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PAPER

Emulating multiparticle emitters with pair-sources: digital discovery of a quantum optics building block

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Abstract

Linear quantum optics is advancing quickly, driven by sources of correlated photon pairs. Multi-photon sources beyond pairs would be a powerful resource, but are a difficult technology to implement. We have discovered a way in which we can combine multiple pair-sources to act analogous to sources of four, six or even eight correlated photons for the creation of highly entangled quantum states and other quantum information tasks. The existence of such setups is interesting from a conceptual perspective, but also offers a useful abstraction for the construction of more complicated photonic experiments, ranging from state generation to complex quantum networks. We show that even just going from probabilistic two-photon sources to effective four-photon sources allows conceptually new experiments for which no other building principles were known before. The setups which inspired the formulation of these abstract building blocks were discovered by a computer algorithm that can efficiently design quantum optics experiments. Our manuscript demonstrates how artificial intelligence can act as a source of inspiration for the scientific discoveries of new ideas and concepts in physics.

Probabilistic photon pair creation processes have long been a workhorse for photonic quantum information, and are at the core of many fundamental experiments and early-state applications of quantum optics [1]. Pair sources can be realized through non-linear processes such as spontaneous parametric down conversion (SPDC) or four-wave mixing [2]. Combining photon pair creation processes through linear optical components is at the basis of many recent integrated photonics advances [3–6].

The experimental realization of optical non-linearities that produce more than two correlated photons is an active area of research [7–11]. While these multi-photon sources would be a powerful resource for the creation of highly entangled photonic states [12], current implementations are not yet reliable enough for this task.

In this work we present previously unknown experimental setups that emulate a probabilistic multiphoton-emitter built only from photon-pair sources. Concretely, we show how probabilistic pair sources can be combined combined to generate effective four-, six- and even eight-photon emitters. In the remaining text, we explain the interference process these constructions are based on. We also show how our findings can have practical application in quantum state generation, for quantum communication and for quantum gates. We aim to introduce not only concrete constructions for specific quantum optical setups, but also develop an abstract way of viewing parts of those setups that act as a resource and can be used as a building block in more general constructions. Most of our examples deal with effective four-photon emitters, which we use to demonstrate that abstracting a complicated experimental configuration into a simple abstract object allows for the design of new experiments with properties for which no blueprints were known so far.

The results of this work are especially promising as integrated photonic chips have made impressive technological progress recently and our methods offer great potential for the design of experimentally realizable setups [3, 4, 6, 13–15].

At a bigger picture, we show that it is possible to identify new conceptual ideas in quantum physics from solutions discovered with AI techniques presented in [16, 17]. Researchers have started to use artificial-intelligence based design to discover suitable and experimentally feasible setup blueprints [16, 18–23] (see a review in [24]). The setups we show in figures 2–5 are the result of our own algorithmic search for experimental designs. In this paper, we demonstrate the conceptualization and application of the solutions found by a computer. This result therefore also contributes to the emergent field of automated scientific discovery, which has previously shown interesting ways to rediscover known physical symmetries [25], conserved properties [26], physical coordinate [27] or symbolic formulas for physical systems [28–30] and the discovery of new ideas in quantum optics [31, 32].

Background: probabilistic multi-photon emitters—*Photon pairs*—The action of a probabilistic pair source can be summarized by the formula

$$\left(1+ga^{\dagger}b^{\dagger}+\mathcal{O}\left(g^{2}\right)\right)|\mathrm{vac}\rangle\,, \tag{1}$$

where $a^{\dagger}$ and $b^{\dagger}$ are creation operators acting on the vacuum $|\mathrm{vac}\rangle$ and g is e.g. the pump parameter for an SPDC source. If one can choose the degree of freedom in which a particular source creates the two particles, it is possible to create entangled quantum states (which are essential features of quantum information) by combining multiple sources. This can be e.g. done through the framework of *entanglement by path identity* [31, 33] (explained in figure 1).

Entanglement by path identity and experimental feasibility—With the purpose of keeping this paper self-contained, we explain the necessary background in the following paragraph. A more detailed introduction can be found in [33]. The idea of path identity has been first proposed and experimentally demonstrated by Leonhard Mandel's group (after a suggestion by Jeff Ou) [36]. The idea is to overlap the paths of photons generated in different crystals such that there is no information about the origin of the photon. This idea has been applied in many recent experiments, for instance for quantum imaging [37], quantum metrology [38] and others [33].

This idea has also been introduced for the generation of quantum entanglement and multi-photon quantum interferometry [31], which is relevant in our manuscript. The experimental realization of creating a four-particle GHZ state from entanglement by path identity is shown in the bottom row of figure 1.

In the concrete representation, a blue laser (e.g. 400 nm) is split at a beam splitter. The two beams L_{p1} and L_{p2} each are directed to a SPDC crystal ($C1$ and $C2$), which probabilistically creates horizontally polarized photon pairs (depicted as red beams, e.g. 800 nm). The two laser beams propagate further and go through two more SPDC crystals ($C3$ and $C4$) which can also prepare photon pairs (red beams, vertically polarized photon pairs). In the meantime, the 800 nm photons produced in $C1$ and $C2$ also propagate through the transparent crystals $C3$ and $C4$ (without interactions), in such a way that their path is identical with the paths of photons produced in $C3$ and $C4$. In this way, there are only two possibilities how a four photon state with one photon in each of the detectors can be produced. The two possibilities have opposite polarisations, thus a GHZ state is generated.

The coherence requirements dictate that the path lengths L_1, L_2, L_3 and L_4 are equal within the coherence length of the down-converted photons as well as $L_{p3}=L_1$ within the coherence length of the pump laser. More detailed calculations on when coherence and indistinguishability can be assumed are provided in [33, 39] and the SI of [31]. The feasibility of path identity experiments has been demonstated in integrated photonics [2, 6] and bulk-optics [35, 40].

Destructive (frustrated) multi-photon interference—Besides generating entanglement, overlapping the paths of crystals can lead to interesting multi-photon interference effects. These effects are used in the computer-discovered concepts we describe in this work, so we briefly overview the idea.

In figure 2, we show an interference effect based on the path indistinguishability of two (figure 2(a)) and four (figure 2(b)) photons. In figure 2(a), two SPDC crystals can produce photons. The paths of the generated photons are overlapped such that there is no information about which of the two crystals ($A1$ and $A2$) they are generated in, and we add a tunable phase ϕ between the crystals. If we consider a case where only one photon pair is created, we do not know in which of the two crystals they were generated. As such, the quantum state is in a coherent superposition of being created in $A1$ or $A2$. The quantum state can be written as

$$|\psi\rangle=|1,1\rangle_{A1}+\mathrm{e}^{\mathrm{i}\phi}|1,1\rangle_{A2}=\left(1+\mathrm{e}^{\mathrm{i}\phi}\right)|1,1\rangle\,, \tag{2}$$

where $|1,1\rangle$ stands for one photon in paths a_1 and a_2, and the subscript indicates the origin of the photon pair. Changing the phase changes the photon pair probability; for example, if the phase is $\phi=0$, the amplitude doubles (the probability increases by a factor of four, with respect to the single crystal pair probability). For $\phi=\pi$, the two terms destructively interfere, and despite the fact that two crystals could

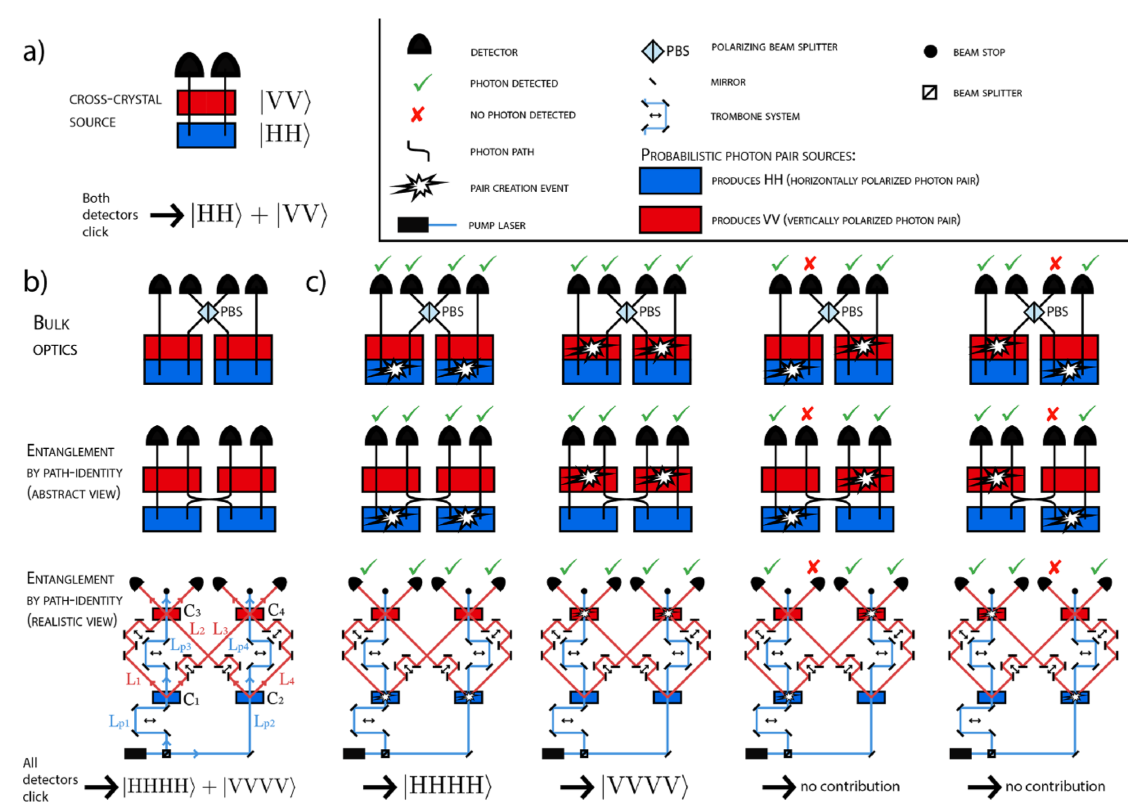

Figure 1. Creation of entangled states with linear optics. Highly entangled photonic quantum states can be created by the principle of *entanglement by path identity* [31, 33]. Multiple photon sources can be arranged in a way such that the paths of the emitted photons overlap and it becomes impossible to distinguish the origin of a photon when it arrives at a detector. Given the event of a detector clicking, a superposition of all possible origins arises. (a) shows a cross-crystal source [34], an experimental setup of two probabilistic two-photon sources which are combined to create a Bell state. Sources are shown as rectangular boxes, their colors indicate different photonic modes (e.g. polarization or orbital angular momentum). For the purposes of this text, we can assume that each crystal probabilistically emits a pair of photons with the modes encoded by the color of the crystal (the two photons can also have different modes). For experimental realization, mode shifters are used to control the output of each crystal and phase shifters adjust the relative phases between photon pairs [5, 35]. The black lines passing through the sources indicate the paths that the emitted photons take. The black half-ellipses at the end of the paths show the position of the detectors. When the detectors click, we know that two photons have been created, but have no information about their origin. Since each of the two sources creates a correlated pair of a different mode (either both horizontally polarized or both vertically polarized) and both crystals are pumped at the same rate, the clicking of both detectors selects for a two-dimensional Bell state. (b) Shows an experiment based on entanglement by path identity, which creates a two-dimensional four-particle GHZ state in two variations. The top shows a bulk optics setup, the bottom shows a setup with entanglement by path identity in abstract and concrete experimental representation (explained in detail in the main text). (c) Shows four possible events for both setups. Due to the probabilistic nature of the pair emissions it is at any time possible that two creation processes happen at the same time. By conditioning (or post-selecting) on a simultaneous click in all four detectors, we are selecting for events where each of the four photons travels to a different detector. The first two events satisfy this condition and produce each one of the terms of the two-dimensional GHZ state. Any other combination of two photon pair creation, either from one or multiple sources, will lead to (at least) one detector not seeing a photon (see the two examples on the right). As the state of the four photons is projected onto a superposition of all possible configurations, these setups result in a two-dimensional four-particle GHZ state with the click of all four detectors.

produce photon pairs, no photon pairs are detected in the final detectors. This interference mechanism was observed for the first time in 1994 [41], and integrated on a chip in 2019 [42].

In [43], a multi-photon generalization of this effect was proposed and observed for the first time in [2, 40], as seen in figure 2(b). Here, four crystals are arranged in such a way that there are two different ways to produce one photon in each of the four detectors b_1, b_2, b_3, and b_4. This can only happen if crystals B_1 and B_2 create four photons simultaneously, or if crystals B_3 and B_4 do. All other four-photon events do not produce four-fold coincidence detections (i.e. one photon in each of the four detectors).

If we add a phase between the two layers, the state can be written as

$$\begin{aligned} |\psi\rangle &\approx |1,1,1,1\rangle_{B_1\&B_2} + \mathrm{e}^{\mathrm{i}\phi}\,|1,1,1,1\rangle_{B_3\&B_4} \\ &= \left(1+\mathrm{e}^{\mathrm{i}\phi}\right)|1,1,1,1\rangle\,. \end{aligned} \tag{3}$$

As before, we see that four-photon events can constructively and destructively interfere by changing the phase ϕ. (Note: lower-order effects, i.e. when no pair or only one pair is created, are ignored because they cannot lead to four-fold coincidence counts. Higher-order events, where three or more pairs are created, are neglected here for simplicity because they occur with much smaller probabilities compared to four-photon

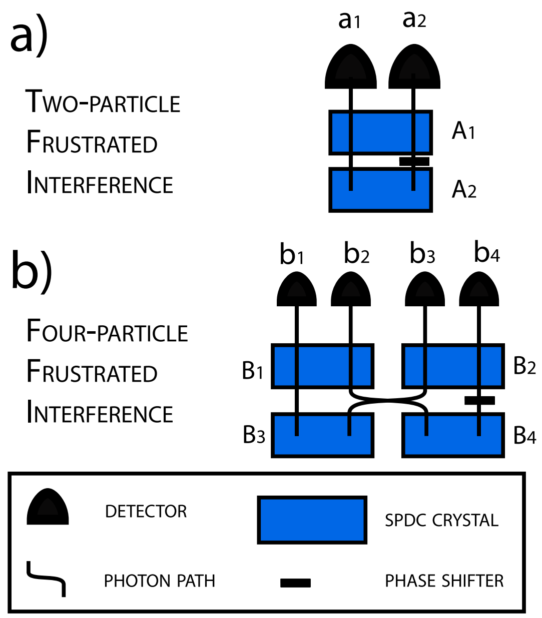

Figure 2. Examples for destructive interference. We show a setups resulting in destructive interference effects based on (a) two photons [41, 42] and (b) four photons [2, 40, 43]. Here, the two (four) photons can originate from two different locations, upper row and lower row. When the photons are arranged in such a way that there is no way to distinguish them, the final quantum state is in a coherent superposition of being created in either of the two origins, which allows for multi-photon interference. Destructive interference is a key element of the setups we propose later in this paper. In both examples, setting the phase shift to $\phi = \pi$ results in two terms with opposite sign for coincidence in all detectors. A detailed discussion can be found in the main text.

events. See details in [2, 40]). This four-photon event is a building block in the new experimental setup that we present below, which is the new result in this paper.

Photon Triplets and beyond—Highly entangled quantum states, such as the GHZ state are at the core of discoveries about fundamental physics [44]. Multi-particle sources have been investigated for their usefulness in creating such states. There have been attempts to experimentally realize three-photon sources through third-order parametric down conversion (TOPDC) [11, 45–48]. There are also other proposals for producing three photons through TOPDC, which have not yet been realized [9, 49–51]. Another approach to three-photon sources are cascaded SPDC crystals, as investigated experimentally in [52–55]. Multi-photon emitters as a quantum informational resource have been explored in [12, 56, 57]. Particularly, [12] describes that multi-photon emitters of higher photon number than two are a resource that allow for much higher entanglement than pair-sources. For example, it is possible to create a ten-dimensional six-particle GHZ state with four-photon sources, while only two-dimensional six-particle GHZ states are possible with pair-sources without ancillary photons. Similar to equation (1), a probabilistic four-photon source can be described as

$$\left(1 + g a^{\dagger} b^{\dagger} c^{\dagger} d^{\dagger} + \mathcal{O}\left(g^2\right)\right) |\text{vac}\rangle\,, \tag{4}$$

where $a^{\dagger}$, $b^{\dagger} c^{\dagger}$ and $d^{\dagger}$ are creation operators acting on the vacuum $|\text{vac}\rangle$ and g is e.g. the pump parameter.

Emulating multiparticle emitters with pair-sources—The setup shown in figure 3 acts analogously to a probabilistic four-particle emitter. When all detectors click, the additional components either produce four correlated particles or none (as described by equation (4)). All cross-terms, which would create only two photons, destructively interfere. This is achieved by an interference that works similar to frustrated multiphoton interference, an effect described in [43] and experimentally observed in [2, 40].

The relevant combinations of possible creation events can be categorized as follows: *(1)* two crystals fire and produce only one click in each of the ancillary detectors (a_i) and no clicks in the main detectors (b_i), analogous to a four-photon detector not firing. There are two combinations of crystals that produce this click-pattern. *(2)* emission events in four crystals sending one photon to each of the eight detectors (ancillary and main), analogous to a four-photon detector firing. There are two such combinations. *(3)* three crystals fire and produce one click in each of the ancillary detectors and two of the main detectors. All of these events interfere destructively. If their contributions would not cancel out, they would cause cross-terms. There are four pairs of such terms.*(4)* three or four crystals fire and send more than one photon to one detector. Such terms can be excluded by post-selecting the final experiment on clicks in each detector, as the additional photon will be missing in a different detector.

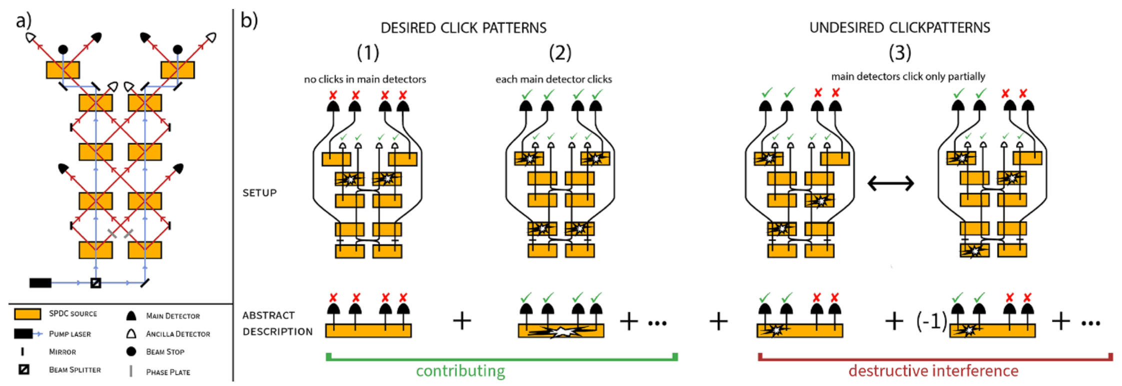

Figure 3. Quantum interference of setup for emulating a four-particle emitter (post-selected). (a) Concrete experimental blueprint of the idea (following the same idea as described in figure 1.) A laser (blue lines) is split into two arms. Each of the two arms pump 5 SPDC crystals. The paths of the generated photons (red lines) are overlapped such that no information about their origin exists. Detailed examination of click patterns produced by the four-particle emitter. (b) Abstract description: different click-patterns have different combinations of two-photon sources that can create them. For this setup to emulate a four-photon emitter, it is essential to produce a vacuum term, where no main detector clicks, and a four-photon term, where all four main detectors click. All events which create only two photons should destructively interfere with another event. Pair creation events are shown with a star shape on the corresponding source. Following the paths from the emitters to the detectors shows that this event results in exclusively ancillary detector clicks (the smaller, bottom row of detectors). This is comparable to a four-photon emitter not firing to the four main detectors (cross for no detection, checkmark for detection). (3) Shows two events that send only two photons to the main detectors, which would not occur in a four-photon emitter. Due to a phase difference their contributions cancel. Higher order excitations produce other click-patterns but have a lower count-rate due to having a smaller probability.

Real multi-photon emitters so far have only been demonstrated for $N = 3$ (photon triplets, with measured count rates of 0.1–5 Hz [48, 52, 54] and proposed count rates of $\sim$10 Hz [9] to $\sim$160 Hz [51]), and is experimentally unclear how it can be achieved for $N > 3$.

We show a way to emulate the critical behaviour of true multi-photon emitters, roducing $N = 4$ (and two bigger examples), using already well-established experimental techniques. Specifically, we only need photon-pair-creation processes (e.g. SPDC), four of them at the same time. Experiments with four and more simultaneous pair creations have been reported in many cases [58–60]. A fraction of $2/\binom{13}{4}$ of all fourth order SPDC event correctly generate four-photon emission. This factor stems from the fact that in this case four out of 10 crystals are firing (unordered sampling with replacement). With realistic experimental values ($p = g^2 = 0.16$, repetition rate $r = 10^8$ Hz) we estimate a count rate of $\sim$180 Hz for a four-photon emitter. This is similar to the highest proposed $N = 3$-photon emitter count rate. However, we produce an effective $N = 4$-photon probabilistic emission, and our proposal is based purely on well-known experimental technology. For a more conservative estimation with $p = 0.1$ [59] we expect a count rate of ~28 Hz.

To consider a decreased efficiency due losses at detectors and SPDC crystals, we assume the efficiency of each detector to be $E_D = 95\%$ and the transmission loss to be 1% per element for AR coated surfaces of the optical elements. the transmissivity of an individual crystal to be $E_T = 99\%$. A conservative estimate of the overall efficiency—using the longest path (passing through four crystals—is $E = E_D^8 \times (E_T^4)^8 \approx 48\%$, which reduces the effective count rate to $\sim$13 Hz.

Application of concept—At this point, we wondered about the broadness of the insight we have gained from building the abstraction of describing a combination of pair-sources as multi-particle emitters. Can it be employed in more scenarios than where we have initially encountered it?

To show that our abstract view does not only simplify the description of a particular setup, but can also be useful for designing experiments, we apply it to construct generalizations of setups for high-dimensional (A) state creation, (B) entanglement swapping, and (C) quantum gates (see SI).

(A) State creation—Previously, it was not clear how to create beyond four-particle GHZ states with more than three dimensions with pair-sources, as simple extensions would lead to cross-terms [16, 61, 62]. The experimental setup for the state $|\mathrm{GHZ}\rangle_4^3 = |0000\rangle + |1111\rangle + |2222\rangle$ is shown in figure 4(a). With the setup we have found, we can create the state $|\mathrm{GHZ}\rangle_4^4 = |0000\rangle + |1111\rangle + |2222\rangle + |3333\rangle$ (figure 4(b)). We see that it uses the emulated four-photon emitter to extend the three-dimensional setup, avoiding cross terms. This extension can be performed multiple times to produce states of arbitrary dimension d ($|\mathrm{GHZ}\rangle_4^d$). This is shown in figure 4(c).

While already an effective four-photon emitter can be used to design, by hand without computers, experimental setups that go beyond current known design rules for two-photon emitters, we also discovered (with an automated computational search [17]) effective six- and eight-photon emitters. They are shown in figure 5, and follow similar design principles as the four-photon emitters. They as well can now be used as

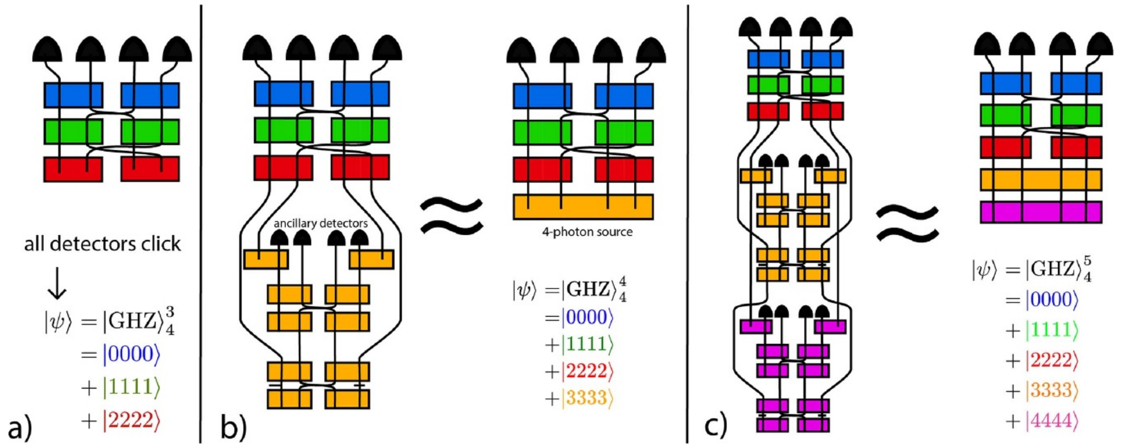

Figure 4. Creation of multi-particle entangled states (post-selected). Colors indicate different photonic modes. (a) Shows an experimental setup based on entanglement by path identity for creating a three-dimensional four-particle GHZ state, introduced in [31]. An intuitive explanation why the photon paths are set-up in this way can be reached through an abstract graph-theoretical description [63]. (In short: these are the only three possibilities to produce 4-photon coincidences in all four detectors from two pair sources.). While it is an extension of the two-dimensional setup shown in figure 1, there is no straightforward way of adding higher dimensions due to resulting cross terms [64] (b) shows our proposed setup which achieves the creation of the state $|\mathrm{GHZ}\rangle_4^4$ using entanglement by path identity. This setup extends the three-dimensional setup by including the setup shown in figure 3. As this behaves effectively as a four-photon source, which sends a photon to each of the four detectors, a fourth term is included in the superposition. It is essential that this four-photon source is used in an experiment conditioned on all detectors clicking. (c) illustrates how one can construct setups for the creation of four-particle GHZ states for five dimensions with two emulated four-particle sources, showing that this abstraction can be applied multiple times. A four-photon source is a useful resource, as multiple copies can be stacked together multiple times (analogously to (b) and (c)) to create high-dimensional four-particle GHZ states in a straightforward way. A more detailed description of how to construct setups for arbitrarily high dimensional four-particle GHZ states is provided in the SI. Without knowing the construction proposed in figure 3 we are not aware of any human or algorithmic construction, which can achieve arbitrarily high dimensions with only pair-sources.

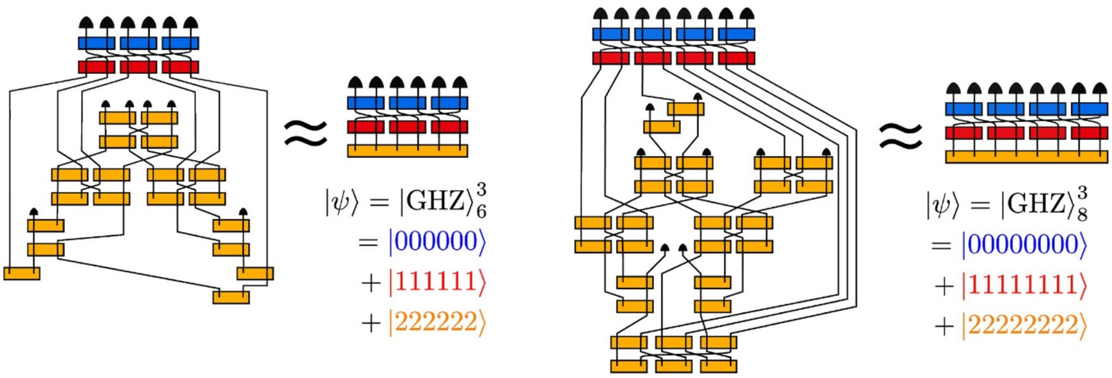

Figure 5. Creation of multi-particle entangled states for larger photon numbers (post-selected). We also discovered effective six-photon emitters (left) and eight-photon emitters (right). Already the effective four-photon emitters in figure 4 can be used as a design component in a conceptual way to create experimental blueprints for which no designs where known before. The effective six-photon emitters enhance that capability, and can be used for the generation of high-dimensional 6-photon GHZ states or 8-photon GHZ states with arbitrary dimension. Here it is shown for 3-dimensional GHZ states, but this structure can easily be expanded to arbitrary high dimensions, in the same way as demonstrated in figure 4(c). Furthermore, this opens up much more complex studies of the principle of Entanglement by Path identity [12]. For example, while two-photon emitters do not allow for 3- or higher dimensional GHZ states with 6 or more photons [43, 65], this experimental bound is not applicable anymore for multi-photon emitters such as these shown here [12]. The code to verify and explore these effective multi-photon emitters are available on github.

abstract design components, without any further computation, allowing for the generation of setups for which no blueprints are known so far. While we can now use these elements in an abstract way, and comprehend the underlying physics that lead to this behaviour, it remains an interesting open question for the moment how to construct generalized N-particle emitters.

We now estimate the count rates, including experimental loss, for the six- and eight- photon setup in figure 4. Following the same calculation as done for the four-photon emitter above, we compute the count-rates similar to the above case of the four-particle emitter. For the six-particle case we get

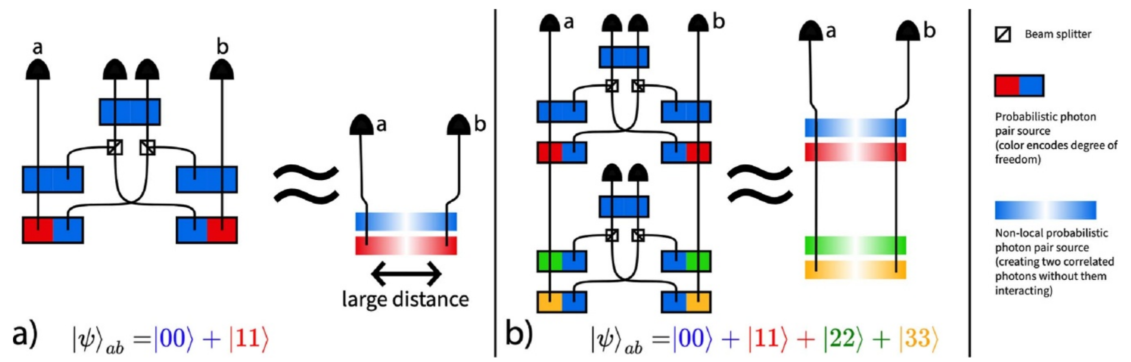

Figure 6. Non-local pair source emulated by pair sources (post-selected). (a) Shows a setup that behaves as two pair-sources sending a photon to each of the detectors a and b. An important distinction from two regular pair-sources (such as an SPDC crystal) however, is that the photons are not created in the same location. They can be spacelike separated, allowing for the non-local creation of entanglement. (b) Shows that the emulated pair sources can be used as a building block in the same way as the four-photon source while maintaining the possibility to spacelike separation of the two photon paths (a) and (b). Stacking two copies of the two-dimensional setup from (a) results in a non-local four-dimensional two photon source.

$C_6 = 2/\binom{19+6-1}{6} \times r \times p^6 = 0.025$ Hz and for the eight-particle case we get $C_8 = 2/\binom{28+8-1}{8} \times r \times p^8 = 3.6 * 10^{-6}$ Hz. The overall efficiency would be $E_6 = E_{\mathrm{D}}^{12} \times (E_{\mathrm{T}}^{6})^{12} \approx 26\%$ for the six-photon emitter and $E_8 = E_{\mathrm{D}}^{16} \times (E_{\mathrm{T}}^{7})^{16} \approx 14\%$ for the eight-photon emitter, reducing the effective count-rate even further.

(B) Non-local entanglement generation—Many quantum communication applications rely on the ability to distribute entanglement between different parties. A famous example for non-local entanglement generation is *entanglement swapping*, which creates entanglement between two photons that never interact [66]. Recently, new advances have been made in chip-based multi-photon quantum communication [67, 68], demonstrating the capabilities of state-of-the-art experimental platforms for this purpose. In figure 6(a) we show a setup which creates a Bell state between the photons sent to separate parties, a and b, without a common source between them. The two paths can be space-like separated, thus generating entanglement non-locally. Following a similar abstraction to the previous section, we can describe the setup as a non-local Bell state source. A vital component of this setup is the crystal which sends two photons to the two ancillary detectors, leading to a vacuum term without photons in a or b. This setup can be stacked in the same way as the four-particle emitter can, to produce higher-dimensional non-local entanglement generation (figure 6(b)). The two-dimensional base setup can be stacked k times to non-locally create a $2k$-dimensional Bell state experiment using $2k$ ancillary particles (where $k \in \mathbb{N}$). Similar approaches could also be taken to find general constructions for experiments with more than two non-local parties. At a big picture, the diagram represents a method for the non-local generation of high-dimensional entanglement, which has not been known before (e.g. there is no experimental proposal for high-dimensional entanglement swapping with SPDC crystals and linear optics).

Algorithmic design aiding human design—Solutions found by a computer algorithm are a key component of this work. The setups shown in figures 4(b), 5(a), (b) and 6 were found by the computer algorithm PYTHEUS [17]. Another important element of this work is to understand, which part of a setup can be used as a building block. By applying these insights we were able to construct more complex experiments by hand. This was done for the construction of 5-dimensional (and beyond) four-particle GHZ states in figure 4(c) and the creation of non-local four-dimensional (and beyond) entanglement between two photons in figure 6(b). This shows that solutions found by a computer can serve as an inspiration for human problem solving.

Outlook—In this article, we have presented an experimental setup, which emulates probabilistic multi-particle emitters using only pair sources. We have described how this abstraction can be used for general constructions of quantum experiments, focusing on effective four-photon emitters. Further, setups for emulating six- and eight-photon emitters have been found and hint at an exciting zoo of structures for creating entanglement. Programmable photonic devices such as the one from [6] promise the realization of increasingly complex multi-photon entanglement. The approach followed here could be a way of exploring new settings for these experimental platforms. As large quantum systems become computationally unfeasible to simulate, the generalizablity as shown in our manuscript will be important to design large-scale quantum technologies. A core incredient to our approach is an abstract representation of quantum optics in terms of colored and weighted graphs [16, 43, 63, 64], which we did not use here for the sake of accesibility for a broader audience. It is both computationally efficient for inverse-design done by computers and interpretable by humans. An extension of our approach to other domains of physics will be an interesting future project. For example in the field of quantum circuit design, abstract representations in terms of graphs [69] and graph-based information flow [70] could allow for a direct translation of our approach. At a big picture, our approach can be seen as a source of inspiration for new ideas in quantum optics, and we show here that such artificial systems can lead to new scientific abstractions. We use insight gained from singular examples found through a computer algorithm[1] and generalize to a whole class of solutions, which is a crucial element for scientific understanding [71–74]. In this context one important question emerges: How can a machine autonomously identify new core concepts and find correct abstractions and generalizations?

Data availability statement

No new data were created or analysed in this study.

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