing [30]. For metrology, we can envision the polarization entanglement to be useful to detect small birefringence of materials, with an accuracy beyond the classical shot noise limit [31]. The Bell states generated can also be useful for quantum communication, where the large bandwidth can immediately translate to speed. Specifically, one can frequency-multiplex many communication channels simultaneously across the bi-photons spectrum [25].

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